Technological Educational Institute of Piraeus
KINGSTON University
MSc Postgraduate Course in the
Structural Design and Construction Management

Basic Principles on the

Design of Concrete Structures Subjected to Seismic Actions

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Larissa, February 2011

It is dedicated

To my family

and those who patiently work for a better world

Foreword

The purpose of this handout is to provide a text for the postgraduate student attending the courses of **Structural Design and Construction Management** at the Technological Educational Institute (**TEI**) **of Piraeus**, in the subject of **Earthquake Resistant Structures.**

The text is mainly referred to my lecture courses, based on the indicative content and the learning strategies applied by the Kingston University in co-operation with the TEI of Piraeus, for this module.

A lot of effort has been disbursed to cover fundamental demands of knowledge in a simple and easily understood way, since the content of this sector is really huge.

Wherever possible, simple illustrations or examples have been used to clarify the text.

Reproduction of detailed working drawings has been avoided, since these are often confusing to the student until the fundamentals of the subject are fully understood.

In the hope that a large part of my targets has been realised, I hand over this textbook to the postgraduate students attending the courses of the above module, accepting every criticism of good faith which could be proved useful in the future.

Larissa, February 2011

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Introduction

The earthquake has begun to become a problem for humans since they started building. This is because a structural system is designed basically for gravity loads and not for the horizontal inertial loads that are generated during an earthquake.

Indeed, the seismic actions on a structure are not a result of externally applied loads. They are mainly derived from distortions due to the ground motions caused by the earthquake. Consequently they are different from wind or gravity loads, which are applied on the structure externally.

Although catastrophic earthquakes take usually place to certain geographical areas, the so called 'seismic zones', the damage they cause in densely populated areas and the number of deaths, give rise to a world-wide interest.

Because of the deaths and the damage to buildings, the earthquakes have several economic, psychological, social and even political effects. This is the reason that many scientists, such as seismologists, engineers, psychologists, economists and so on deal with this problem. All these scientific branches are eventually directed to a unique target: the effort of creating **earthquake-resistant structures**.

The behavior of a structure during an earthquake depends on two basic parameters: (a) the intensity of the earthquake and (b) the quality of the structure.

The **quality** of the structure is a parameter with sufficient level of reliability since it depends on the structural system, the design procedure and careful construction. However, the **intensity** of the earthquake is a parameter with very high uncertainty.

In fact, the intensity of the earthquake at a certain point is a function of several factors, such as the epicentral distance, the focal depth, the magnitude of the earthquake on the Richter scale, the geological formations between the epicenter and the reference point, the local soil conditions and so on. The term 'intensity' expresses the seismic hazard, and, on the relevant response spectra, reflects to a degree, the maximum ground displacements, velocities and accelerations.

For every geographical area, the ideal solution for estimating the seismic hazard would have been the existence of response spectra, based on long-term observations of seismic action. However, due to the lack of such material, the estimation is usually based on two, not particularly reliable, methods:

1. Estimation of the expected maximum acceleration with a specific probability of occurrence for a certain return period and

2. Estimation of the expected intensity, measured on the behavior of structures to the earthquake, or, to a certain degree, on scales, such as the Modified Mercalli (MM) scale.

The seismic **design philosophy** can generally be summarized in the following requirements:

- Serviceability limit state: Structures must resist low-intensity earthquakes without any structural damage. This means that during small and frequent earthquakes all structural components should remain in their elastic range.

- Ultimate limit state: Structures should withstand earthquakes of medium intensity, with a very light and repairable damage in their structural elements. This intensity (earthquake design) has a peak acceleration, with 90% probability of not being exceeded in 50 years.

- Collapse limit state: Structures should withstand earthquakes of high-intensity, with a return period much longer than their design life without collapsing.

The application of the above criteria implies that the maximum seismic intensity along with its return period must be taken into account when designing a structure. Furthermore, it denotes that the elastic limit of the structure is allowed to be exceeded during earthquakes of medium or high intensity. This means that the structure should be able to undergo high elastic deformations without losing a large percentage of its strength.

Eventually the problem of seismic behavior of structures is primarily an energy-related one. In order for a structure to avoid collapse, it should be in position to absorb and dissipate the kinetic energy imparted in it during the seismic excitation.

The understanding of this simple energy – balance – principle, is the key for the development of modern earthquake resistant design.

Basic Principals on Engineering Seismology

What Is Seismology

Seismology is the study of earthquakes and seismic waves that move through and around the earth. A seismologist is a scientist who studies earthquakes and seismic waves.

What Are Seismic Waves

Seismic waves are the waves of energy caused by the sudden breaking of rock within the earth or an explosion. They are the energy that travels through the earth and is recorded on seismographs.

Types of Seismic Waves

There are several different kinds of seismic waves, and they all move in different ways. The two main types of waves are **body waves** and **surface waves**. Body waves can travel through the earth's inner layers, but surface waves can only move along the surface of the planet like ripples on water. Earthquakes radiate seismic energy as both body and surface waves.

Body - Waves

Traveling through the interior of the earth, **body waves** arrive before the surface waves emitted by an earthquake. These waves are of a higher frequency than surface waves.

P - Waves

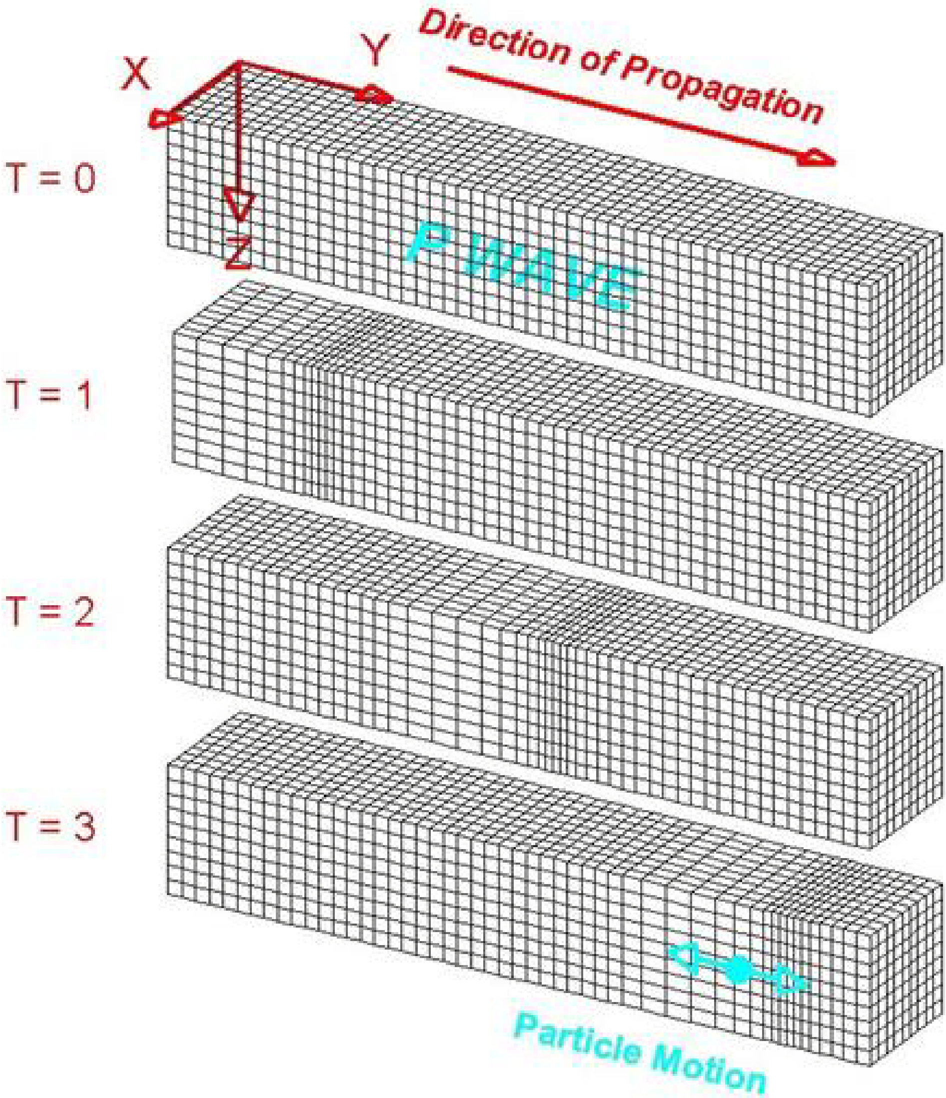
The first kind of body wave is the P wave or **P**rimary wave. This is the fastest kind of seismic wave, and, consequently, the first to 'arrive' at a seismic station. The P wave can move through solid rock and fluids, like water or the liquid layers of the earth. It pushes and pulls the rock it moves through just like sound waves push and pull the air.

Have you ever heard a big clap of thunder and the windows rattle at the same time? The windows rattle because the sound waves were pushing and pulling on the window glass much like P waves push and pull on rock.

Sometimes animals can hear the P waves of an earthquake. Dogs, for instance, commonly begin barking hysterically just before an earthquake 'hits' (or more specifically, before the surface waves arrive). Usually people can only feel the bump and rattle of these waves.

P waves are also known as **compressional waves**, because of the pushing and pulling they do.

Subjected to a P wave, particles move in the same direction that the wave is moving in, which is the direction that the energy is traveling in, and is sometimes called the 'direction of wave propagation'



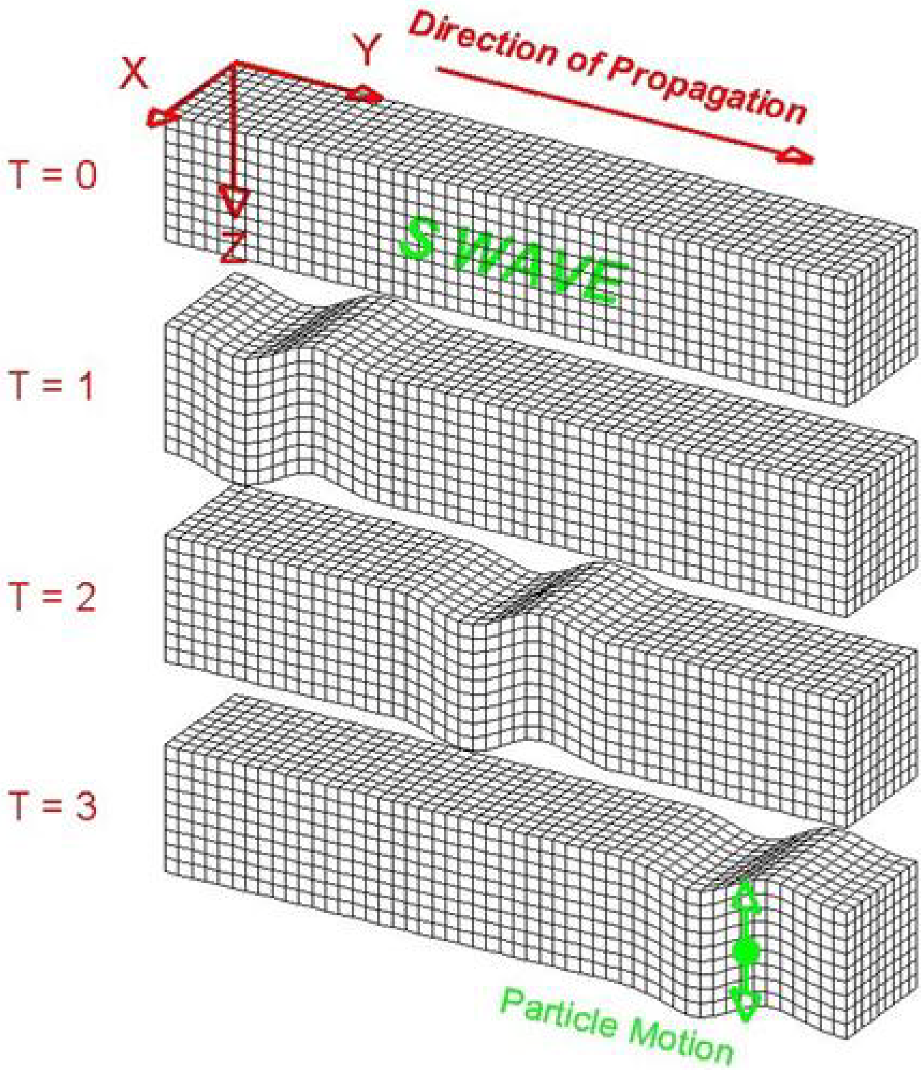
P waves travel through a medium by means of compression and dilation.

S - Waves

The second type of body wave is the S wave or Secondary wave, which is the second wave you feel in an earthquake. An S wave is slower than a P wave and can only move through solid rock, not through any liquid medium.

It is this property of S waves that led seismologists to conclude that the Earth's outer core is a liquid.

S waves move rock particles up and down, or side-to-side perpendicular to the direction that the wave is traveling in (the direction of wave propagation).



An S – wave travels through a medium

Surface Waves

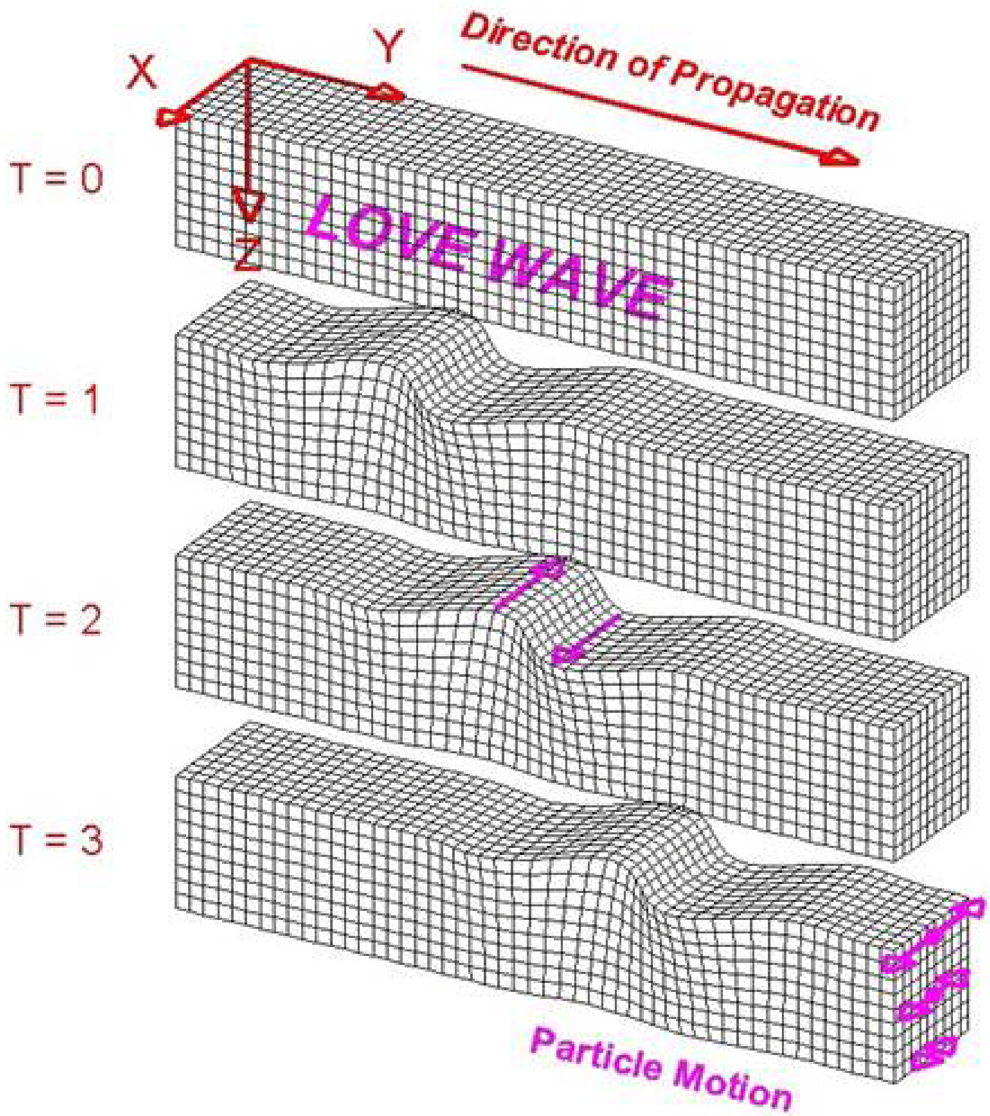
Travelling only through the crust, **surface waves** are of a lower frequency than body waves, and are easily distinguished on a seismogram as a result.

Though they arrive after body waves, it is surface waves that <u>are almost entirely responsible for the damage and destruction associated with earthquakes</u>. This damage and the strength of the surface waves are reduced in deeper earthquakes.

Surface waves are divided in **Love** waves and **Rayleigh** waves.

Love Waves

The first kind of surface wave is called a **Love wave**, named after A.E.H. Love, a British mathematician who worked out the mathematical model for this kind of wave in 1911. It's the fastest surface wave and moves the ground from side-to-side. Confined to the surface of the crust, Love waves produce entirely horizontal motion.

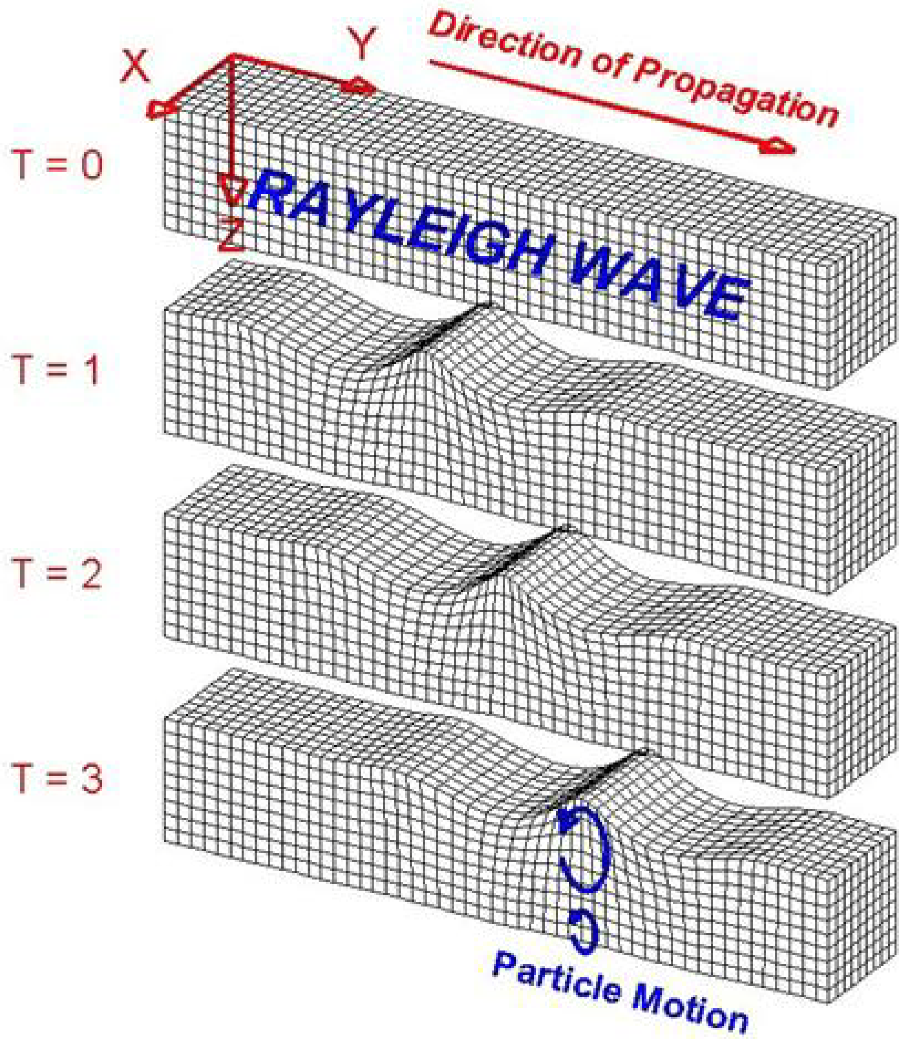


A Love wave travels through a medium

Rayleigh Waves

The other kind of surface wave is the Rayleigh wave, named for John William Strutt, Lord Rayleigh, who mathematically predicted the existence of this kind of wave in

1885. A Rayleigh wave rolls along the ground just like a wave rolls across a lake or an ocean. Because it rolls, it moves the ground up and down, and side-to-side in the same direction that the wave is moving. Most of the shaking felt from an earthquake is due to the Rayleigh wave, which can be much larger than the other waves.



Rayleigh waves travel through a medium

Making P and S Waves

You can imitate the motion of P and S waves using a Slinky (the metal ones work best). The S wave can also be simulated using a piece of rope in place of a Slinky. These activities work best with a partner and on a flat surface such as a table or the floor.

Making P Waves

P waves consist of a **compessional** (shortening) motion and a **dilational** (expanding) motion that both lie along a line. As you make your own P wave in this exercise, try to identify the **compressions** and **dilations** in the Slinky. Here's how you do it:

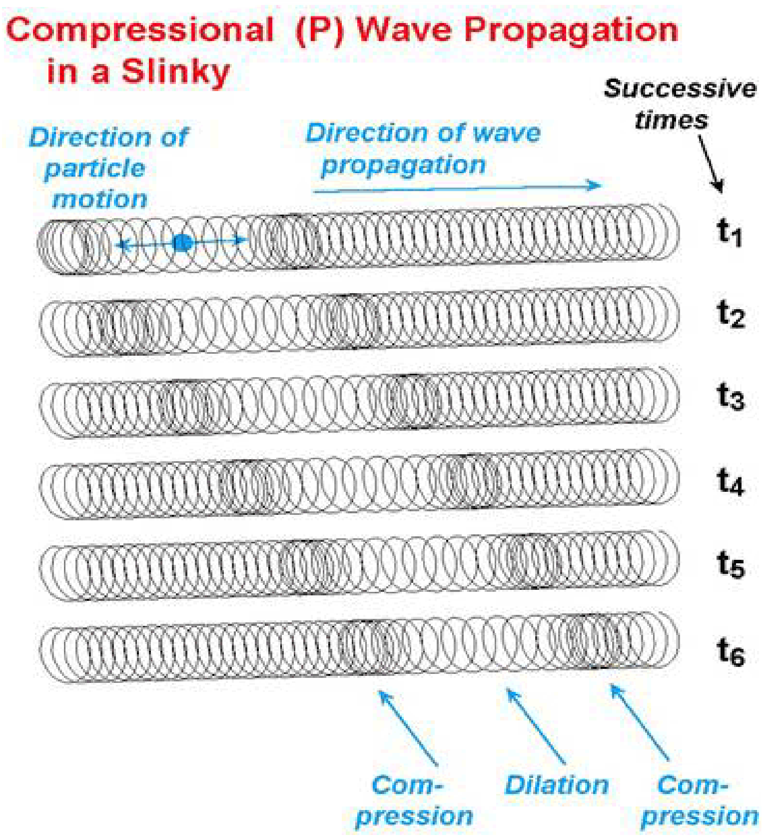
1. Place the Slinky on a flat surface. Have your partner hold the opposite end of the Slinky. If you don't have a partner, you can tie the Slinky onto a hook in the wall or onto a door knob (close the door first) and try this activity in the air.

2. Holding the other end of the Slinky, walk away from your partner, or from the wall or door.

3. Stop walking away when the Slinky isn't sagging anymore (if in the air) or there is no more slack. Don't pull the Slinky too tight; just take up the slack.

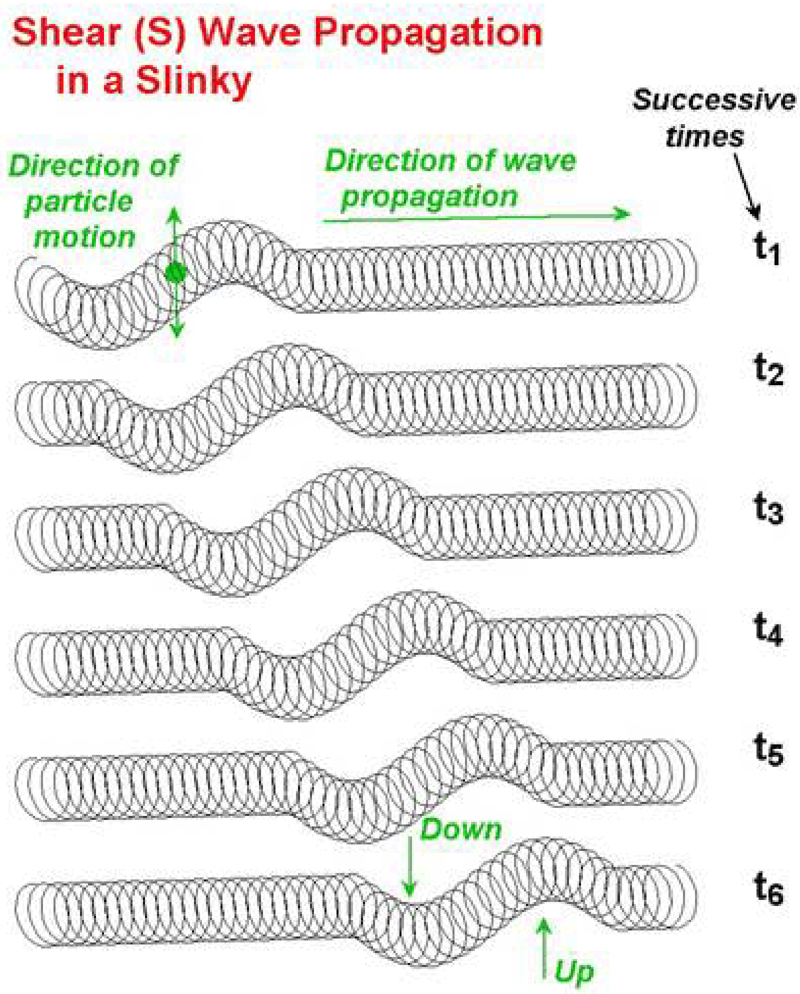
4. Push your end of the Slinky towards your partner in one, quick motion (if the Slinky is suspended in the air, quickly jerk your end of the Slinky towards the wall and then back). Don't let go off the Slinky.

You'll see waves similar to P waves moving back and forth along the Slinky as below:



Making S Waves

When making your S wave, notice how the Slinky itself moves in a direction perpendicular to the direction that the energy is traveling in (perpendicular to the direction of wave propagation). S waves are more complex than P waves, but they should be easier to simulate in this activity:



1. Place the Slinky on a flat surface, and have your partner hold the opposite end of the Slinky. If working alone, tie one end of the Slinky to a hook on the wall or a door knob (close the door first).

2. Holding the other end of the Slinky, walk away from your partner, or from the wall or door.

3. Stop walking when the Slinky has only some slack left. If working alone and the Slinky is suspended in the air, you want to stop walking only when the Slinky no longer sags in the air. Don't pull the Slinky tight; just take up most of the slack.

4. Quickly jerk your end of the Slinky from side to side once. If the Slinky is suspended in the air, a quick jerk up and down once is sufficient. Don't let go of the Slinky.

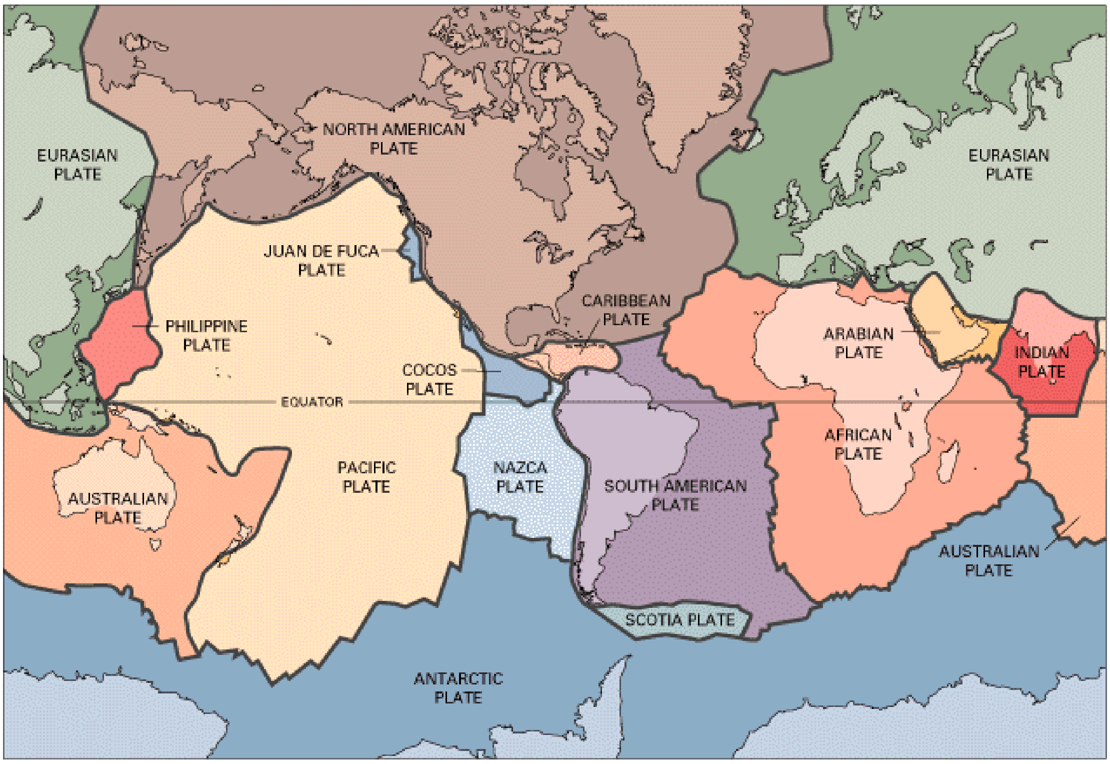
You'll see waves similar to S waves moving along the Slinky like in the preceding picture:

Where Do Earthquakes Happen?

Earthquakes occur all the time all over the world, both along plate edges and along faults.

Along Plate Edges

Most earthquakes occur along the edge of the **oceanic** and **continental plates**. The earth's **crust** (the outer layer of the planet) is made up of several pieces, called **plates**.



An image of the world's plates and their boundaries. Notice that many plate boundaries do not coincide with coastlines.

The plates under the oceans are called oceanic plates and the rest are continental plates. They are moving around by the motion of a deeper part of the earth (the **mantle**) that lies underneath the crust.

These plates are always bumping into each other, pulling away from each other, or past each other. The plates usually move at about the same speed that your fingernails grow.

Earthquakes usually occur where two plates are running into each other or sliding past each other.

Along Faults

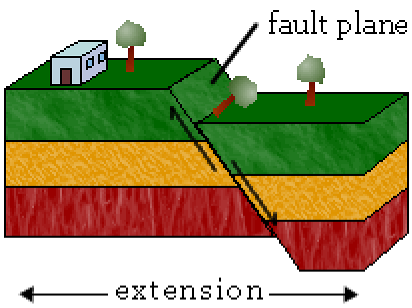
Earthquakes can also occur far from the edges of plates, along faults. **Faults** are cracks in the earth where sections of a plate (or two plates) are moving in different directions.

Faults are caused by all that bumping and sliding the plates do. They are more common near the edges of the plates.

Types of Faults

Normal faults are the cracks where one block of rock is sliding downward and away from another block of rock.

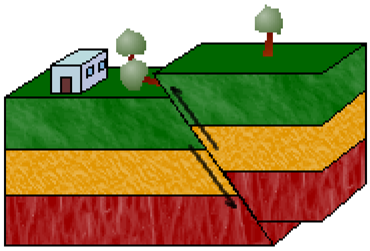
These faults usually occur in areas where a plate is very slowly splitting apart or where two plates are pulling away from each other. A normal fault is defined by the hanging wall moving down relative to the footwall, which is moving up.



A normal fault. Tthe 'footwall' is on the 'upthrown' side of the fault, moving upwards. The 'hanging wall' is on the 'downthrown' side of the fault, moving downwards.

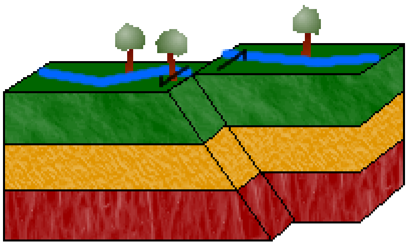
Reverse faults are cracks formed where one plate is pushing into another plate. They also occur where a plate is folding up because it's being compressed by another plate pushing against it. At these faults, one block of rock is sliding underneath another block or one block is being pushed up over the other.

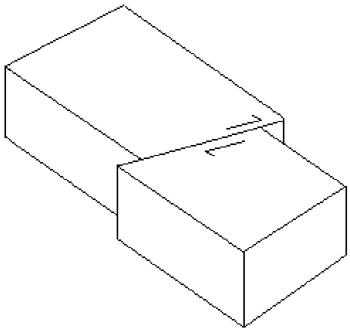
A reverse fault is defined by the hanging wall moving up relative to the footwall, which is moving down.



A reverse fault. This time, the 'footwall' is on the 'downthrown' side of the fault, moving downwards, and the 'hanging wall' is on the 'upthrown' side of the fault, moving upwards. When the hanging wall is on the upthrown side, it 'hangs' over the footwall.

Strike-slip faults are the cracks between two plates that are sliding past each other horizontally. This type of fault is caused by shearing forces and can cause powerful earthquakes.



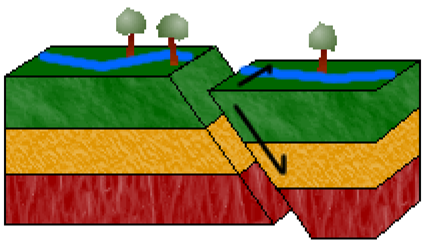


Two strike-slip faults.

***Left**, a left-lateral strike-slip fault. No matter which side of the fault you are on, the **other** side is moving to the **left**.*

***Right**, a right-lateral strike-slip fault. No matter which side of the fault you are on, the **other** side is moving to the **right**.*

Oblique-slip faults are a combination of normal and strike-slip faulting, i.e. a mixing of shearing and tensional or compressional forces.



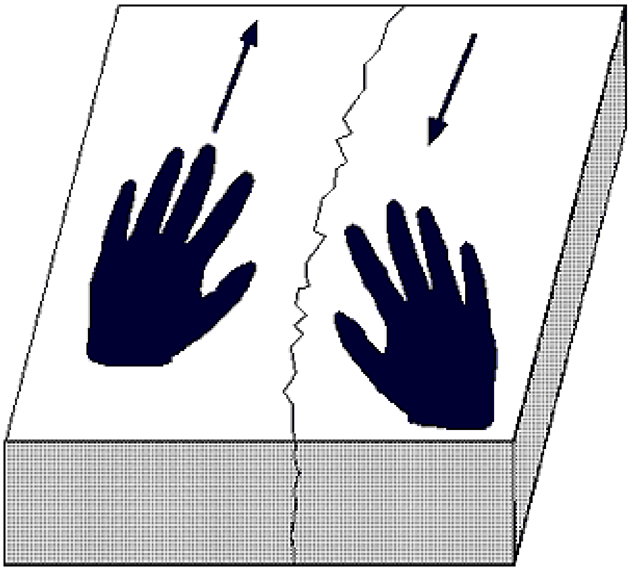
Why Earthquakes Happen

Earthquakes are usually caused when rock underground suddenly breaks along a fault. This sudden release of energy causes the seismic waves that make the ground shake.

When two blocks of rock or two plates are rubbing against each other, they stick a little. They don't just slide smoothly; the rocks catch on each other. The rocks are still pushing against each other, but not moving. After a while, the rocks break because of all the pressure that's built up.

When the rocks break, the earthquake occurs. During the earthquake and afterward, the plates or blocks of rock start moving, and they continue to move until they get stuck again. The spot underground where the rock breaks is called the **focus** of the earthquake. The place right above the focus (on top of the ground) is called the **epicenter** of the earthquake.

Try this little experiment:



1. Break a block of foam rubber in half.
2. Put the pieces on a smooth table.
3. Put the rough edges of the foam rubber pieces together.
4. While pushing the two pieces together lightly, push one piece away from you along the table top while pulling the other piece toward you. See how they stick?
5. Keep pushing and pulling smoothly.

Soon a little bit of foam rubber along the crack (the fault) will break and the two pieces will suddenly slip past each other. That sudden breaking of the foam rubber is the earthquake. **That's just what happens along a strike-slip fault.**

How Are Earthquakes Studied

Seismologists study earthquakes by going out and looking at the damage caused by the earthquakes and by using seismographs. A **seismograph** is an instrument that records the shaking of the earth's surface caused by seismic waves. The term **seismometer** is also used to refer to the same device, and the two terms are often used interchangeably.

The First Seismograph

The first seismograph was invented in 132 A.D. by the Chinese astronomer and mathematician Chang Heng. He called it an "earthquake weathercock."

Each of the eight dragons had a bronze ball in its mouth. Whenever there was even a slight earth tremor, a mechanism inside the seismograph would open the mouth of one dragon. The bronze ball would fall into the open mouth of one of the toads, making enough noise to alert someone that an earthquake had just happened. Imperial watchman could tell which direction the earthquake came from by seeing which dragon's mouth was empty.

A large-scale model of Cheng Heng's original earthquake weathercock.

In 136 A.D. a Chinese scientist named Choke updated this meter and called it a "seismoscope." Columns of a viscous liquid were used in place of metal balls. The height to which the liquid was washed up the side of the vessel indicated the

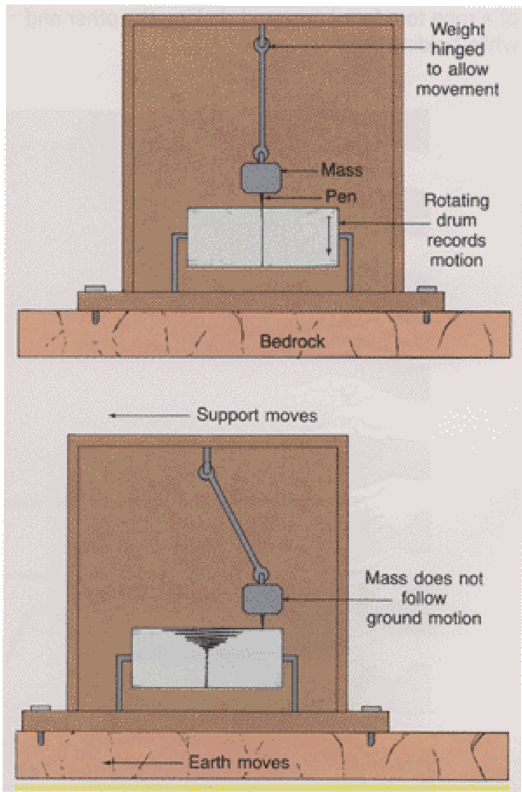
intensity and a line joining the points of maximum motion also denoted the direction of the tremor.

Modern Seismographs

Most seismographs today are electronic, but a basic seismograph is made of a drum with paper on it, a bar or spring with a hinge at one or both ends, a weight, and a pen. The one end of the bar or spring is bolted to a pole or metal box that is bolted to the ground. The weight is put on the other end of the bar and the pen is stuck to the weight. The drum with paper on it presses against the pen and turns constantly.

When there is an earthquake, everything in the seismograph moves except the weight with the pen on it. As the drum and paper shake next to the pen, the pen makes squiggly lines on the paper, creating a record of the earthquake. This record made by the seismograph is called a **seismogram**.

By studying the seismogram, the seismologist can tell how far away the earthquake was and how strong it was. This record doesn't tell the seismologist exactly where the epicenter was, just that the earthquake happened so many miles or kilometers away from that seismograph. To find the exact epicenter, you need to know what at least two other seismographs in other parts of the country or world recorded. We'll get to that soon. First, let us learn how to read a seismogram.



Two illustrations of a modern seismograph in action (from Lutgens&Tarbuck, 1989)

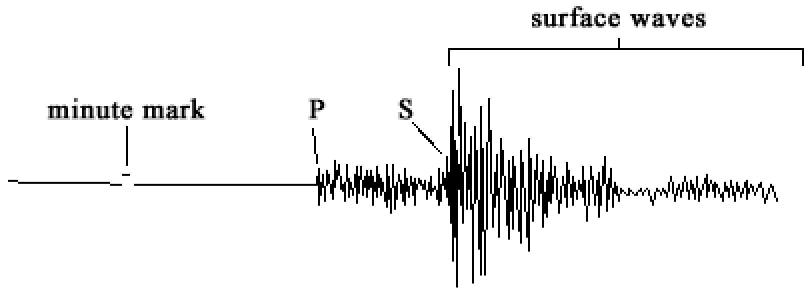
How to Read a Seismogram

When you look at a seismogram, there will be wiggly lines all across it. These are all the seismic waves that the seismograph has recorded. Most of these waves were so small that nobody felt them.

These tiny **microseisms** can be caused by heavy traffic near the seismograph, waves hitting a beach, the wind, and any number of other ordinary things that cause some shaking of the seismograph.

There may also be some little dots or marks evenly spaced along the paper.

These are marks for every minute that the drum of the seismograph has been turning. How far apart these minute marks are, will depend on what kind of seismograph you have.



A typical seismogram

So which wiggles are the earthquake?

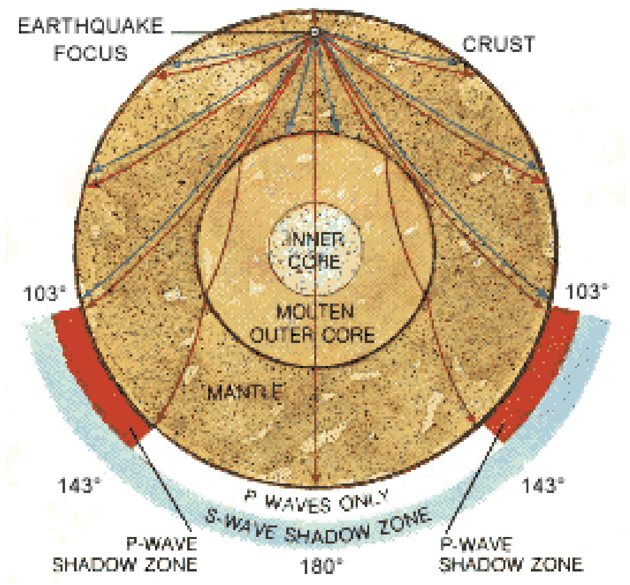
The **P wave will be the first** wiggle that is bigger than the rest of the little ones (the microseisms). Because P waves are the fastest seismic waves, they will usually be the first ones that your seismograph records.

The **next** set of seismic waves on your seismogram will be the **S waves**. These are usually bigger than the P waves.

If there aren't any S waves marked on your seismogram, it probably means the earthquake happened on the other side of the planet. S waves can't travel through the liquid layers of the earth so these waves never made it to your seismograph.

The **surface waves** (Love and Rayleigh waves) are the other, often larger, waves marked on the seismogram. They have a lower **frequency**, which means that waves (the lines; the ups-and-downs) are more spread out.

Surface waves travel a little slower than S waves (which, in turn, are slower than P waves) so they tend to arrive at the seismograph just after the S waves.



A cross-section of the earth, with earthquake wave paths defined and their shadow-zones highlighted.

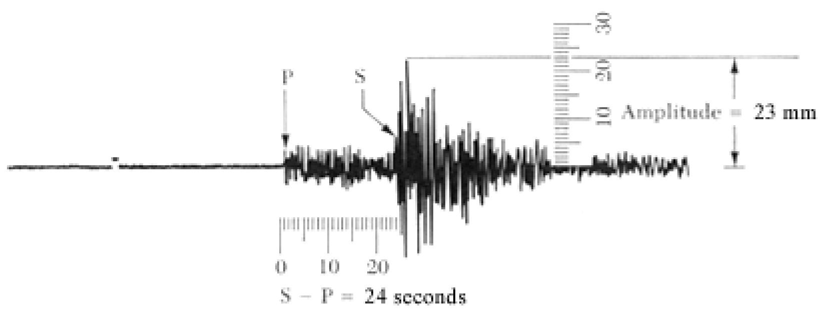
For shallow earthquakes (earthquakes with a focus near the surface of the earth), the surface waves may be the largest waves recorded by the seismograph. Often they are the only waves recorded a long distance from medium-sized earthquakes.

How to Locate an Earthquake's Epicenter

To figure out just where that earthquake happened, you need to look at your seismogram and you need to know what **at least two other seismographs** recorded **for the same earthquake**.

You will also need a map of the world, a ruler, a pencil, and a compass for drawing circles on the map.

Here's an example of a seismogram:



Our typical seismogram from before, this time marked for this exercise (from Bolt, 1978).

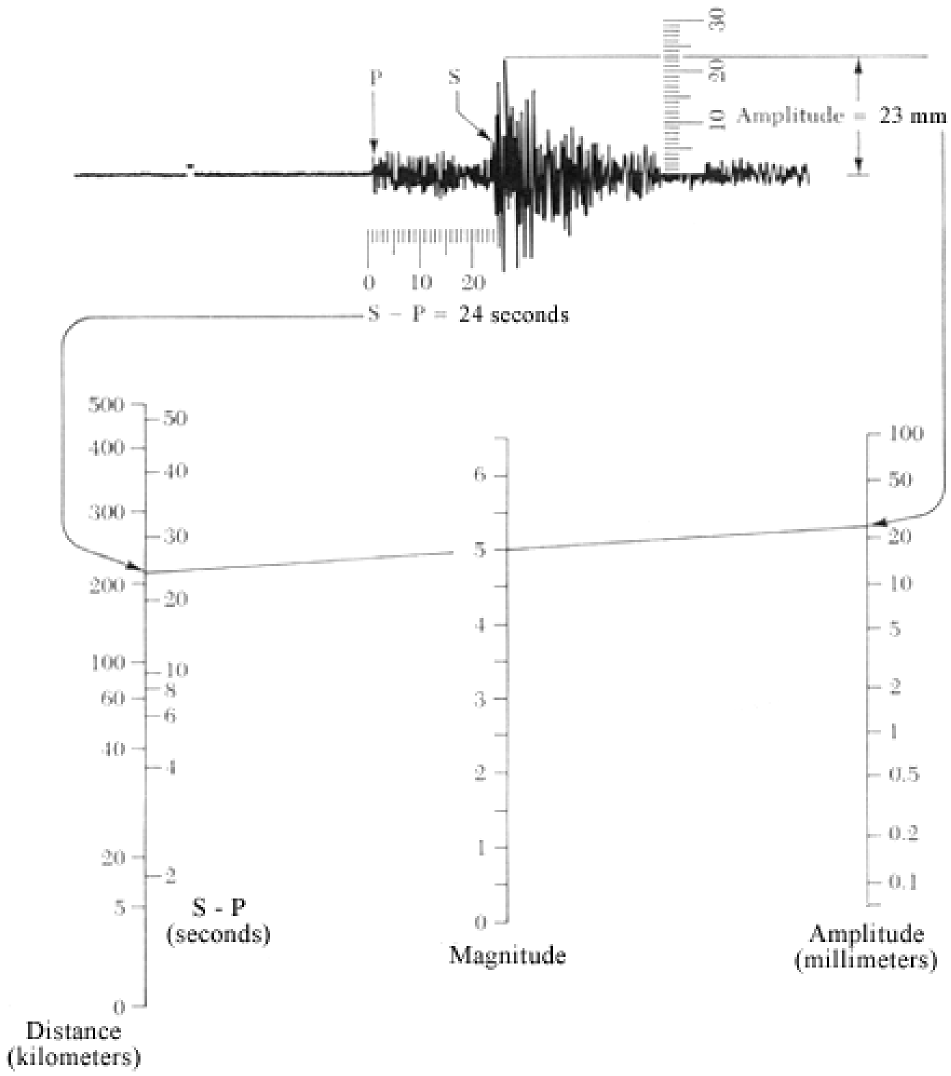
One minute intervals are marked by the small lines printed just above the squiggles made by the seismic waves (the time may be marked differently on some seismographs).

The distance between the **beginning** of the first P wave and the **first S wave** tells you how many seconds the waves are apart.

This number will be used to tell you **how far** your seismograph is from the epicenter of the earthquake.

Finding the Distance to the Epicenter and the earthquake's Magnitude

1. Measure the distance between the first P wave and the first S wave. In this case, the first P and S waves are 24 seconds apart.



Use the amplitude to derive the magnitude of the earthquake, and the distance from the earthquake to the station. (from Bolt, 1978)

2. Find the point for 24 seconds on the left side of the previous chart and mark it. According to the chart, this earthquake's epicenter was 215 kilometers away.

3. Measure the amplitude of the strongest wave. The **amplitude** is the height (on paper) of the strongest wave. Here, the amplitude is 23 millimeters. Find 23 millimeters on the right side of the chart and mark that point.

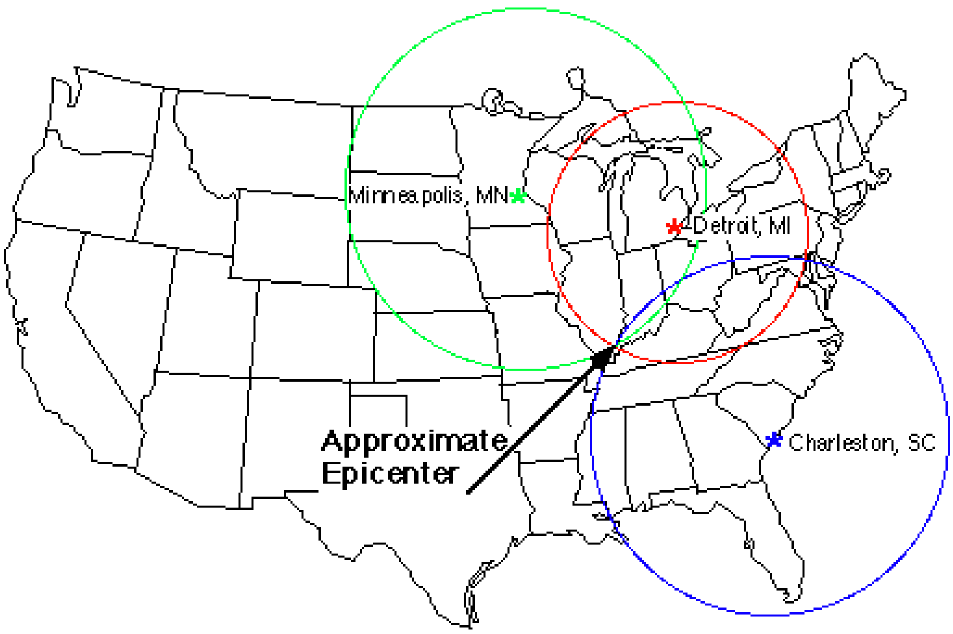
4. Place a ruler (or straight edge) on the chart between the points you marked for the distance to the epicenter and the amplitude. The point where your ruler crosses the middle line on the chart marks the **magnitude** (strength) of the earthquake. This earthquake had a magnitude of 5.0.

Finding the Epicenter

You have just figured out how far your seismograph is from the epicenter and how strong the earthquake was, but you still don't know exactly where the earthquake occurred.

This is where the compass, the map, and the other seismograph records come in.

Check the scale on your map. It should look something like a piece of a ruler. All maps are different. On your map, one centimeter could be equal to 100 kilometers or something like that.



The point where the three circles intersect is the epicenter of the earthquake. This technique is called 'triangulation.'

Figure out how long the distance to the epicenter (in centimeters) is on your map. For example, say your map has a scale where one centimeter is equal to 100 kilometers. If the epicenter of the earthquake is 215 kilometers away, that equals 2.15 centimeters on the map.

Using your compass, draw a circle with a radius equal to the number you came up with in Step #2. The center of the circle will be the location of your seismograph. The epicenter of the earthquake is somewhere on the edge of that circle.

Do the same thing for the distance to the epicenter that the other seismograms recorded (with the location of those seismographs at the center of their circles). All of the circles should overlap. The point where **all** of the circles overlap is the approximate epicenter of the earthquake.

How Are Earthquake Magnitudes Measured

The Richter scale

The magnitude of most earthquakes is measured on the **Richter scale**, invented by Charles F. Richter in 1934.

The Richter magnitude is calculated from the amplitude of the largest seismic wave recorded for the earthquake, no matter what type of wave was the strongest. It is based on a logarithmic scale (base 10).

Charles Richter studying a seismogram.

What this means is that for each whole number you go up on the Richter scale, **the amplitude of the ground motion** recorded by a seismograph goes up ten times.

Using this scale, a magnitude 5 of an earthquake would result in ten times the level of ground shaking as a magnitude 4 earthquake (and 28-32 times as much energy would be released).

To give you an idea how these numbers can add up, think of it in terms of the energy released by explosives: a magnitude 1 seismic wave releases as much energy as blowing up 6 ounces(6x28.35 gr) of TNT. A magnitude 8 earthquake releases as much energy as detonating **6 million tons of TNT**.

Fortunately, most of the earthquakes that occur each year are magnitude 2.5 or less, too small to be felt by most people.

The Richter magnitude scale can be used to describe earthquakes so small that they are expressed in negative numbers. The scale also has no upper limit, so it can describe earthquakes of unimaginable and (so far) inexperienced intensity, such as magnitude 10.0 and beyond.

Although Richter originally proposed this way of measuring an earthquake's "size," he only used a certain type of seismograph and measured shallow earthquakes in Southern California.

Scientists have now made other "magnitude" scales, all calibrated to Richter's original method, to use a variety of seismographs and measure the depths of earthquakes of all sizes.

Here is a table describing the magnitudes of earthquakes, their effects, and the estimated number of those earthquakes that occur each year.

Earthquake Magnitude Scale

Magnitude	**Earthquake Effects**	**Estimated Numb/Year**
2.5 or less	Usually not felt, but can be recorded by seismograph.	900,000
2.5 to 5.4	Often felt, but only causes minor damage.	30,000
5.5 to 6.0	Slight damage to buildings and other structures.	500
6.1 to 6.9	May cause a lot of damage in very populated areas.	100
7.0 to 7.9	Major earthquake. Serious damage.	20
8.0 or greater	Great earthquake. Can totally destroy communities near the epicenter.	One every 5 to 10 years

Earthquake Magnitude Classes

Earthquakes are also classified in categories ranging from minor to great, depending on their magnitude.

Class	Magnitude
Great	8 or more
Major	7 - 7.9
Strong	6 - 6.9
Moderate	5 - 5.9
Light	4 - 4.9
Minor	3 -3.9

The Mercalli Scale

Another way to measure the strength of an earthquake is to use the **Mercalli scale**. Invented by Giuseppe Mercalli in 1902, this scale uses the observations of the people who experienced the earthquake to estimate its intensity.

The mercalli scale isn't considered as scientific as the richter scale, though. Some witnesses of the earthquake might exaggerate just how bad things were during the earthquake and you may not find two witnesses who agree on what happened; everybody will say something different. The amount of damage caused by the earthquake may not accurately record how strong it was either.

Giuseppe Mercalli

Some things that affect the amount of damage that occurs are:

- the building designs,
- the distance from the epicenter and
- the type of surface material (rock or dirt) the buildings rest on.

Different building designs hold up differently in an earthquake and the further you are from the earthquake, the less damage you'll usually see. Whether a building is built on solid rock or sand makes a big difference in how much damage it takes. Solid rock usually shakes less than sand, so a building built on top of solid rock shouldn't be as damaged as it might if it was sitting on a sandy lot.

What Are Earthquake Hazards

Earthquakes really pose little direct danger to a person. People can't be shaken to death by an earthquake. Some movies show scenes with the ground suddenly opening up and people falling into fiery pits, but this just doesn't happen in real life.

The Effect of Ground Shaking

The first main earthquake hazard (danger) is the **effect of ground shaking**. Buildings can be damaged by shaking themselves or by the ground beneath them settling to a different level than it was before the earthquake (**subsidence**).

These men barely escaped when the front of the anchorage J.C. Penny's collapsed during the 1964 Good Friday earthquake.

One side of this Anchorage street dropped drastically during the 1964 Good Friday earthquake.

Buildings can even sink into the ground if **soil liquefaction** occurs.

These buildings in Japan toppled when the soil underwent liquefaction.

Liquefaction is the mixing of sand or soil and **groundwater** (water underground) during the shaking of a moderate or strong earthquake. When the water and soil are mixed, the ground becomes very soft and acts similar to quicksand.

If liquefaction occurs under a building, it may start to lean, tip over, or sink several feet. The ground firms up again after the earthquake has past and the water has settled back down to its usual place deeper in the ground. Liquefaction is a hazard in areas that have groundwater near the surface and sandy soil.

Buildings can also be damaged by **strong surface waves** making the ground heave and lurch.

Any buildings in the path of these surface waves can lean or tip over from the movement.

The ground shaking may also cause landslides, mudslides, and avalanches on steeper hills or mountains, all of which can damage buildings and hurt people.

Ground Displacement

The second main earthquake hazard is **ground displacement** (ground movement) along a fault. If a structure (a building, road, etc.) is built across a fault, the ground displacement during an earthquake could seriously damage or rip apart that structure.

This road, which crosses the San Andreas fault, was cut in half by the 1906 earthquake. One end of the road slid 6.5 meters past the other during the quake.

From the previous picture it is obvious that San Andreas fault is a **right-lateral** transverse (strike-slip) fault, because the other side of the road (on the opposite side of the fault) has moved to the right, relative to the photographer's position.

Flooding

The third main hazard is **flooding**. An earthquake can **rupture** (break) dams or levees along a river. The water from the river or the reservoir would then flood the area, damaging buildings and maybe sweeping away or drowning people.

The Seward, Alaska, railroad yard was a twisted mess after being hit by a tsunami in 1964. The tsunami was triggered by the Good Friday earthquake

Tsunamis and seiches can also cause a great deal of damage.

A **tsunami** is what most people call a tidal wave, but it has nothing to do with the tides on the ocean. It is a huge wave caused by an earthquake under the ocean. Tsunamis can be tens of feet high when they hit the shore and can do enormous damage to the coastline.

Seiches are like small tsunamis. They occur on lakes that are shaken by the earthquake and are usually only a few feet high, but they can still flood or knock down houses, and tip over trees.

Fire

The fourth main earthquake hazard is **fire**. These fires can be started by broken gas lines and power lines, or tipped over wood or coal stoves. They can be a serious problem, especially if the water lines that feed the fire hydrants are broken.

For example, after the Great San Francisco Earthquake in 1906, the city burned for three days. Most of the city was destroyed and 250,000 people were left homeless.

San Francisco burning after the 1906 earthquake

Most of the hazards to people come from man-made structures themselves and the shaking they receive from the earthquake.

Conclusions

In conclusion, the real dangers to people are:

- being crushed in a collapsing building,
- drowning in a flood caused by a broken dam or levee,
- getting buried under a landslide, or
- being burned in a fire.

Complementary concepts of engineering seismology

Geographical distribution of earthquakes

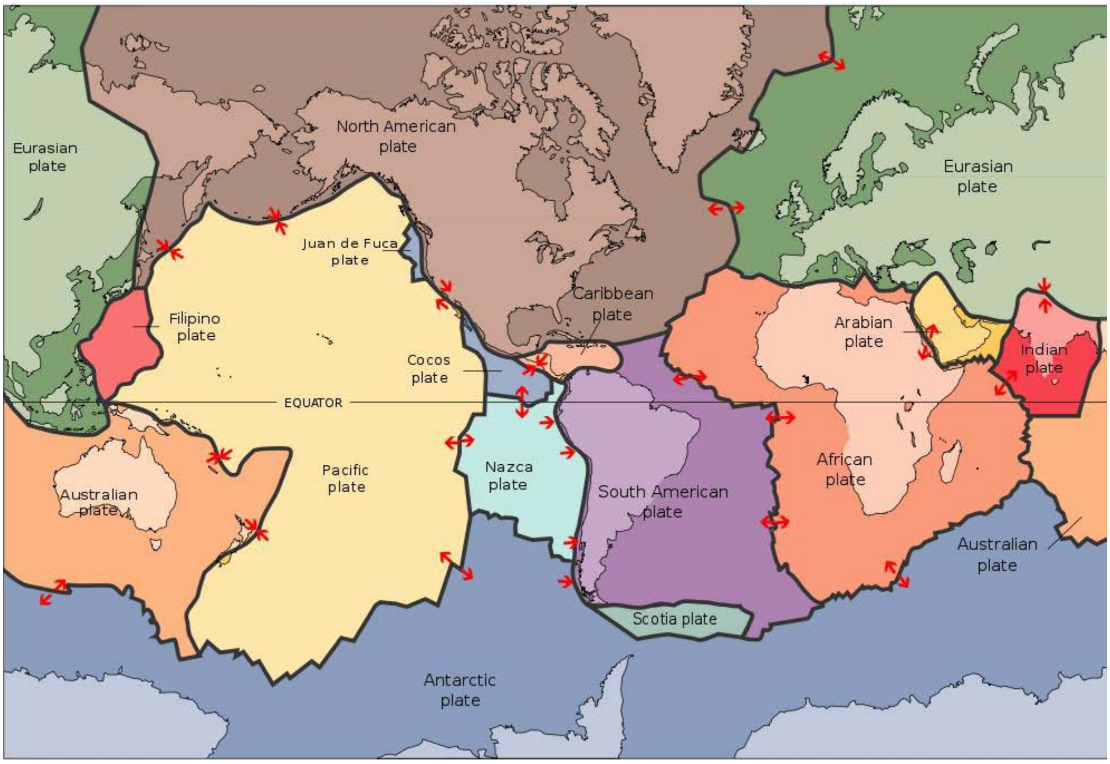
An earthquake is a ground vibration caused mainly by the fracture of the earth crust or by a sudden movement along an already existing fault. This is the majority of the cases which constitute the so called ‘tectonic earthquakes’.

Very rarely earthquakes may be caused by volcanic eruptions.

A well established and widely accepted theory of tectonic earthquakes is the ‘**elastic rebound theory**’ developed in 1906 by Reid. According to this theory, earthquakes are caused by a **sudden release of elastic strain energy** in the form of kinetic energy along the length of a geological fault.

The accumulation of the above strain energy can be explained by the theory of motion of lithospheric plates, which constitute the crust of the earth.

These plates are originated in the oceanic rifts and they sink in the continental trench system.



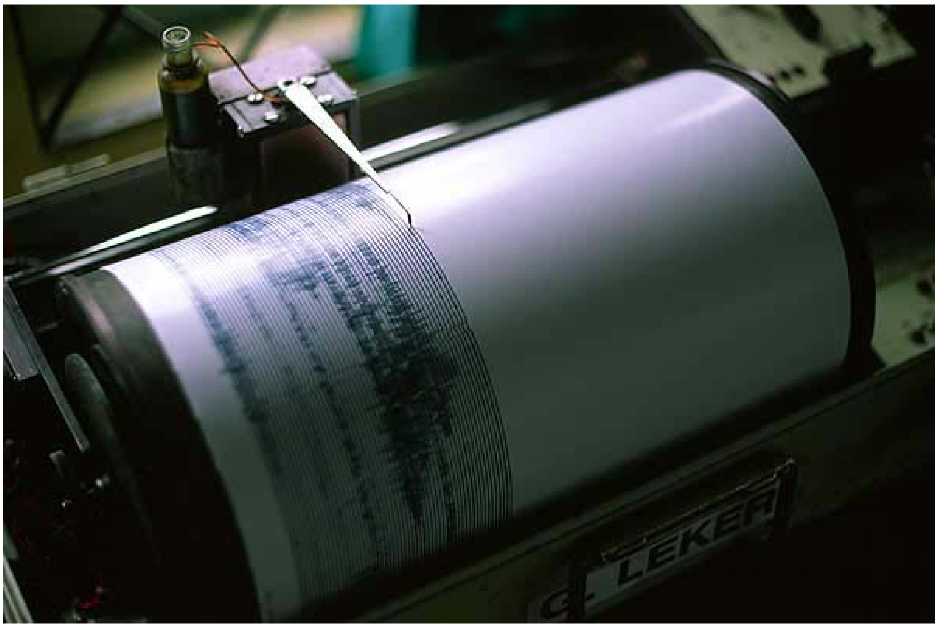
Tectonic plates

The boundaries of the lithospheric plates coincide with the geographical zones which experience frequent earthquakes.

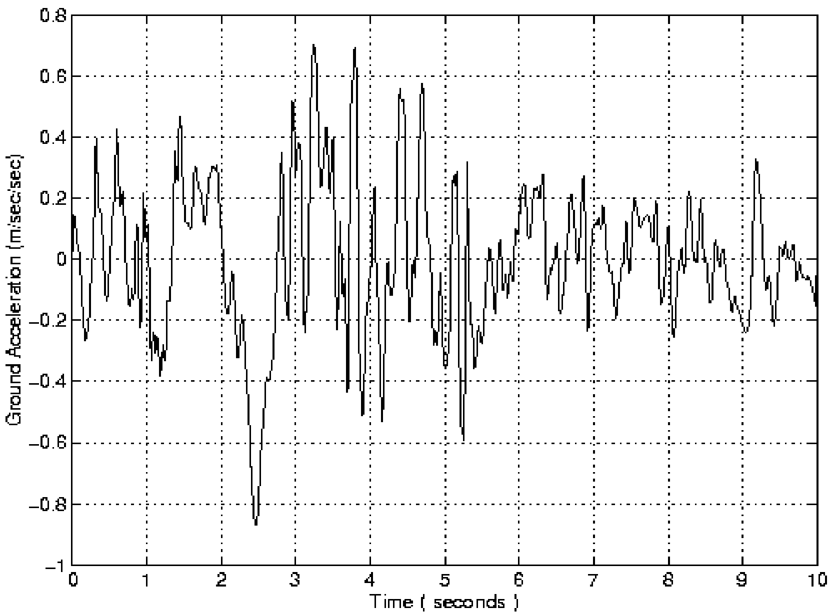
Recording equipment of earthquakes

The evaluation of earthquake motions is mainly performed by two basic categories of instruments:

1. The seismographs which record the displacement of the ground as a function of time. They operate on a continuous real-time basis. Their recordings are of interest mainly to the seismologists.



A typical seismograph



A typical accelerogram

2. The accelerographs for ground acceleration as a function of time.

They are adjusted to start operating whenever the ground acceleration exceeds a certain level. They are used for recording strong ground motions that are of interest to structural engineers for the design of structures (strong motion accelerographs)

The evaluation of the earthquake phenomenon

The magnitude and the intensity are terms that were developed in an effort to evaluate the earthquake phenomenon.

Earthquake magnitude

The magnitude of an earthquake measures the energy which is released in the form of seismic waves at the point of origin. It is expressed on the Richter scale, named after the seismologist who invented it.

The local magnitude M_L of an earthquake is a function of the energy E, released from the epicenter

$$\log E = 12.24 + 1.44 M_L (erg)$$

This relation indicates that, if the magnitude of the earthquake is increased by a unit, then the corresponding increase of energy is about 28 times.

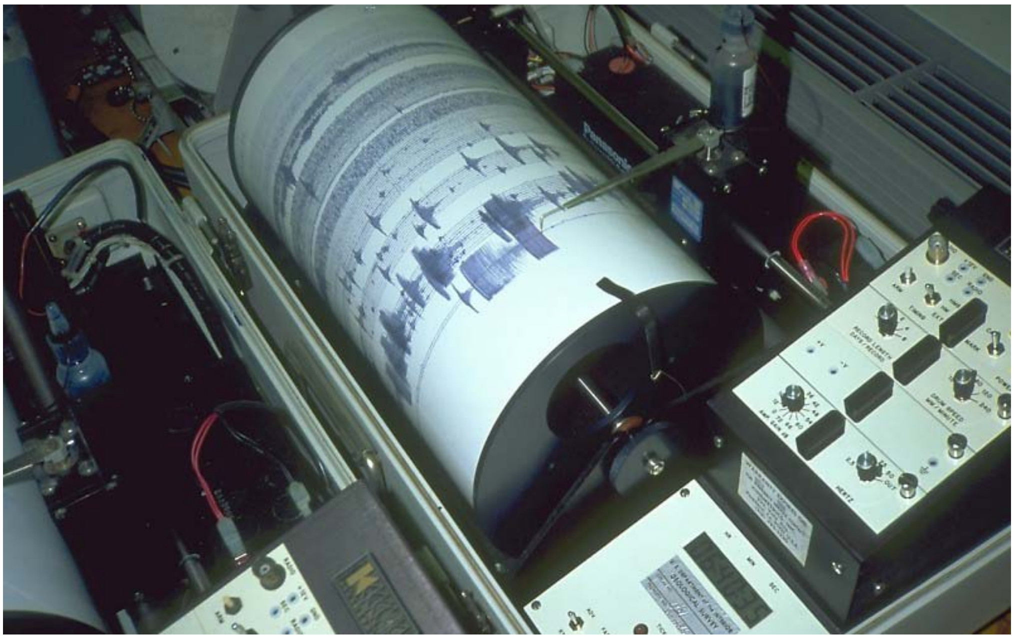
Earthquake intensity

The term intensity of an earthquake is a measure of the consequences on the people and the structures of a certain area. Of course it is impossible to measure the damage due to an earthquake using a single quantity system. For this reason the damage is estimated using empirical intensity scales, the most common of which is the modified Mercalli (MM) scale.

An earthquake has only one magnitude but different intensities from place to place. The intensity generally attenuates as the distance from the epicenter increases. The soil conditions have a significant effect on the distribution of structural damage.

If the points of equal intensity are connected on a map, the curves that yield are called isoseismal contours and divide the affected area into sections of equal intensity.

From the structural design point of view, the ideal way to estimate the seismic hazard of an area is the existence of long-term records of strong seismic motions (accelerograms) along with the statistical processing of their basic elements.



Instruments for keeping seismological records

However, unfortunately, such seismological records did not exist before the last century, and the information is generally limited.

Therefore the only way to estimate the seismic hazard is the one which combines limited seismic motion records with the estimations of intensity of previous earthquakes, using scales such as the MM scale.

Seismicity

The term Seismicity is a parameter which increases both with the magnitude and the frequency of occurrence of an earthquake in an area.

For this reason the definition of seismicity is based on the statistical law of Gutenberg, giving the frequency N (number of earthquakes per year) as a function of their magnitude M (or larger)

$$logN = a - bM ,$$

where *a* and *b* are statistically defined constants, which, for the area of Greece used to have the values

α = 5.99 and b = 0.94

Based on the values of a and b, the number of earthquakes per year, Nm, that have a magnitude M or larger is

$$N_m = 10^a / 10^{bM} .$$

Seismic hazard

The seismic hazard in an area expresses the probability of occurrence of an earthquake with acceleration a_g or intensity I larger than a certain value, in a certain period of time.

Of course it can also express the acceleration a_g or intensity I, for which the probability of exceeding (a_g or I) in a certain period is less than a certain level.

Generally the intensity of an earthquake or the maximum acceleration are parameters that are decreased as the distance from the epicenter increases. However, the statistical evaluation of a large number of earthquakes have produced some empirical attenuation laws, relating the intensity or maximum acceleration with the magnitude M of the earthquake and the distance Δ from the epicenter.

Ambraseys, Simson & Bommer (1966) for instance have proposed the following attenuation relationship:

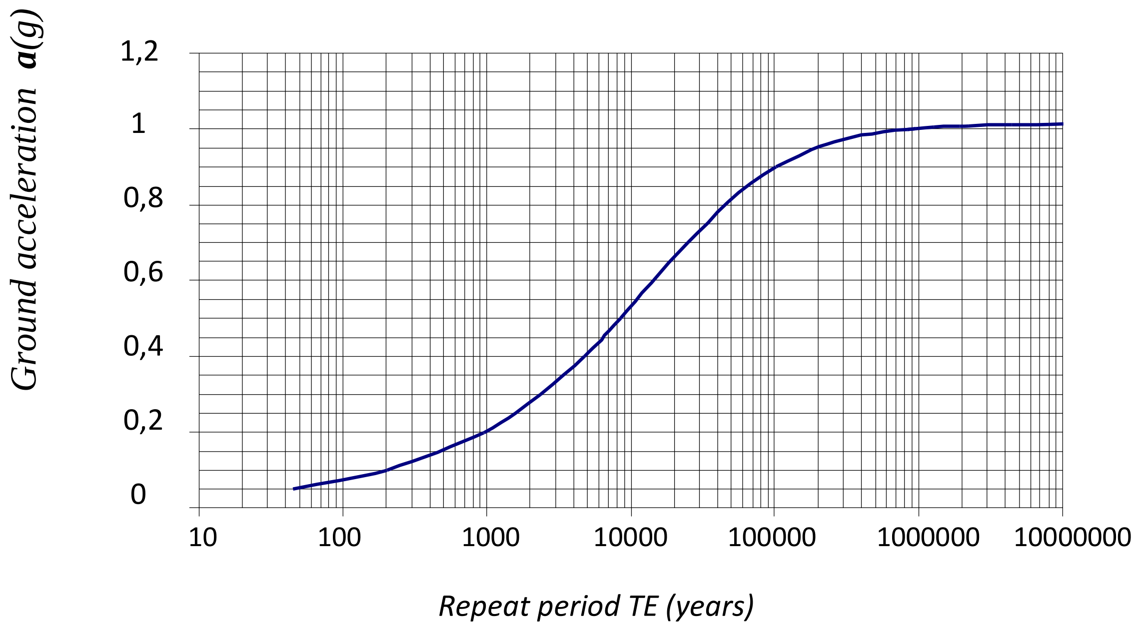
$$loga = -1.47 + 0.266M - 0.922logR + 0.1S_A + 0.094S_S + 0.25P$$

where $R = \sqrt{\Delta^2 + 3.5^2}$, Δ is the epicentral distance in km, M the magnitude of the earthquake on the Richter scale and a the peak ground acceleration.

For rocks S_A and $S_S = 0$, while:

P = 1 for 16% and P = 0 for 50% probability of exceeding.

The above attenuation relationship gives rise to draw the "ground acceleration versus repeat period" curve, which is of the following form:



Indeed, assuming rocks, a probability of exceeding 50% and a known value of M (Richter scale), for each value of acceleration a_1 (cm/sec^2), a certain value of the epicentral distance Δ_1 (km) is yielded.

Then, taking into account that the seismic area A_1 (associated with the value a_1) is a circle with a radius Δ_1, where the unknown repeat period T_1 corresponds, from a given area A_0 with its repeat period T_0, we can solve for T_1 the equation

$$A_0 T_0 = A_1 T_1 \quad \text{where} \quad A_1 = \pi \cdot \Delta_1^2 .$$

We therefore end up with a pair of values (a_1, T_1).

Repeating the procedure for a satisfactory number of pairs, the curve of the preceding figure can be drawn.

Conclusions

Summarizing the basic concepts presented above the following points could be of special interest:

1. As a natural phenomenon, an earthquake is of special interest for structural engineers and becomes hazardous in certain seismic areas when it is considered in relation with structures.

2. The magnitude of an earthquake on the Richter scale measures the energy released at its point of origin. The destructiveness however of an earthquake, although partly related to its magnitude, is a function of many other parameters like the focal depth, the epicentral distance, the soil conditions and the mechanical properties of the structures.

3. The intensity of an earthquake expresses the consequences on both the people and the structures of a certain area.

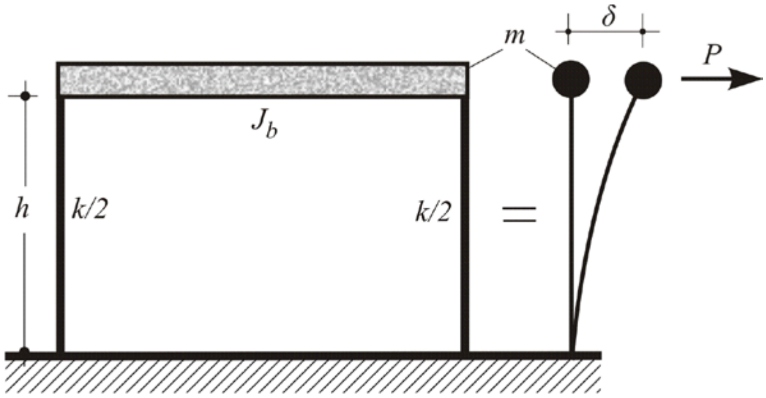
4. The earthquake is an independent phenomenon and for a reliable estimate of seismicity and seismic hazard, we need long term records.

5. Taking into account that the estimate of seismic hazard of an area is based on information of limited reliability, it is logic to base the safety of structures on specially designed extra reserves of strength and energy-dissipation mechanisms at a low additional cost. This point is the basic concept for the design of earthquake resistant structures.

BASIC MECHANICS ON SEISMOLOGY

Single degree of freedom oscillators

Consider the following system where a mass, m, is resting on two columns of height h and stiffness k.



If a force P is applied on the center of gravity (CG) of the mass, then, on the plane of paper, the only move the mass can do is a parallel to the ground. In this case we say that the system is a single degree of freedom (SDOF) oscillator. Examples of such systems are water towers, bridges, machines resting on springs etc.

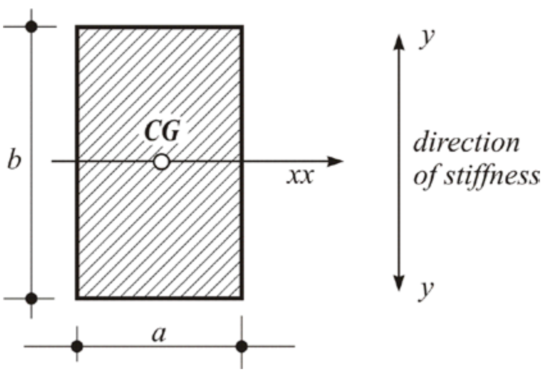
Depending on the way a column is supported, its stiffness is:

$$k = \frac{12EJ_c}{h^3}\cdot\frac{12\rho+1}{12\rho+4} = \frac{P}{\delta} \quad \left(\textit{where} \quad \rho = \frac{J_b}{4J_c}\right)$$ in general, or

$$k = \frac{12EJ}{h^3} = \frac{P}{\delta}$$ if both ends are fixed, or

$$k = \frac{3EJ}{h^3} = \frac{P}{\delta}$$ if one end is fixed the other is pinned or free.

The term J, represents the second moment of area of the column's cross section with respect to a cendroidal axis, perpendicular to the direction of stiffness.



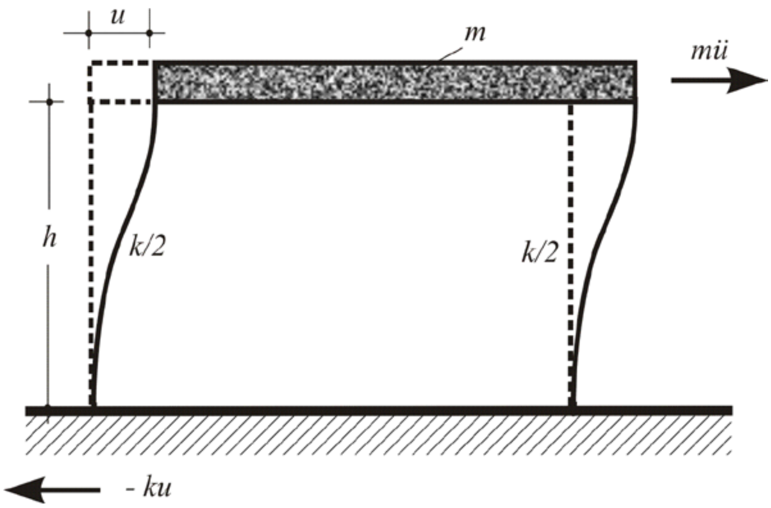
Taken into account that the second moment of area of a rectangular cross section is:

$J_{xx} = \dfrac{a \cdot b^3}{12}$, once xx is perpendicular to the stiffness direction, we conclude that the side which is parallel to the direction of stiffness has to be raised to the power of 3.

The displacement δ, is another way to express the stiffness of the column. In other words k is the force which causes a mass displacement equal to the unit length.

Free oscillations

Consider a SDOF system shown below, which, being under acceleration **ü**, has been forced to a horizontal displacement **u**. Both the acceleration and the corresponding displacement vary with respect to time.



If there is no dumping on the system and **k** is its total stiffness, the inertial force **mü** obviously must be compensated by the equal and opposite force **–ku**. This situation, which is just a simple way of thinking, is expressed by the D' Alembert second order differential equation:

$m \cdot \ddot{u} + k \cdot u = 0$ (1), or $\ddot{u} + \omega^2 \cdot u = 0$ (2), where $\omega = \sqrt{\dfrac{k}{m}}$.

The quantity $\omega = 2\pi/T$, called natural frequency of the system, is expressed in rad/sec. The magnitude T, called natural period of the system, denotes the necessary time for a full circle of oscillation.

The general solution of the above differential equation (2), will yield if we find two partial solutions that satisfy the equation. Indeed, we note that the function

$u = \sin(\omega t)$ is a solution of (2), because it is:

$\dot{u} = \omega\cos(\omega t)$ and $\ddot{u} = -\omega^2\sin(\omega t)$.

Therefore equation (2) becomes: $-\omega^2\sin(\omega t) + \omega^2\sin(\omega t) = 0$ and is satisfied!

Besides, the function:

$u = \cos(\omega t)$ is also a solution of (2) as similarly can be found out.

The general solution of equation (2) is therefore

$$u = C_1 \sin(\omega t) + C_2 \cos(\omega t) \qquad (3)$$

where C_1 and C_2 are constants that can be calculated from the conditions of the system. Actually, if for **t = 0** the velocity of the system is equal to zero, i.e.

if $\dot{u} = 0$, or $\omega \cdot C_1 \cos(\omega t) - \omega \cdot C_2 \sin(\omega t) = 0$ (4), then u becomes maximum.

From (4) yields: $\omega \cdot C_1 \cdot 1 - \omega \cdot C_2 \cdot 0 = 0$ or $C_1 = 0$.

Consequently equation (3) becomes: $u = C_2 \cos(\omega t)$ and its maximum value, for $\cos(\omega t) = 1$, is

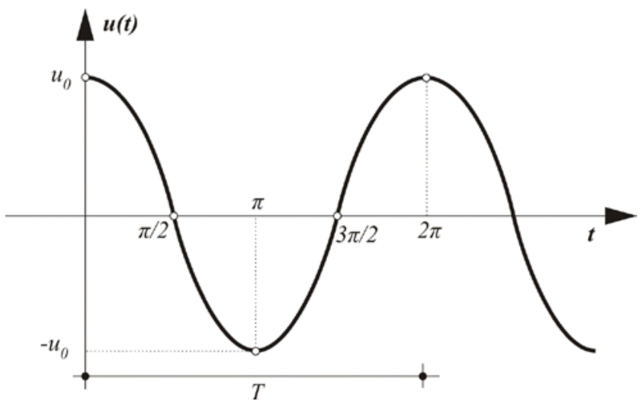
$$\mathbf{u_{max} = C_2 = u_0}$$

The value $\mathbf{u_0}$ is obviously the amplitude of oscillation.

Finally, the solution of differential equation, takes the form

$$u = u_0 \cos(\omega t)$$

and has the following graphical representation



Damping

All the structures during their oscillation present **damping**, i.e. absorbing of energy. As a result, the amplitude of their free oscillation is getting less and less by the time.

Damping exists even in ideal materials and is due to the internal friction developed during the deformation. In real structures it is also due to other reasons, like small cracks appeared in reinforced structures, friction developed on the nodes of steel structures, on the non elastic deformation of non loaded elements (walls) etc.

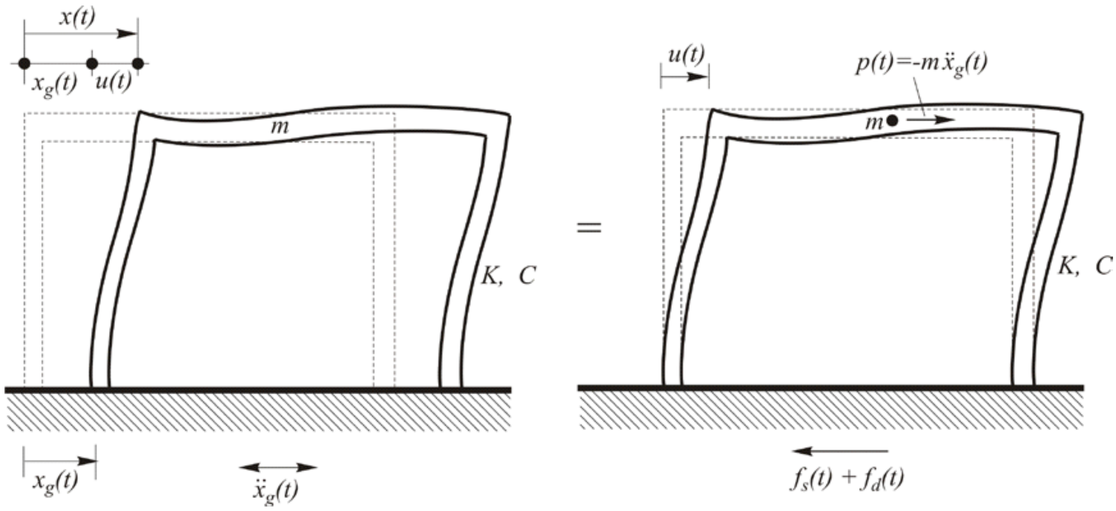
For the mathematic simulation of damping, we consider an accessional force, proportional to the relevant velocity, i.e. $f_d(t) = C \cdot \dot{u}(t)$.

The value of C is practical impossible to be calculated.

The D' Alembert equation with damping

During an earthquake, the ground, and consequently the base of a structure which is founded on it, is quickly moved with an alternate sign, around an initial location of rest. From the dynamic point of view, the magnitude we are interested in is the ground acceleration $\ddot{x}_g(t)$. The mass of structure, due to its inertia, does not follow the motion of base; it moves differently, presenting its own oscillation. Due to this different motion between mass and base, the structure is deformed and develops internal forces.

The ground-move is presented by $x_g(t)$ and the relevant mass-move, with respect to its base, by u(t). The total move realized during t time, measured from the initial position of structure (absolute move) is: $x(t) = x_g(t) + u(t)$.



Keeping in mind the D' Alembert theorem, it has to be noted:

- The left system (real situation) is equivalent to the right system
- On the right system the force acted on the center of mass-gravity is:

$$p(t) = -m \cdot \ddot{x}_g \,.$$

Applying the Newton's second law for the horizontal direction it holds:

$$p - f_s - f_d = m\ddot{u} \,.$$

Substituting the relevant quantities,

$$m\ddot{u} + C\dot{u} + Ku = -m\ddot{x}_g,$$

or dividing by the mass m,

$$\ddot{u} + 2\zeta\omega\dot{u} + \omega^2 u = -\ddot{x}_g,$$

where ω is the natural frequency of structure defined as before, i.e.

$$\omega = \sqrt{\frac{K}{m}}$$

and ζ is the damping ratio defined by the relation:

$$\zeta = \frac{C}{2\sqrt{Km}} = \frac{C}{2m\omega}$$

The natural period of the oscillator is of course associated with the natural frequency through the equation

$$T = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{m}{K}}$$

The natural frequency is dependent on the mass and the stiffness of the structure only; not on the excitation. The damping ratio ζ is a pure (non dimensional) number and, depending on the material of the structure, can be calculated experimentally. The value ζ =1 is called critical damping. In this case the structure comes back to its initial point of equilibrium without oscillations.

Response spectrum

A response spectrum is a diagram that gives the maximum response for a magnitude of our interest, e.g. absolute acceleration, relevant displacement etc., of **all** the SDOF oscillators under a specific damping, for a given seismic excitation, according to their natural period.

The procedure to construct a response spectrum may be the following:

- Choice of damping ratio e.g. ζ = 5%, for which the spectrum responses.
- Choice of natural period of an oscillator, e.g. T = 0.1 sec.
- Calculation of oscillator's time history response u(t) for the given seismic excitation
- Calculation of the absolutely maximum value of response: max $|u(t)|$.
- Repetition of the above procedure for many values of natural period T.
- Depiction on a diagram of the various values max $|u(t)|$ versus T.

Through this curve the maximum displacement of any structure may be calculated for this seismic excitation, provided its damping ratio is the same with that of spectrum.

Apart from the relevant displacement, response spectra can be created for any other magnitude, e.g. absolute acceleration. Usual response spectra are for:

- Relevant displacements: provide values for max $|u(t)|$ and are represented by **SD** or **Sd** (Spectral Displacement)
- Relevant velocities: provide values for max $|\dot{u}(t)|$ and are represented by **SV** or **Sv** (Spectral Velocity)
- Absolute accelerations: provide values for max $|\ddot{x}(t)|$ and are represented by **SA** or **Sa** (Spectral Acceleration)

For usual values of natural periods T and damping ratios ζ, an increase of damping generally implies a decrease of the spectral values.

This is the reason that on the same diagram more than one spectra, corresponding to different damping ratios, are presented.

Pseudospectra

For small values of the damping ratio (ζ≤ 20%) it holds approximately:

$$SA \cong \omega^2 \cdot SD = PSA \qquad \text{(a)}$$

$$SV \cong \omega \cdot SD = PSV \qquad \text{(b)}$$

where: PSA (Pseudo Spectral Acceleration)

PSV (Pseudo Spectral Velocity)

Spectral limits

Spectra tend to have characteristic values for very small and very large natural periods, as follows:

For structures of very large stiffness (T → 0):

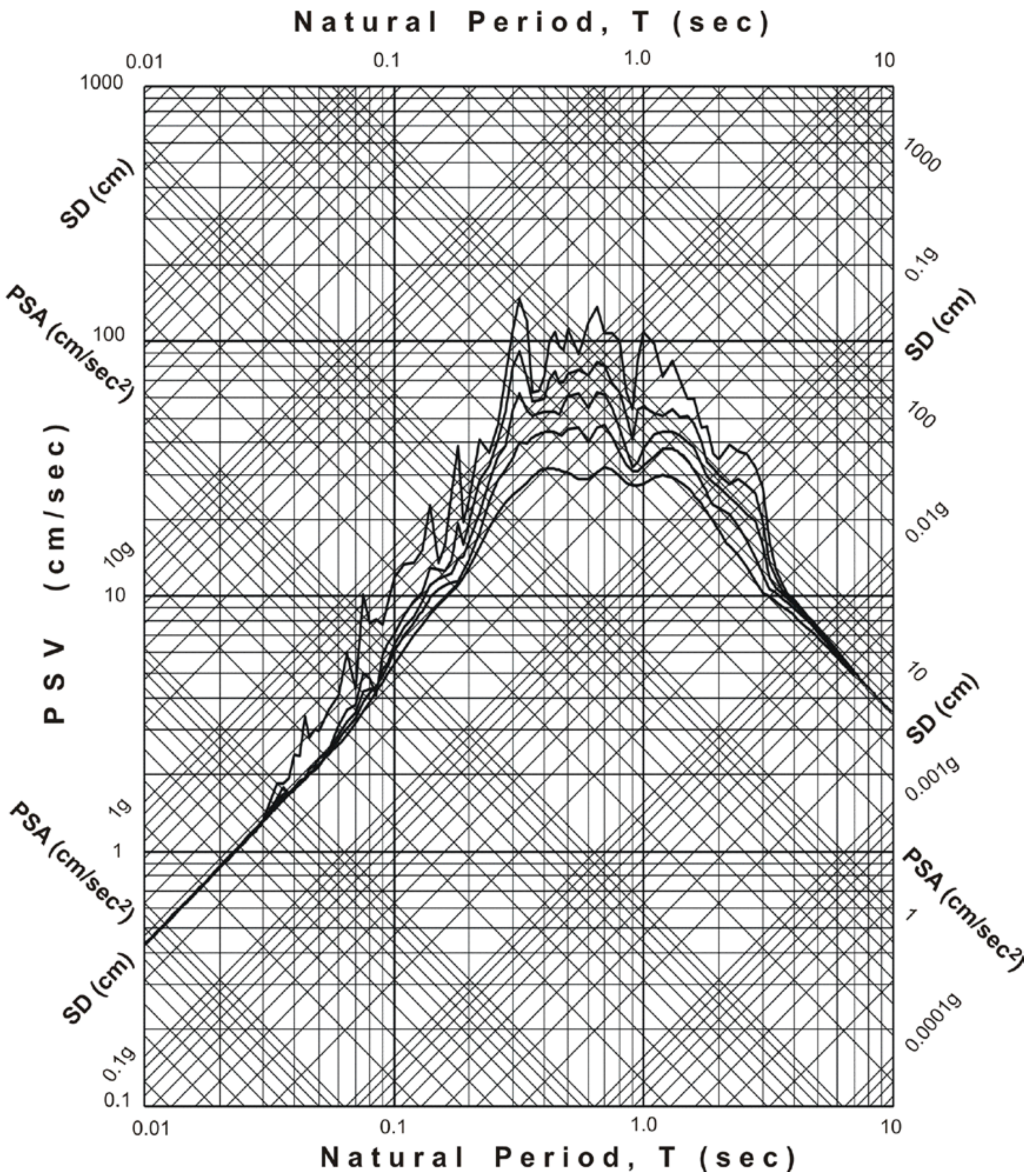
SD → 0 SV → 0 SA → $\ddot{x}_{g,max}$

For structures of very small stiffness (T → ∞):

SD → $x_{g,max}$ SV → $\dot{x}_{g,max}$ SA → 0.

Three-part logarithmic form of spectrum

The linear logarithmic relations (a) and (b) give rise to draw all three spectra in one three-part diagram with logarithmic axes.



Response spectra of Kalamata's earthquake (1986) for ζ=0, 2,5,10 and 20 in 3l-form

The horizontal axis corresponds to the natural period, T and the vertical to the pseudo-velocity, **PSV**. Apart from these axes, there are two more; the first, under 45° with horizontal, corresponds to the spectral displacement, **SD** and the second, under 135°, corresponds to the spectral pseudo-acceleration **PSA**.

The projection of a spectral point, corresponding to a natural period T, on the three axes, SD, PSV and PSA gives the values of the corresponding spectral magnitudes for a SDOF oscillator presenting this period.

The above spectral depiction is called three-logarithmic form of spectrum, due to the three logarithmic axes of the spectral magnitudes. It is also referred to as four-logarithmic form, if we take into account – the logarithmic as well – axis of natural periods.

Characteristic spectral regions

On a spectral response, especially when it has the three-logarithmic form, we can distinguish different regions. In particular:

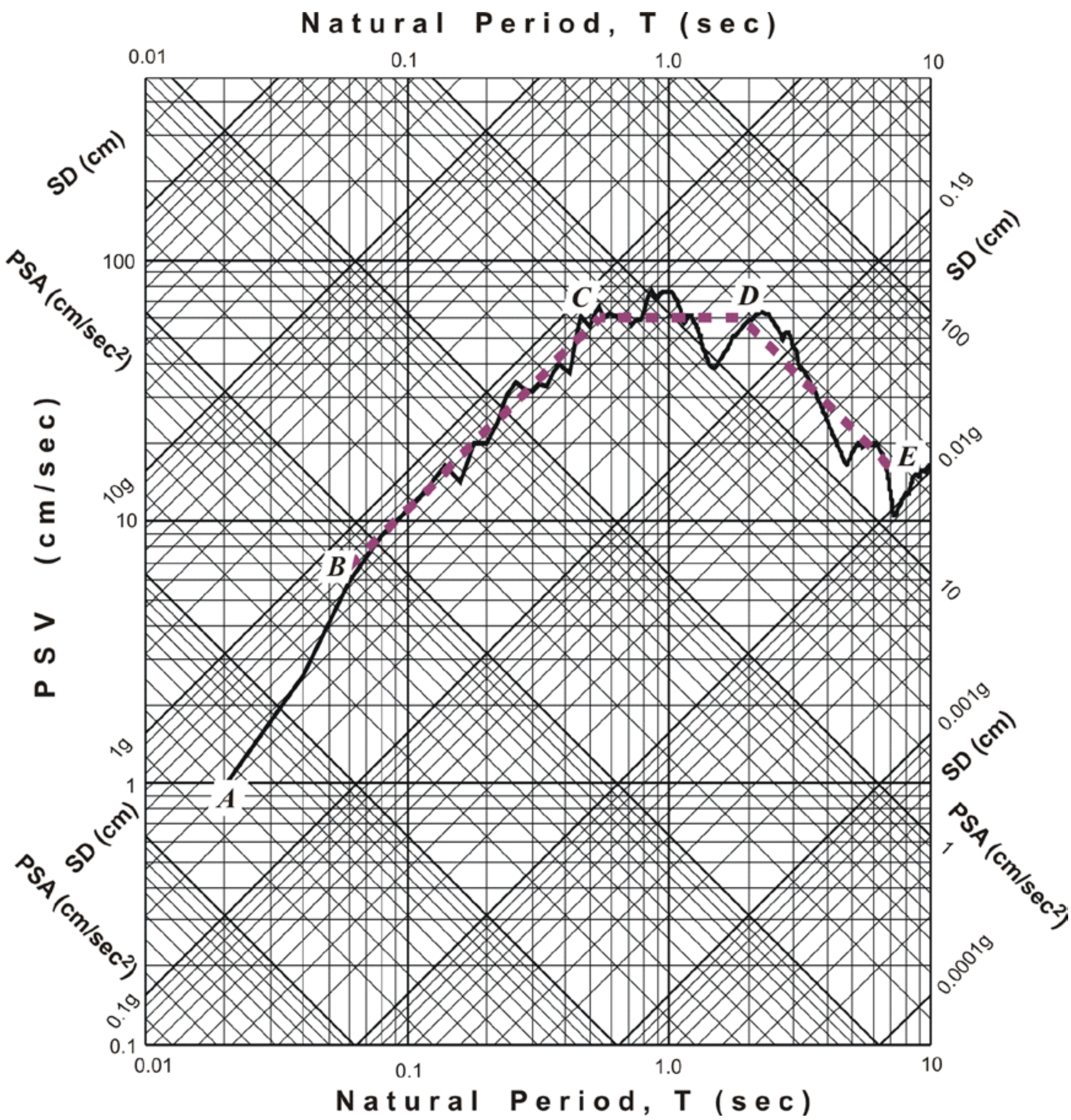


Fig A *Response spectrum from the El Centro (1940) earthquake for ζ=5%*

- For small periods, the spectral acceleration is practically equal to the ground acceleration.
- In the region BC, the spectral acceleration is almost constant.
- In the region CD, the spectral velocity is almost constant.
- In the region DE, the spectral displacement is almost constant.

The width of natural period for each region depends on the characteristics of the seismic excitation, which in turn are affected by the magnitude of the earthquake, the mechanism of creation, the distance from the epicenter and the local properties of the ground.

Effective acceleration and velocity

The peak ground acceleration, pga = $\ddot{x}_{g,max}$ and the peak ground velocity, pgv = $\dot{x}_{g,max}$, developed during an earthquake are not the proper indices for the evaluation of its intensity or destructivity, because they do not provide information for the duration of the excitation.

For this reason when a design spectrum is going to be constructed, the Effective Peak Acceleration (EPA) and the Effective Peak Velocity (EPV) are used to evaluate the intensity of the ground motion. The effective values of acceleration and velocity do not have any natural meaning but they constitute a normalized scheme for the seismic excitation parameters.

Their evaluation can be realized making use of the regions BC and CD of the previous region, where the spectral acceleration and velocity keep respectively constant values. There is not a clear way of estimating them, but the relations of Newmark & Hall, 1969, McGuire, 1975, are often in use:

$$EPA = PSA_{BC}/2.5$$

$$EPV = PSV_{CD}/2.5\ ,$$

where PSA_{BC} is the average value of spectral accelerations for damping ratio ζ=5% in the period region between 0.1 and 0.5 and PSV_{CD} is the average value of spectral velocities in the period region close to 1.0 sec. The coefficient 2.5 corresponds to earthquakes of a normal duration. For very small or very large length of time, the above values must be accordingly corrected.

Specifically for earthquakes of small duration the values must be decreased while for a large duration they have to be increased. The necessary correction does not follow

a specific procedure and is realized in a rational way, taking into account the remaining characteristics of the seismic excitation.

The values of EPA and EPV, yielded from the above procedure may be greater or less from the corresponding maximum values of the ground motion. Usually it is:

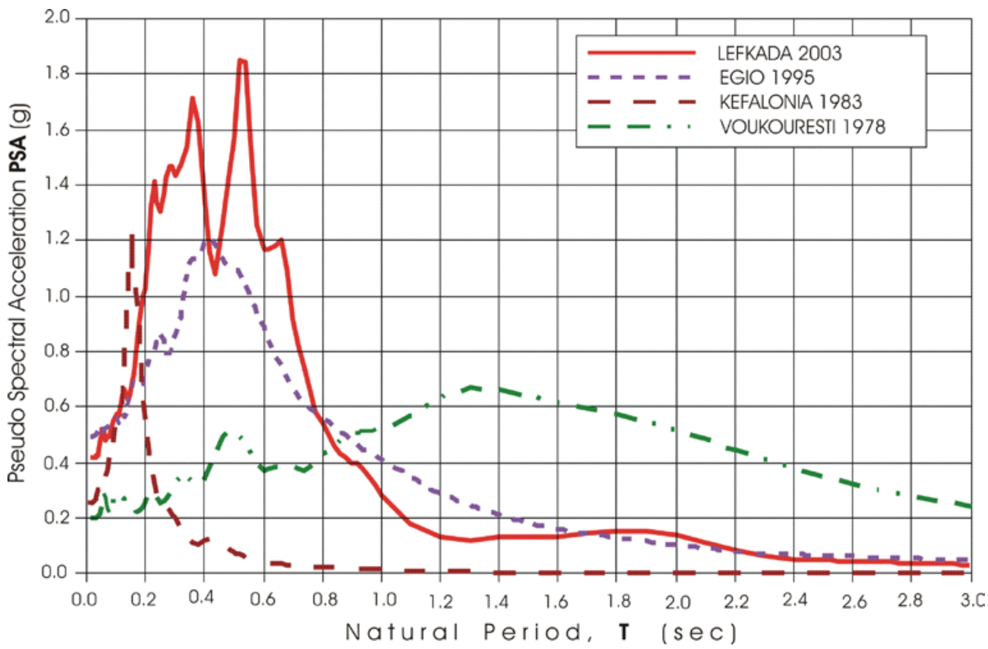
EPA < pga and EPV > pgv.

Elastic design spectrum

The response spectra of recorded earthquakes present significant variation, depending mainly on the characteristics of seismic vibration and the local ground conditions. For this reason, at the design stage of structures we use a flattened spectrum that covers all the spectral forms of possible earthquakes that can hit the region of work.

For the construction of a design spectrum the parameters to be taken into account are:

- The effective values of the local ground motion (as described before) and
- The local ground conditions at the region of work.



Response Spectra for damping ratio ζ=5%

Ground acceleration

Values of the expected ground acceleration and velocity can be derived as a result of a seismic risk design after statistical processing of seismic events that happened in

the greater region of the work. Such investigations are elaborated for significant works, while for standard and usual constructions the values are provided by the Codes according to the area in which the structure belongs.

In the Greek seismic code three zones of seismic risk are stated; for each zone the effective acceleration, A (g) is presented in the following table.

Seismic risk zone	Effective acceleration, A (g)
I	0.16
II	0.24
III	0.36

These values have been derived through a seismic risk design and correspond to a repeat period of about 500 years, i.e. they occur once every 500 years on average.

Considering that seismic events follow the Poisson's distribution, this means that there is a possibility of 10% to occur an earthquake in the next 50 years (which is a conventional life duration of structures), that will cause an acceleration greater than that of the table. This possibility is acceptable for conventional constructions.

However, the values of the above table have to be multiplied by the **importance factor of structure γ_I**, when the building is of great significance or value. The values of γ_I, are fluctuated from 1.0 to 1.30. Through this way the possibility of excess is decreased and the design covers seismic events corresponding to a greater repeat period (1000 or 2000 years). In the following as a ground acceleration will be considered the value $\gamma_I \cdot A$. In the Greek seismic code this value is presented by a_g.

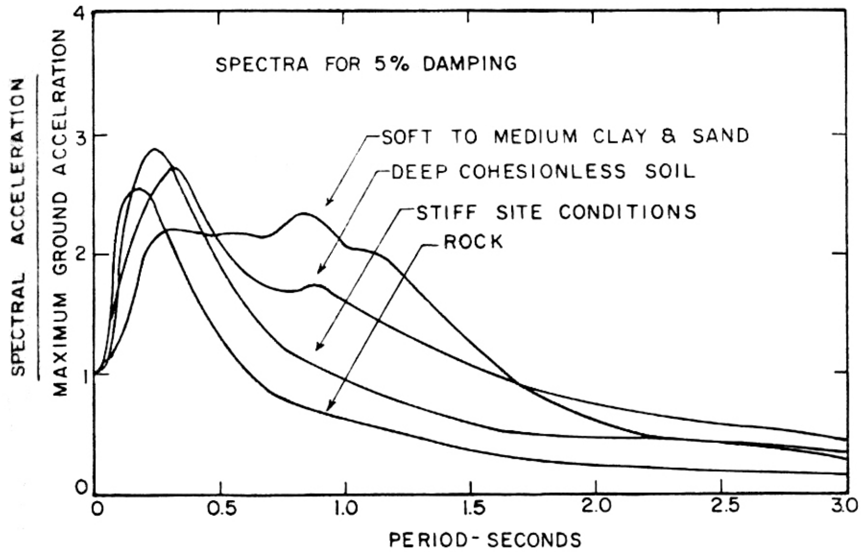
The Greek seismic code considers that the corresponding to each region value of ground acceleration $\gamma_I \cdot A$ is independent of the local ground conditions. On the contrary, the Euro-code 8 assumes that the above values of table hold only for rocky and very hard soil; therefore if a structure is going to be founded on a softer ground, then these values are multiplied by the **soil coefficient, S**. The values of S are fluctuated between 1.00 and 1.40.

Soil influence

Apart from the ground acceleration value, which is influenced – according to Euro-code 8 – by the soil class, the quality of ground on which the structure is founded, may significantly influence the form of design spectrum.

The dependence of design spectrum upon the ground conditions is expected, as the structure will be excited by the ground motion on the level of foundation and this motion is the result of the ground response to the seismic excitation.

The large influence of soil characteristics on the response spectra is shown on the next figure, where the average normalized response of the California and Japan earthquakes is depicted.



Elastic design spectrum (Greek seismic code and Euro-code 8)

The modern seismic codes take into account the influence of the ground properties on the form of the design spectra modifying the characteristic periods T_B and T_C, which define the start of the regions: BC, where the spectral acceleration is almost constant. and CD, where the spectral velocity is almost constant, shown already in the Fig A of the preceding unity.

The Greek seismic code includes four soil classes A, B, C and D, while the Euro-code 8 has five, A, B, C, D and E. A description of each class is provided in the corresponding code.

It has to be notified that the characteristic period T_D, which defines the start of the constant displacement region, is not soil dependant.

Characteristic periods of a design spectrum according to the **Greek** seismic code

Soil class	**T_B (sec)(1)**	**T_C (sec)(1)**	**T_D (sec)(2)**
A	0.10	0.40	2.50
B	0.15	0.60	2.50
C	0.20	0.80	2.50
D	0.20	1.20	2.50

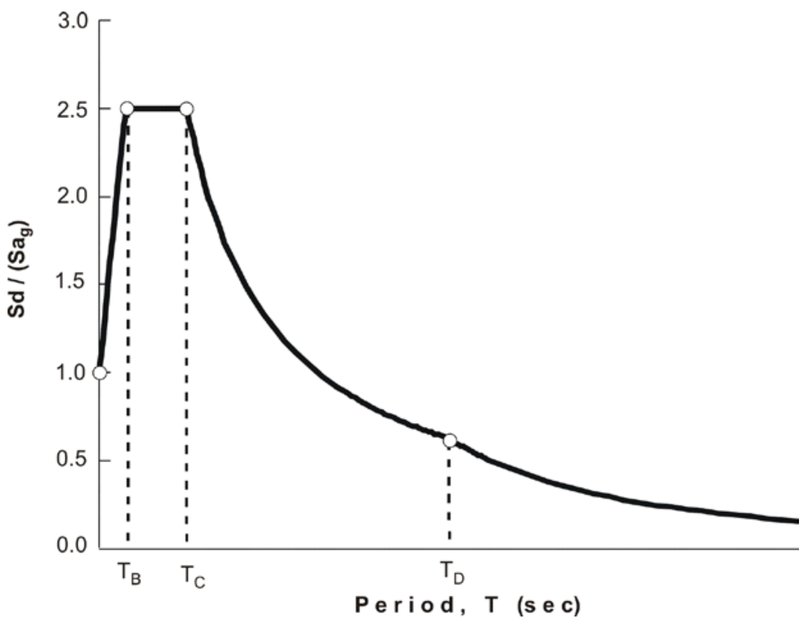
(1) In the Greek seismic code T_B and T_C are referred to as T_1 and T_2 respectively.

(2) T_D is used only for structures presenting seismic isolation.

<u>Soil coefficient and characteristic periods of a design spectrum according to the</u> **<u>Euro- code 8</u>**

Soil class	**S**	**T_B (sec)**	**T_C (sec)**	**T_D (sec)**
A	1.00	0.15	0.40	2.00
B	1.20	0.15	0.50	2.00
C	1.15	0.20	0.60	2.00
D	1.35	0.20	0.80	2.00
E	1.40	0.15	0.50	2.00

In the following figure is depicted the form of the elastic design spectrum according to Euro-code 8 for a damping ratio ζ=5%. The corresponding spectrum for the Greek code is similar, apart from the soil coefficient S. We classify four regions:



1. For $T \leq T_B$ the design spectral acceleration, Sd, presents an upward route by an increase of the period. For T = 0, $Sd = S \cdot a_g$ and for $T = T_B$, $Sd = 2.5 \cdot S \cdot a_g$. It is reminded that $a_g = \gamma_I \cdot A$, where $A = a_{g,d}$ is the design acceleration for a rocky soil and a repeat period of 475 years.

2. For $T_B \leq T \leq T_C$ the spectral **acceleration** remains constant: $Sd = 2.5 \cdot S \cdot a_g$.

3. For $T_C \leq T \leq T_D$ the spectral **velocity** remains constant and consequently the spectral acceleration is reversely decreased by the increase of period, following the relation: $Sd = 2.5 \cdot S \cdot a_g \cdot (T_C/T)$.

4. For $T_D \leq T$ the spectral **displacement** remains constant and consequently the spectral acceleration is reversely decreased by the **square** increase of period, following the relation: $Sd = 2.5 \cdot S \cdot a_g \cdot (T_C \cdot T_D/T^2)$.

For a damping ratio different from 5%, the spectral values are multiplied by the damping modification factor, η, given by the equation:

$$\eta = \sqrt{\frac{7}{\zeta + 2}}$$ for the Greek seismic code and

$$\eta = \sqrt{\frac{10}{\zeta + 5}}$$ for the Euro-code 8,

where the value of ζ is entered as percentage.

Seismic force distribution - Displacements

In this part the horizontal seismic force will be distributed on to the columns that sustain a slab of a single storey structure. Then the displacement of the slab will be estimated as an algebraic sum of a parallel movement along with a rotation.

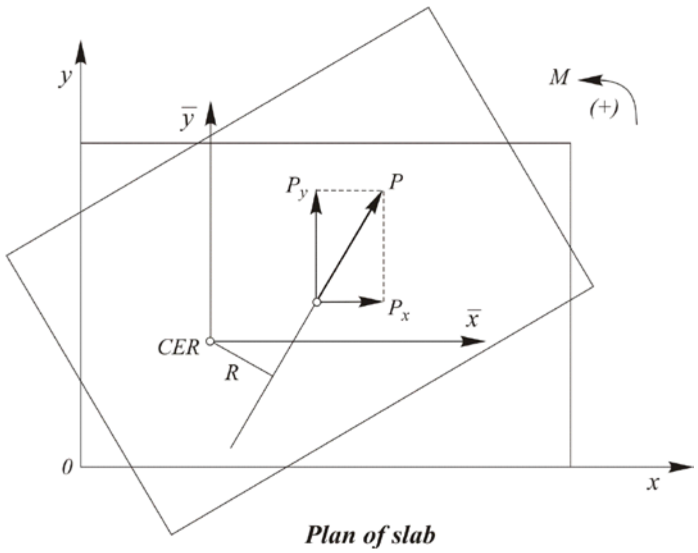
Consider a single floor structure that behaves elastically, with double fixed columns and a horizontal seismic force, P, of a random direction acted on the mass of the slab.

It has to be noted that the slab behaves as a non deformable structure, like a rigid disc. In this case we characterize the function of slab as diaphragmatic. This theory aims at finding out the movement and rotation of the slab due to the horizontal seismic force along with the distribution of this force to the existing columns.

a) Displacement and rotation of slab

The seismic force is obviously applied on the center of gravity (CG) of the slab, which, as a result, will move and rotate.

The rotation of the slab will be realized with respect to a point, called **C**enter of **E**lastic **R**otation (CER), the location of which depends on the stiffnesses of columns which sustain the slab. Of course the slab will rotate around the CER only if there is an eccentricity (distance) of the seismic force with respect to the CER; in other words the rotation is realized only when the force does not pass through the CER. In this case we have a static eccentricity of the structure.



Plan of slab

If we call $\mathbf{k_{ix}}$ the stiffness of the i^{th} column for a **y-y** seismic direction, i.e. stiffness, where the second moment of area of the column's cross section has been taken with

respect to a $\mathbf{x_0}$-$\mathbf{x_0}$ cendroidal axis parallel to x-x, $\mathbf{k_{iy}}$ the corresponding stiffness for a **x-x** direction and $k_{i\omega}$ the column's rotational stiffness, then the coordinates of CER with respect to a Cartesian system, are given through the following relations:

$$x_{CER} = \frac{\sum_{i=1}^{n}(x_i \cdot k_{ix})}{\sum_{i=1}^{n} k_{ix}}$$

$$y_{CER} = \frac{\sum_{i=1}^{n}(y_i \cdot k_{iy})}{\sum_{i=1}^{n} k_{iy}}$$

where x_{CER} and y_{CER} are the coordinates of CER, x_i and y_i are the coordinates of the i^{th} column's cross sectional centroid and n the number of columns.

Now, if we define a new coordinate system $\bar{x}O\bar{y}$ with axes parallel to the previous and having the CER as origin, then, for any point S, it holds:

$$\bar{x}_S = x_S - x_{CER}$$

$$\bar{y}_S = y_S - y_{CER}$$

Similarly for the Center of gravity (CG), it holds:

$$\bar{x}_{CG} = x_{CG} - x_{CER}$$

$$\bar{y}_{CG} = y_{CG} - y_{CER}$$

We therefore can consider all the columns of structure equivalent to "**one**" only column, presenting a stiffness equal to the total stiffness of columns and laid on the CER, i.e.

$$k_x = \sum_{i=1}^{n} k_{ix}$$

$$k_y = \sum_{i=1}^{n} k_{iy}$$

$$k_\omega = \sum_{i=1}^{n}\left(k_{i\omega} + \bar{x}_i^2 \cdot k_{ix} + \bar{y}_i^2 \cdot k_{iy}\right)$$

where, $k_{i\omega} = \frac{\mathrm{GJ_p}}{\mathrm{h}}$. In this equation, are:

- G the shear modulus of elasticity, also called the modulus of rigidity, related with the Jung's modulus E, by the equation $G = \frac{E}{2(\nu + 1)} \approx 0.4 \cdot \mathrm{E}$, where ν is the Poisson's ratio, keeping the absolute value of $\varepsilon_q/\varepsilon$, which is roughly 0.25.

- J_p the polar moment of inertia, expressed by $J_p = \frac{\pi \cdot D^4}{32}$. For columns with square sections of side α, it is: $J_p = 0.1406 \cdot \alpha^4$.
- h the height of the structure.

However, the term $k_{i\omega}$, being too small compared to the others, **is omitted**.

It can be observed that the further away elements of large stiffness (wall columns) are laid, the greater becomes the rotational stiffness of structure, resulting in a reduction of the columns' and structure's rotation.

Now, as a result of the seismic force P, if

- u and v are respectively the movements of the slab on the x-x and y-y directions and
- ω is the rotation of the slab with respect to the CER, then obviously:

The movement u of the slab on the x-x direction will be expressed as the ratio of the horizontal component of P divided by the total stiffness on the x-x direction, i.e.

$$u = \frac{P_x}{k_x}$$

Similarly, the movement v of the slab on the y-y direction will be expressed as the ratio of the vertical component of P divided by the total stiffness on the y-y direction, i.e.

$$v = \frac{P_y}{k_y}$$

Finally, the rotation of the slab around the CER will be expressed as the ratio of the moment M of P (with respect to CER) divided by the total rotational stiffness of structure, i.e.

$$\omega = \frac{M}{k_\omega} = -\frac{P \cdot R}{k_\omega}$$

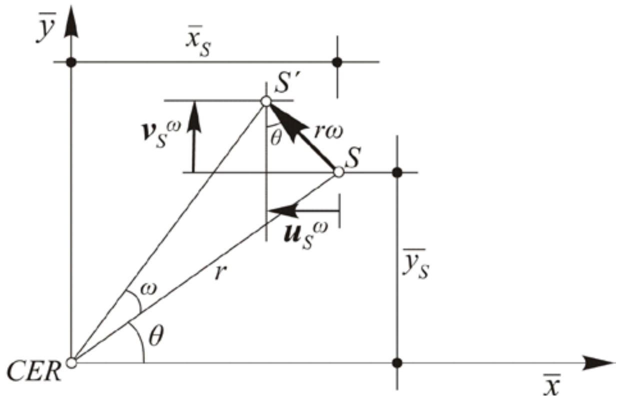
where R is the lever of P (i.e. the CER 's distance from P).

Taking instead the corresponding components of P, i.e. P_x and P_y, along with their levers with respect to the CER, the previous equation becomes:

$$\omega = \frac{-P_x \cdot \bar{y}_{CG} + P_y \cdot \bar{x}_{CG}}{k_\omega} \qquad (a)$$

b) Force distribution to columns

In order to realize the distribution of seismic force, finding thus the shear forces of columns, it is necessary to calculate the movements of columns' heads along with their rotation due to the slab's displacement.



If S is the CG of a column and u_S and v_S are respectively its horizontal and vertical movements due to the slab's rotation, then the total horizontal displacement of S (see figure above), is:

$$u_S = \frac{P_x}{k_x} - u_S^\omega$$

The first term comes from the horizontal movement of slab while the second expresses the horizontal movement of S due to the slab's rotation. It has to be noted that the second term is different from point to point, depending on the location of S with respect to CER. From figure it is:

$$u_S^\omega = (r\cdot\omega)\cdot\sin\theta = (r\cdot\sin\theta)\cdot\omega = \bar{y}_S \cdot \omega.$$

Putting this value of u_S^ω into the previous equation, it yields

$$u_S = \frac{P_x}{k_x} - \bar{y}_S \cdot \omega$$

In this equation if we substitute the value of ω coming from equation (α), we end up with the total horizontal displacement of column

$$u_S = \frac{P_x}{k_x} + \frac{P_x \cdot \bar{y}_{CG} - P_y \cdot \bar{x}_{CG}}{k_\omega} \bar{y}_S$$

Similarly for the total vertical disposition of S is:

$$v_S = \frac{P_y}{k_y} + \bar{x}_S \cdot \omega$$

or

$$v_S = \frac{P_y}{k_y} + \frac{P_x \cdot \bar{x}_{CG} - P_y \cdot \bar{y}_{CG}}{k_\omega} \bar{x}_S$$

Therefore the values of shear forces are:

$Q_{ix} = k_{ix} \cdot u_S$ and

$Q_{iy} = k_{iy} \cdot v_S$.

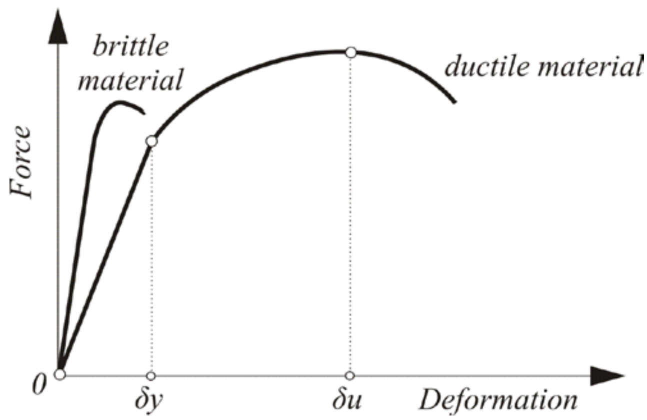
Ductility of structures

From the economic point of view, according to all modern Seismic codes, every design of structures, made of any material especially of reinforced concrete, is based on their **ductility**.

A material is characterized as **ductile**, if, during its loading, it can resist a high level of distortions. For members or structures of reinforced concrete, ductility means their ability to be deformed beyond their yield point, without significant decrease of their strength.

A brittle material, like chalk, or even a brittle structure, as soon as the load reaches its maximum level, may suddenly fail, without any warning of the coming failure. Consequently there is a high risk of collapse in such structures with a loss of lives.

Typical diagrams of force versus deformation are depicted below for brittle and ductile materials.



The ductility factor

For the ductile material of the preceding figure, δy is the deformation corresponding to the first yield, while δu is the deformation corresponding to the maximum force the material can sustain without a decrease of its strength.

The force may be a load, moment or stress, while the deformation may be an elongation, curvature, or twist. We could give the following definitions:

a. **Ductility:** is the absolute value of the marginal deformation **δu** or the inelastic deformation (**δu – δy**).

b. **Ductility factor**: μ = δu/δy, or some other form, e.g. φu/φy, or θu/θy. It is easily calculated and widely used.

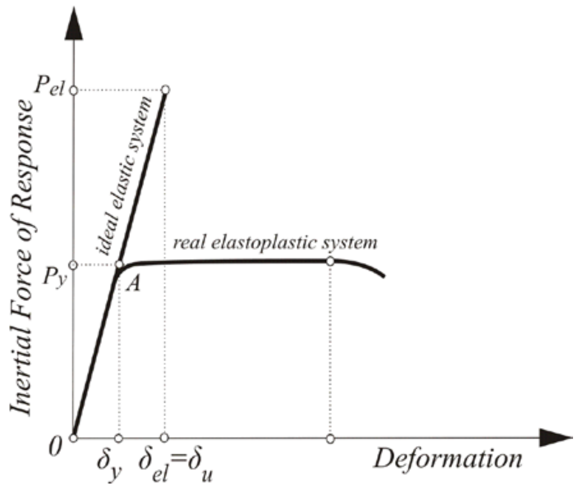
c. The **absorbed energy** is expressed through the area underneath the diagram.

The above definitions are generally referred to a monotonic loading until failure.

The significance of ductility

The following picture illustrates the response of a structure under a seismic excitation, for the cases of **elastic** and **inelastic** behavior.

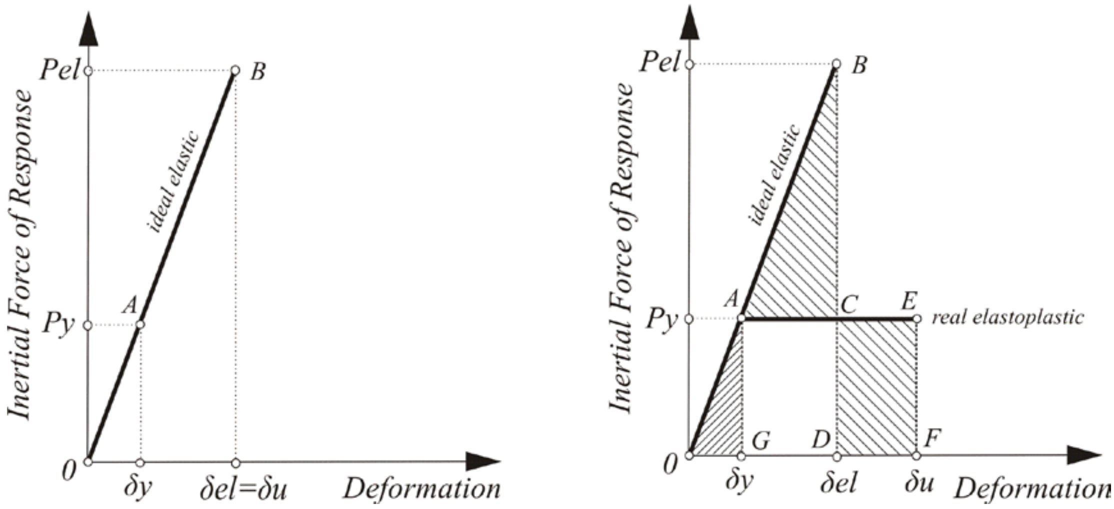
The maximum inertial force of the structure's response is P_{el} for the elastic structure, while for the elastoplastic (inelastic) structure is P_y. The ratio of these values, usually called behavior factor, is q= P_{el}/P_y.



According to the results derived from dynamic analysis of Blume (1961, 1970) on systems of Single Degree of Freedom (SDOF), two behaviors have been arisen:

- responses with equal deformation and
- responses with equal absorbed energy.

For the first behavior it holds: q = μ (a), i.e. P_{el}/P_y = δu/δy, while for the second $q = \sqrt{2\mu - 1}$ (b). A brief proof of this relation is given below:



Given the equivalence of the absorbed energies, from the right scheme of the above figure, it is: (OBD) = (OAEF) or

$$\frac{1}{2} P_{el} \cdot \delta_{\mathrm{el}} = \frac{1}{2} P_y \cdot \delta_{\mathrm{y}} + \left(\delta_{\mathrm{u}} - \delta_{\mathrm{y}}\right) P_y \quad \text{or}$$

$$\frac{1}{2} P_{el} \cdot \delta_{\mathrm{el}} = P_y \cdot \delta_{\mathrm{u}} - \frac{1}{2} P_y \cdot \delta_{\mathrm{y}} \quad \text{or, dividing by } P_y \cdot \delta_u,$$

$$\frac{1}{2} \cdot \frac{P_{el}}{P_y} \cdot \frac{\delta_{el}}{\delta_{\mathrm{u}}} = \frac{P_y \cdot \delta_u}{P_y \cdot \delta_u} - \frac{1}{2} \frac{P_y \cdot \delta_y}{P_y \cdot \delta_u} \quad \text{or, since } \frac{\delta_{el}}{\delta_y} = \frac{P_{el}}{P_y} = q,$$

$$\frac{1}{2} \cdot q \cdot \frac{\delta_{\mathrm{el}}}{\mu \delta_y} = 1 - \frac{1}{2\mu} \quad \text{or}$$

$$q^2 = 2\mu\left(1 - \frac{1}{2\mu}\right) = 2\mu - 1 \quad \text{and finally} \quad q = \sqrt{2\mu - 1}.$$

Comparing equations (a) and (b) with corresponding results of dynamic analyses on SDOF systems conducted by Clough in 1966, it has been concluded that these equations are close to reality for SDOF systems, but they can proportionally approximate multistory buildings.

The crucial conclusion arising from equations (a) and (b) is that **the necessary seismic force for an elastoplastic system is only <u>30%</u> of** the corresponding force for **an elastic**, proving therefore the economy of structures.

Obviously it is not an economical design of a structure to be able to undertake a possibly greater earthquake without damage, thus presenting a linearly elastic behavior, because the action of a seismic excitation can be received either through large forces in the elastic region or through smaller forces in the elastoplastic region, provided, in the second case, the system offers this possibility.

Therefore the ability of a system for plastic deformation during an earthquake is a property of very high significance, as we can design structures for much smaller forces than those demanded for elastic systems.

The greater is the available ductility factor, the larger are the safety margins against earthquake.

The elastoplastic behavior of a building can be ensured through an appropriate configuration of the bearing structure, such as the demand of having "strong columns and weak girders", along with a proper arming of the structural elements.

The design cost without damage is dependant to:

- the **significance** of structure
- the **type** of structure, as, a yielding on statically indeterminate elements, results in a redistribution of internal forces to the adjacent members.
- the possibility of an earthquake event.

Behavior criteria of ordinary structures

The most modern codes apply the following criteria relating to structures' behavior:

- Weak earthquakes: structures without any damage, within the elastic region of stresses, where Hook's law holds.
- Intermediate earthquakes: structures with a minimal damage on bearing and some damage on non-bearing elements.
- Strong earthquakes (earthquakes of design): structures with a limited, reparable damage on bearing elements, but a fairly small possibility of collapse.

In the case of a seismic event having the magnitude of design, the collapse can be avoided if the members along the joints of structure have been properly designed to undertake large elastoplastic deformations without a significant decrease of their strength, in other words **if they are ductile**.

The Greek seismic codes present the procedure of design i.e. calculations, structural and reinforcement details, so that a structure should ensure a satisfactory degree of ductility, without having to calculate the demanding or available ductility. Besides, the codes aim at the following points:

- Damage should occur at non-bearing elements, thus ensuring "**strong columns – weak girders**".

- Brittle failures from shear or anchoring should always follow the ductile flexural failures, i.e. it is necessary an application of capacity design.
- Finally to ensure ductility, accompanied by concrete and steel strength, a tensile and compression percentage of reinforcement along with tightening.

Any unexpected override of loads, shocks, temperature changes, foundation slides etc., which are usually ignored during design, may be undertaken by the ductility of the structure.

The ability of structure to present a ductile behavior, is expressed through the behavior factor, q.

Structural elements like slabs, secondary girders i.e. girders that do not seat on columns, or joints without concurrent vertical elements, are considered to be elements without a serious demand of ductility, regardless of belonging or not to a girder or carrier with or without increased demands of ductility.

The ductility of reinforced concrete structures is dependent on the ductility of their materials, the design of members, joints and their structural reinforcement details.

Methods of seismic analysis in structures

From the seismic point of view, before designing a structure, an engineer must be concentrated on what we call '**response**' of the building under the excitation.

By this term we mean all the magnitudes of internal forces (bending moments, shear and axial forces, stresses etc.) along with deformations (displacements, turnings etc.) which arise as a result of the periodic motions of the structure's foundations, which in turn generate accelerations and consequently inertial forces on the structure's members.

The response during an earthquake is, by nature, dynamic. Therefore the dynamic characteristics of the structure, i.e. its natural period and damping are crucial for the corresponding calculations.

In the Greek Seismic code (EAK 2000), two only linear methods of calculating the seismic response are incorporated: the **dynamic spectral** method and the **simplified spectral** (equivalent static) method.

The reliability of linear methods is small when $q = 3.5$, while it is sufficient in cases of $q = 1.5$ or $q = 1.0$. This is one of the reasons the code demands in the first case additional special controls (capacity design) of the structure, while in the last two, nothing.

In the first case, a choice of $q = 3.5$, means that we accept and simultaneously aim at the entrance of structure into the inelastic region, which allows for a limit damage situation, equivalent to life protection and significant damage without completely elimination of collapse. For the two other values of q, permitted by the code, the choice of $q = 1.5$ denotes a controlled damage of minor extend which is repairable, while the choice of $q = 1.0$ refers to very limited damage, ready for immediate use.

The modern codes mainly aim at life protection for only one level of seismic risk, the so called 'designed earthquake' with a possibility of excess 10% in 50 years (which is an average life duration of structures) and a repeat period of 474 years.

In practice, the engineer as a rule chooses $q = 3.5$ without asking the owner and without explaining him or her what exactly this choice implies. In these cases, the inelastic response of structure is not calculated through a linear inelastic analysis, but through an 'equivalent' linear elastic analysis with the aid of a properly modified (division by q) design spectrum.

Designing a structure with $q = 3.5$, means that, during the "designed earthquake", all the expected elastoplastic mechanisms will be activated in order to absorb the 71% [= $(1 – 1/q)100$] of the seismic energy derived from the earthquake.

If these mechanisms are partially or totally not activated, this means that:

- the calculation with $q = 3.5$ was inconsistent,
- the yield mechanisms become unreliable,
- the entrance into the inelastic region is no more under control or
- the possibility of collapse is far from sufficiently small.

In other words the elastoplastic mechanisms are the "fuses" of the structure and have to function, i.e. to "blow" under the designed earthquake; otherwise the whole system "is blown".

The simplified spectral method (equivalent static method)

This is the usually applied method for calculating the seismic response of structures. According to the procedure followed, the seismic action is substituted by static 'equivalent' horizontal forces F_i, where i = 1, 2, … N, is the number of stories.

The method can generally be applied in a reliable way, only when for the structure itself, the following two conditions are satisfied:

a.The fundamental modal shape of oscillation is mainly transportational, i.e. torsional oscillations of structure are limited. This condition aims at excluding

those buildings presenting high torsional oscillations during their seismic response. In other words buildings that are “torsionally sensitive” are excluded. Nevertheless the EAK 2000 extends, through a rational way, the application of this method in such structures.

b. The fundamental modal shape of oscillation is predominant, i.e. the higher modal shapes of oscillation barely contribute to the total oscillation of structure. This condition means that, from the various modal shapes of structure, we pick off the **first only**, considering that structure is oscillating because of this. Consequently if the first modal shape is not predominant, having only a small contribution to the total oscillation, the method is not reliable.

Structures that fulfill the above two conditions are characterized as **ordinary**. The more we get away from these conditions the less reliable gets the method.

In addition, a structure is ordinary when:

1. It presents a limited change in both stiffness and mass along its height and

2. The stories function as a diaphragm, i.e. each one is moved as a whole. This function is not guaranteed for longitudinal buildings, or parts of buildings with a ratio of their sides greater than 4, or even for buildings presenting empty areas greater than 35% of their story’s plan.

Magnitude of the seismic forces F_i

The total magnitude of the equivalent horizontal static forces F_i, i.e. the base shear force $V_o = \Sigma(F_i)$ of the structure, is calculated through the equation:

$$V_0 = m \cdot \Phi_d(T), \text{ where:}$$

- m is the **total** oscillating mass of structure, $m = \Sigma W_i/g$. For a standard construction, the weight for the i^{th} story is stated as $W_i = G_i + 0.3Q$, where G are the dead loads of the story and Q the corresponding live loads,
- $\Phi_d(T)$ is the value of the design spectral acceleration calculated through equation 2 of the Greek seismic code and
- T is the natural period of the structure on the seismic direction.

The period T is allowed to be calculated through any approximate method of mechanics.

For a **rectangular** plan of the structure the period can be taken from the formula:

$$T = 0.09H\sqrt{\frac{H}{(H+\rho\cdot \mathrm{L})\mathrm{L}}} \text{ , where:}$$

- H is the total height of the structure
- L is the length along the seismic direction and
- ρ is the ratio of the total cross sectional area of walls over the sum of all the cross sectional areas (walls + columns) of the structure.

Distribution of forces F_i along the height of structure

The base shear force V_0 is distributed to each story, following a triangular allocation of the first modal shape.

In ordinary buildings this distribution is stated as follows:

$$F_i = (V_0 - V_H)\frac{m_i \cdot z_i}{\sum(m_i \cdot z_i)} \text{ , where:}$$

- m_i is the mass of the i^{th} story (i = 1, 2, … N)
- z_i is the distance between the i^{th} story and the base and
- $V_H = 0.07 \cdot T \cdot V_0 \leq 0.25 \cdot V_0$ is an additional force acted on the top of the building, for T ≥ 1 sec. This additional force, for T < 1 sec is taken equal to zero.

Elastic axis. Direction of equivalent static forces

The equivalent static forces must be applied on the direction of **principal axes** of the structure. These axes belong to the so called two principal planes, which are bending planes, vertical and perpendicular to each other, where the horizontal seismic force causes **only a transposition** of the structure, without twist.

The section of the two principal planes constitutes the **elastic axis** of structure. The track of the elastic axis on the slab of the story (its section with the slab), is the so called **elastic center** of this building's story.

However, contrary to single story and some special cases of buildings, the multistory mixed buildings, are comprised of frames and walls; hence they might not actually incorporate principal bending planes or an elastic axis. Consequently, in this general case, the conditions of applying the equivalent static method are no longer in hold.

To this problem, EAK 2000 provides a solution, introducing the concept of the so called **imaginary elastic axis** for any multistory building.

The imaginary elastic axis is a vertical line presenting the following property: When the plane of horizontal seismic forces coincides with it, causing in general some twists on the stories' levels, the sum of the squares of the twisting angles becomes minimum and hence the seismic forces, eventually cause the least torsional strain of structure.

Of course the twisting of structure is not vanished as in the case of a real elastic axis, but it is **minimized**.

In other words, the **imaginary elastic axis** is a vertical line of **optimum** torsional strain of the building, used for this reason in the above method.

The principal directions are determined with respect to this axis, defining thus the directions of the equivalent static forces.

Eccentricities – radius of distortion/gyration – torsional sensitivity

Given the elastic axis of a single story building, the following useful magnitudes can be defined:

1. The **structural or static eccentricity**, e_0, which is the distance between the center of gravity (CG) and the elastic axis; this distance constitutes an index of the building's symmetry.

2. The **radius** of **distortion**, $\boldsymbol{\rho_K}$, with respect to the **elastic** axis, $\rho^2_K = K_z/K$, where: $K_z = u/\theta_z$, is the distortion of structure about the elastic axis, K is the stiffness of structure on the corresponding principal plane, u is the transposition due to a unity force on the principal direction and θ_z is the twist of the diaphragm for a torsional moment $M_z = 1$.

3. The **radius of distortion**, $\boldsymbol{\rho_m}$, with respect to the **CG**, $\rho^2_m = \rho^2_K + e^2_0$.

4. The **radius of** the story's **gyration**, $r = 0.084(L_x^2 + L_y^2)$, for a rectangular plan of the story, with sides L_x, L_y. Then, if:

   - $\rho_m > r$, it follows that the fundamental modal shape has a predominant **transpositional** character, which implies a small influence of torsion.

   - $\rho_m \leq r$, the fundamental modal shape has a predominant **tortional** character, which implies a significant influence of torsion. In this case, the structure is considered to be torsionally sensitive.

All the above magnitudes are defined in the EAK 2000, for each one of the principal (imaginary or not) axes of the stories' building.

Accidental eccentricities – equivalent static eccentricities

The seismic loads, substantially express the inertial forces that are developed from the masses of building's stories during the oscillation of structure. Therefore they should act on the center of gravity (CG) of each story.

Nevertheless they are not actually applied on the CG, but eccentrically, at some distances from the CG, defined from the so called eccentricities, which are:

1. **Accidental eccentricities**, e_a. They take into account the scattering of mass, the elastic and damping properties of the structure, along with any probable torsional oscillations of ground, and are defined as: $e_{ai} = 0.05L_i$, where L_i is the breadth of structure perpendicular to the direction of seismic force.

2. **Equivalent static eccentricities**, e_f, e_r. They take into account the difference (increase or reduction) between the static and dynamic torsional strain of the building.

   Due to the static design demanded by the method – in reality the structure is strained dynamically – there is a torsional divergence, especially on buildings presenting non symmetric columns and walls.

   This divergence is covered by introducing the static loads **eccentrically**.

According to EAK 2000, in torsionally **sensitive** buildings, the above equivalent static eccentricities must be calculated in a rather detailed way, while for **non-sensitive**, they are taken from simple approximative formulae ($e_f = 1.50e_0$, $e_r = 0.50e_0$).

Spatial superposition – seismic directions

The simplified spectral method demands the two horizontal seismic components to be parallel to the principal directions of the building.

Let's assume that a structure is designed through the equivalent static method, initially along the X and then along the Y principal direction. Let us take for instance, a girder under bending and axial load, for which the analysis gave:

- M_x and N_x through a solution on the X-direction, while
- M_y and N_y through a solution on the Y-direction.

The question which arises is: which is the bending moment, M_d and the axial load, N_d, that will be used for dimensionalising the girder? Obviously a simple sum

$$M_d = M_x + M_y \quad \text{and} \quad N_d = N_x + N_y$$

is not correct because the two seismic excitations are statistically independent. The “sum”, i.e. the spatial superposition, has to follow the statistical procedure that gives the extreme possible value of an amount, exM and exN, i.e. the formula of simple quadratic superposition:

$$exM = \pm\sqrt{M_x^2 + M_y^2} \quad \text{and} \quad exN = \pm\sqrt{N_x^2 + N_y^2} \ .$$

Will the girder be dimensionalised using the above extreme values? Obviously not, because these values are possibly maximum or minimum, which, however, do not appear simultaneously.

Rationally, the dimensionalisation will comprise the following 4 couples:

$$[\pm\, exM,\ N] \quad \text{where} \quad N = (\pm\, M_x \cdot N_x + M_y \cdot N_y)/exM \quad \text{and}$$

$$[\pm\, exN,\ M] \quad \text{where} \quad M = (\pm\, M_x \cdot N_x + M_y \cdot N_y)/exN \ .$$

Namely, for dimensionalising a cross section strained by more than one internal forces, we have to combine the extreme value of each force, with the possible simultaneous – to this extreme force-value – values of the other forces.

Example

A three-storey building of ordinary importance, presenting for each storey a load of 2500 kN and a height of 4 m, is founded in an area of Seismic Risk Zone I. The cross-sectional areas of the vertical elements (columns, walls etc) are depicted in the plan of the following figure.

Calculate the seismic design loads for an earthquake direction y-y.

Data: Soil class B → $\theta = 1$ and $T_1/T_2 = 0.15/0.60$

Behavior Factor $q = 3.5$

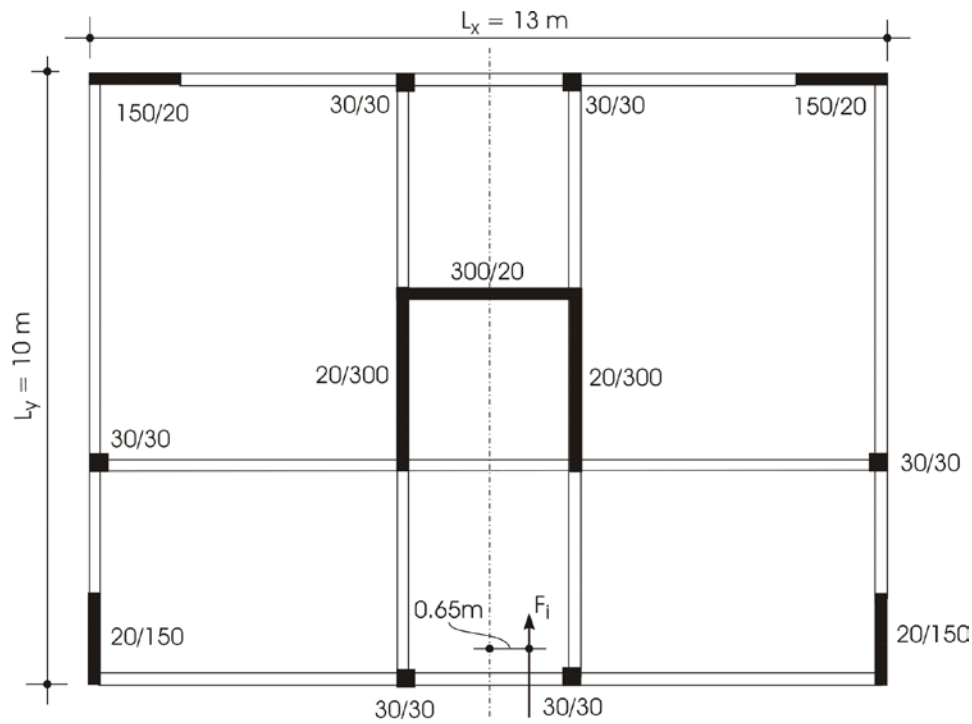
Solution

Applying the restrictions coming from the above data we proceed to the following calculations:

Mass of building:

$$M = \frac{3 \cdot 2500}{g} = \frac{7500\ kN}{g}$$

Natural period of Building: Due to the orthogonal plan of structure we can apply the relation:



$$T = 0.09H\sqrt{\frac{H}{(H+\rho L)L}}$$

where: H = 3·4 = 12 m and $L = L_y$ = 10 m.

Along the seismic direction y-y: $A_{walls} = 0.2\cdot(2\cdot1.5+2\cdot3) = 1.8\ m^2$.

Totally: $A_{walls} + A_{columns} = 0.2\cdot(4\cdot1.5+3\cdot3) + 0.3\cdot0.3\cdot6 = 3 + 0.54 = 3.54\ m^2$.

ρ = 1.80/3.54 = 0.51. Therefore

$$T = 0.09\cdot12\sqrt{\frac{12}{(12+0.51\cdot10)\cdot10}} = 0.29\ sec$$

Since $T_1 < 0.29 < T_2$, the building is stiff, thus we use equation 2b of the EAK code.

Base shear force:

$$V_0 = M\cdot\Phi_d(T) = M\cdot A\cdot\gamma_I\frac{\beta_0}{q}\cdot\theta = \frac{7500}{g}\cdot0.16\cdot g\cdot1\frac{2.5}{3.5}\cdot1 = 857.14\ kN$$

Shear force distribution along height:

$$F = (V_0 - V_H)m_i\cdot z_i/\sum(m_i\cdot z_i)$$

where $V_H = 0$ because $T < 1$ sec.

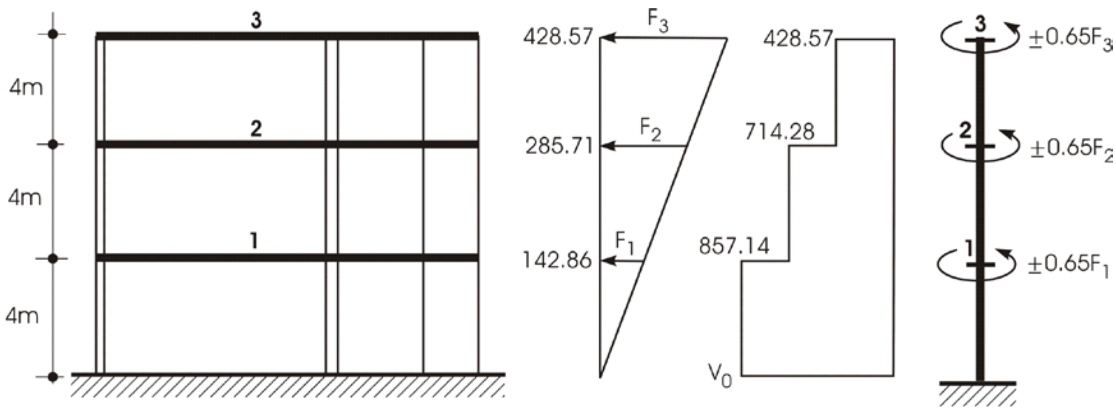
$$\sum(m_i \cdot z_i) = \frac{2500}{g}4 + \frac{2500}{g}8 + \frac{2500}{g}12 = \frac{60000}{g}$$

$$F_1 = 857.14\frac{(2500/g)\cdot 4}{60000/g} = 142.86\ kN$$

$$F_2 = 857.14\frac{(2500/g)\cdot 8}{60000/g} = 285.71\ kN$$

$$F_3 = 857.14\frac{(2500/g)\cdot 12}{60000/g} = 428.57\ kN$$

Each one of the above forces will be applied on the corresponding storey at a distance $0.05Lx = 0.05\cdot 13 = 0.65$ m from both sides of the centre of gravity (CG). This means the existence of a simultaneous torsional moment $\pm\ 0.65F_i$ kNm, on the i^{th} floor.



The dynamic spectral method – General concepts

This method is applied without restrictions to any structure covered by EAK 2000. However, the reliability of method is getting less in cases concerning buildings with high non-symmetries and large variations on mass and stiffness along their height and plan.

It is possible to describe the dynamic response of a structure, through an analysis of its oscillation, in “modal oscillations”.

The number of modal oscillations that a system presents, is, in general, equal to the number of its main degrees of freedom.

The number of degrees of freedom in a system with concentrated masses can be determined by the minimum number of independent movements and twists made by the masses, so that their position can always be geometrically located.

For a plane frame, for instance, with concentrated masses on its horizontal girders which keep their shape – assumptions realistic for current structures – the degrees of freedom are determined by its number of storeys. In this case the independent movements are the horizontal displacements of its girders.

In every modal type, all distinct masses are oscillated “in phase”, meaning that they pass from their rest position and maximum displacement in the same period of time.

Every modal oscillation is directly related to its ‘natural or self period’, i.e. the time necessary for a complete oscillation. The greatest natural period for any system corresponds to its first “fundamental mode”.

The majority of the building responses is calculated by composing some of the first modal shapes. Nevertheless, for high buildings with a framed bearing system, it has been concluded that the first fundamental mode contributes about 80% to the total response, while the second and third modes, about 15%.

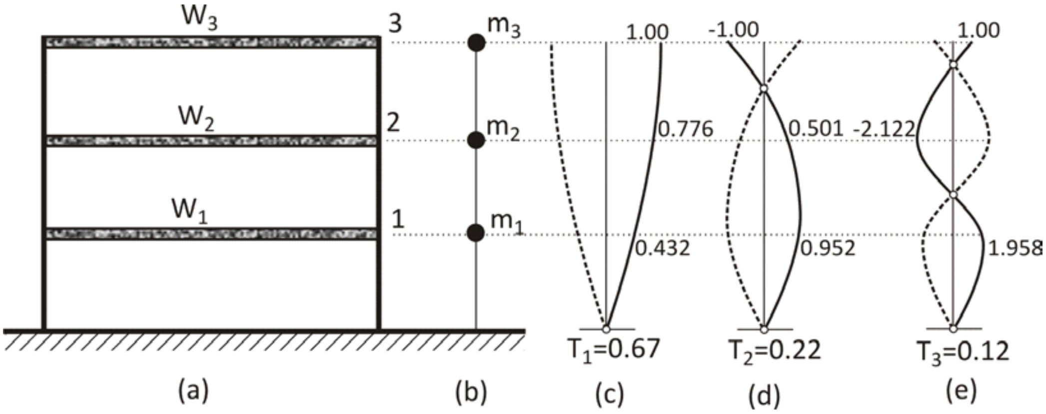
The next figure depicts the three first modal shapes (c,d,e) of a multistory building.

The curves intersect the vertical axis of each mode in a number of points (points of contraflexure, where the base point is concluded), that express the modal order.

The displacements of each mode are relevant without expressing a specific amount. The vectors Φi that define each modal shape are:

$$\Phi_1 = \begin{bmatrix} \Phi_{11} \\ \Phi_{21} \\ \Phi_{31} \end{bmatrix} = \begin{bmatrix} 0.432 \\ 0.776 \\ 1.000 \end{bmatrix}, \quad \Phi_2 = \begin{bmatrix} \Phi_{12} \\ \Phi_{22} \\ \Phi_{32} \end{bmatrix} = \begin{bmatrix} 0.952 \\ 0.501 \\ -1.000 \end{bmatrix}, \quad \Phi_3 = \begin{bmatrix} \Phi_{13} \\ \Phi_{23} \\ \Phi_{33} \end{bmatrix} = \begin{bmatrix} 1.958 \\ -2.122 \\ 1.000 \end{bmatrix}$$

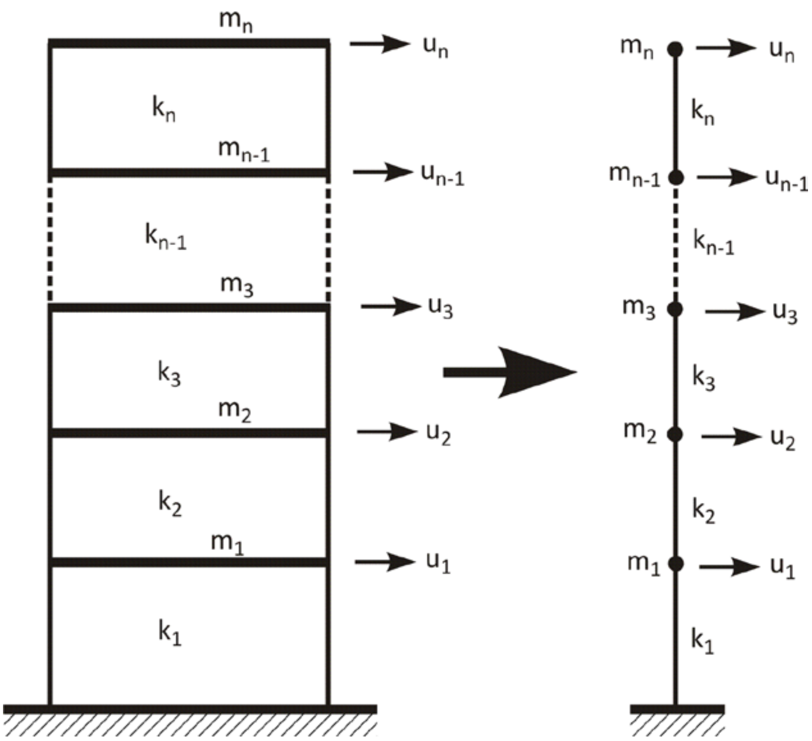
The maximum relevant displacement is 1, keeping the modal shape ratio constant.



(a) Static model, (b) dynamic model, (c), (d), (e) 1st, 2nd, 3rd modal shapes

Free oscillation of n-degree of freedom system without damping

A multi-storey framed structure presenting n floors and therefore **n** degrees of freedom is illustrated below.



A multi storey frame

It has to be noted that k_j is the **total** stiffness of columns connecting the level **j** with the corresponding lower one.

In the lack of damping, the mathematical expression of the dynamic equilibrium in a matrix form is:

$$\boldsymbol{M\ddot{U}} + \boldsymbol{KU} = [\mathbf{0}]$$

where the parameters involved in the above equation, i.e. the **Displacement vector,** the **Mass** and the **Stiffness matrix** are determined in a matrix form as follows:

Displacement vector

$$U = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ \cdot \\ u_{n-1} \\ u_n \end{bmatrix}$$

Mass matrix

$$M = \begin{bmatrix} m_1 & 0 & 0 & \cdot & 0 & 0 \\ 0 & m_2 & 0 & \cdot & 0 & 0 \\ 0 & 0 & m_3 & \cdot & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & \cdot & m_{n-1} & 0 \\ 0 & 0 & 0 & \cdot & 0 & m_n \end{bmatrix}$$

Stiffness matrix

$$K = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 & \cdot & 0 & 0 \\ -k_2 & k_2 + k_3 & -k_3 & \cdot & 0 & 0 \\ 0 & -k_3 & k_3 + k_4 & \cdot & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & \cdot & k_{n-1} + k_n & -k_n \\ 0 & 0 & 0 & \cdot & -k_n & k_n \end{bmatrix}.$$

Taking into account the contents of the above matrices, if we develop the products arising from the initial equation and do the necessary mathematical procedure, the following system of **n** equations yields, expressing the dynamic equilibrium for each mass (1 to n) separately:

$$m_1\ddot{u}_1 + k_2(u_1 - u_2) + k_1u_1 = 0$$

$$m_2\ddot{u}_2 + k_3(u_2 - u_3) + k_2(u_2 - u_1) = 0$$

$$m_3\ddot{u}_3 + k_4(u_3 - u_4) + k_3(u_3 - u_2) = 0$$

. . . .

$$m_{n-1}\ddot{u}_{n-1} + k_n(u_{n-1} - u_n) + k_{n-1}(u_{n-1} - u_{n-2}) = 0$$

$$m_n\ddot{u}_n + k_n(u_n - u_{n-1}) = 0\,.$$

It can be proved that in the above n-degree-of-freedom-system there are **n** natural frequencies $\boldsymbol{\omega_j}$, that correspond to **n** modal shapes $\boldsymbol{\Phi_j}$, where j = 1, 2, … n and

$$\ddot{U}_j = -\omega_j^2 \Phi_j\,.$$

Substituting this value of acceleration above, for a **2-degree-of-freedom-system**, the yielding equation, $\mathbf{K}\cdot\mathbf{\Phi} - \omega^2\mathbf{M}\cdot\mathbf{\Phi} = 0$, holds only if its determinant is zero, i.e.

$$|\boldsymbol{K} - \omega^2\boldsymbol{M}| = 0 \quad \rightarrow \quad \begin{vmatrix} k_1 + k_2 - \omega^2 m_1 & -k_2 \\ -k_2 & k_2 - \omega^2 m_2 \end{vmatrix} = 0 \quad \rightarrow$$

$$\rightarrow \quad \omega^4 m_1 m_2 - \omega^2[(k_1 + k_2)m_2 + k_2 m_1] + k_1 k_2 = 0\,.$$

Putting $\omega^2 = \lambda$, we form a trinomial with two solutions, $\lambda_1 = \omega_1{}^2$ and $\lambda_2 = \omega_2{}^2$, from which the normal frequencies and periods of the system are obtained.

Steps of procedure

Before calculations, the following steps describe the procedure to be followed.

1. Number of modal shapes:

A number of modal shapes (eigen modes), i, will be taken into account, until the sum of the **acting** modal masses ΣM_i reaches the **90%** of the **total oscillating mass** of the system.

2. Orientation of seismic action

While in the Simplified Spectral or Equivalent Static Method the directions of horizontal seismic components had to be considered parallel to the (real or unreal) main directions of building, in the Dynamic method the two horizontal seismic components may have **any direction**. In other words the response of structure is independent to the orientation of these components. This means that:

- The two horizontal and perpendicular to each other components act simultaneously,
- They considered statistically non-associative, and

- The response spectra for the two horizontal directions are equivalent.

As a result of the above, the bending moment of a girder maintains the same value, independently of the seismic excitation's orientation and its maximum, or extreme value should be statistically calculated, i.e. by the sum of the two component contributions.

3. Eccentricity

While in the Simplified Static Method the equivalent static eccentricities had to be taken into account, in the Dynamic method there is no need for this, once possible non symmetries in the structure's plan are automatically considered.

However, the accidental eccentricities, referred in the previous method, remain.

In practice, the mass m_i of each floor, is taken moved from both sides of the centre of gravity at a distance equal to the accidental eccentricity e_{ai} of the respective storey.

In other words the system is solved 4 times for the 2 simultaneous components.

4. Modal analysis

Then follows the estimation of modal shapes, along with the natural periods T_1, T_2, T_3, … for each mode.

5. Use of design spectrum

From the design spectrum, and the previously estimated natural periods (T_1, T_2, T_3…), the maximum design acceleration ($S_{\alpha 1}$, $S_{\alpha 2}$, $S_{\alpha 3 \ldots}$) for each modal shape is determined.

6. Forces of Inertia

For each modal shape, the imaginary portions of masses m_i that participate in this mode is estimated, yielding, according to the following procedure, the values of excitation's coefficients, L_i, and the generalized (modal) masses, M_i.

Then, using these values, through the following typical formulae, the maximum forces-of-inertia $P_{i,j}$ (i=floor, j=mode) are calculated:

1st Mode
$$\begin{cases} L_1 = m_1 \cdot \varphi_{1,1} + m_2 \cdot \varphi_{2,1} + m_3 \cdot \varphi_{3,1} \\ M_1 = m_1 \cdot \varphi_{1,1}^2 + m_2 \cdot \varphi_{2,1}^2 + m_3 \cdot \varphi_{3,1}^2 \\ P_{1,1} = m_1 \cdot \varphi_{1,1} \frac{L_1}{M_1} S_{a1} \\ P_{2,1} = m_2 \cdot \varphi_{2,1} \frac{L_1}{M_1} S_{a1} \\ P_{3,1} = m_3 \cdot \varphi_{3,1} \frac{L_1}{M_1} S_{a1} \end{cases}$$

2nd Mode
$$\begin{cases} L_2 = m_1 \cdot \varphi_{1,2} + m_2 \cdot \varphi_{2,2} + m_3 \cdot \varphi_{3,2} \\ M_2 = m_1 \cdot \varphi_{1,2}^2 + m_2 \cdot \varphi_{2,2}^2 + m_3 \cdot \varphi_{3,2}^2 \\ P_{1,2} = m_1 \cdot \varphi_{1,2} \frac{L_2}{M_2} S_{a2} \\ P_{2,2} = m_2 \cdot \varphi_{2,2} \frac{L_2}{M_2} S_{a2} \\ P_{3,2} = m_3 \cdot \varphi_{3,2} \frac{L_2}{M_2} S_{a2} \end{cases}$$

3rd Mode
$$\begin{cases} L_3 = m_1 \cdot \varphi_{1,3} + m_2 \cdot \varphi_{2,3} + m_3 \cdot \varphi_{3,3} \\ M_3 = m_1 \cdot \varphi_{1,3}^2 + m_2 \cdot \varphi_{2,3}^2 + m_3 \cdot \varphi_{3,3}^2 \\ P_{1,3} = m_1 \cdot \varphi_{1,3} \frac{L_3}{M_3} S_{a3} \\ P_{2,3} = m_2 \cdot \varphi_{2,3} \frac{L_3}{M_3} S_{a3} \\ P_{3,3} = m_3 \cdot \varphi_{3,3} \frac{L_3}{M_3} S_{a3} \end{cases}$$

7. Extreme modular response

For the maximum modal forces of inertia, the corresponding maximum response magnitudes (bending moments, shear forces, displacements etc) of each mode are calculated.

8. Modal superposition

All the above modal quantities are superposed by means of the Square Root of the Sum of Squares (SRSS), i.e.

$$A_s = \sqrt{A_{s,1}^2 + A_{s,2}^2 + A_{s,3}^2}$$

where: A_s is a response magnitude, say, bending moment, located at s, $A_{s,i}$ is the maximum value of the above magnitude at the same location for the ith mode.

This way of superposition is justified on the view that the maximum value of each modal magnitude is not realised simultaneously for all modes. Therefore, based on the theory of probabilities, the most realistic maximum value may be represented by the Square Root of the Sum of Squares.

9. Spatial superposition

On this step, an appropriate superposition of the maximum seismic response for a simultaneous action of all 3 components (2 horizontal + 1 vertical, which is usually ignored), is realised.

Therefore for a magnitude A_s, the maximum responses A_{sx}, A_{sy}, A_{sz} are not developed simultaneously and hence, the maximum value of A_s can be given either through:

$$A_s = \pm\sqrt{A_{sx}^2 + A_{sy}^2 + A_{sz}^2}\,, \quad \text{or}$$

the absolutely maximum value from the following three:

$$A_s = \pm A_{sx} \pm 0.3\ A_{sy} \pm 0.3\ A_{sz}$$

$$A_s = \pm 0.3 A_{sx} \pm A_{sy} \pm 0.3\ A_{sz}$$

$$A_s = \pm 0.3 A_{sx} \pm 0.3\ A_{sy} \pm A_{sz}$$

When the vertical component is ignored, the absolutely maximum value from the following two is considered:

$$A_s = \pm A_{sx} \pm 0.3\ A_{sy}$$

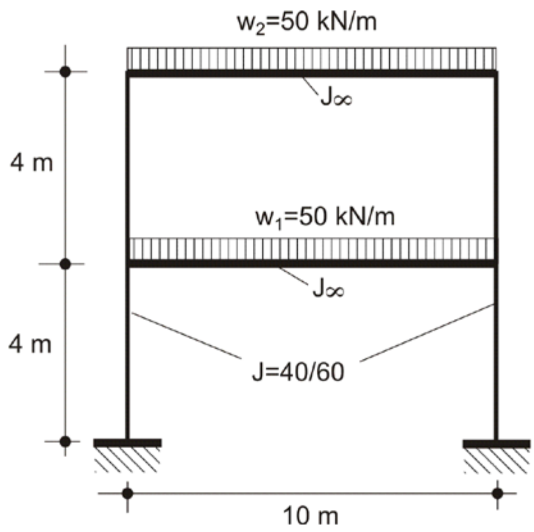
$$A_s = \pm 0.3 A_{sx} \pm A_{sy}$$

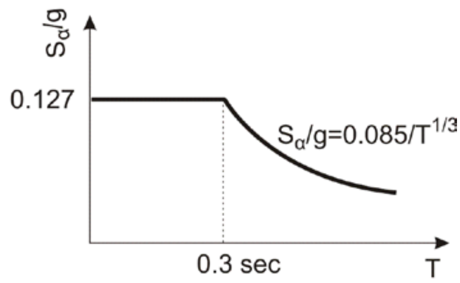
10. Combinations of cross-sectional dimensions

Aiming at a cross-sectional determination, i.e. dimensioning any structural element, EAK 2000 allows the most conservative combination (there are too many), for the magnitude(s) A_s, yielding from the above spatial superposition.

Example

For the framed structure of the following figure, calculate its seismic response, using the dynamic method along with its corresponding spectrum.





Data: $E = 2.1 \cdot 10^7 kN/m^2$,

$$J = \frac{0.4 \cdot 0.6^3}{12} = 7.2 \cdot 10^{-3} m^4 ,$$

$$K = \frac{2 \cdot 12EJ}{h^3} = \frac{24 \cdot 2.1 \cdot 10^7 \cdot 7.2 \cdot 10^{-3}}{4^3} = 56700\ kN/m .$$

Solution

a. Mass matrix

Since the frame is planar with a girder of infinite stiffness, the masses can be considered concentrated on the girder's C.G. It is:

$$m_1 = m_2 = \frac{q \cdot l}{g} = \frac{50 \cdot 10}{10} = 50\ kN/(m/sec^2)$$

Therefore the mass matrix is:

$$M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} = \begin{bmatrix} 50 & 0 \\ 0 & 50 \end{bmatrix} .$$

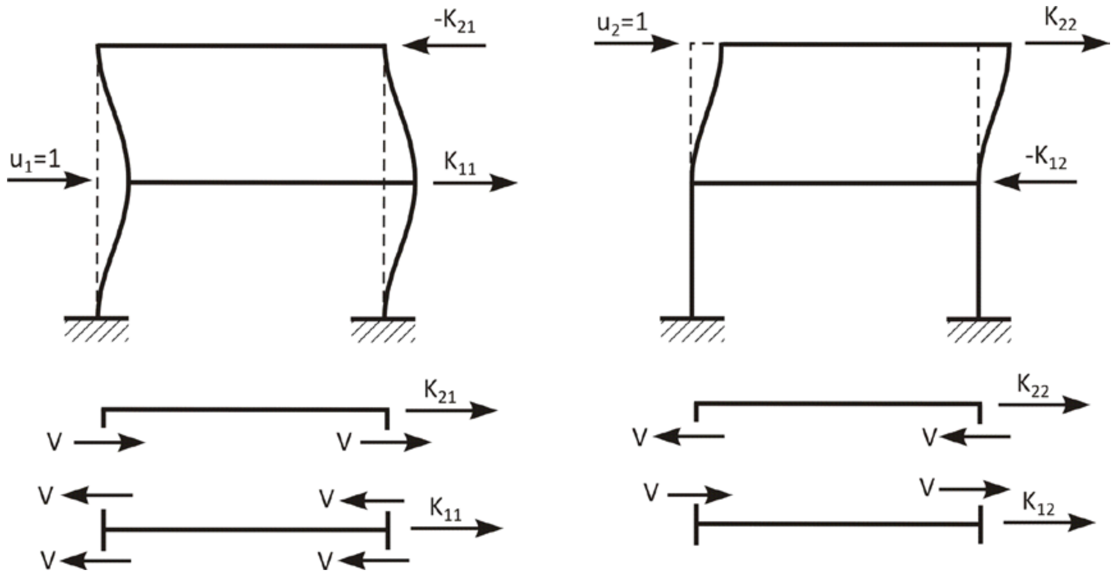
b. Stiffness matrix

There are two degrees of freedom, i.e. as many as the number of storeys. The two independent horizontal displacements of the storeys are u_1 and u_2.

The stiffness matrix of the frame, i.e. the force K, necessary to cause u = 1 on it, is:

$$K = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix}$$

where K_{ij} is the necessary stiffness at the place level i (where the force is acting), to withstand a unit displacement realised at the place level j.



The shear forces, V, developed above and/or below the i^{th} level, corresponding to K_{ij}, are given below, making use of the deformed frame (see previous figure).

It has to be noted here that stiffness **$-K_{21}$** and **$-K_{12}$** are negative, because, trying to keep the rest of the frame in place, their direction is **opposite** to the applied unity of displacement. Therefore:

For $u_1 = 1$ on the **first** floor, it is: $K_{21} = -2V$ and $K_{11} = 4V$ while

For $u_1 = 1$ on the **second** floor, it is: $K_{22} = 2V$ and $K_{12} = -2V$, where:

$$V = \frac{12EJ}{h^3} \cdot 1 = 2.835 \cdot 10^4 \, kN$$

The above four values of stiffness, constitute the elements of the stiffness matrix of this structure and confirm the general case presented at the beginning of this chapter. Finally it is:

$$K = 2.835 \cdot 10^4 \cdot 2 \begin{bmatrix} 2 & -1 \\ -1 & 1 \end{bmatrix} = \begin{bmatrix} 2 \cdot 5.67 \cdot 10^4 & -5.67 \cdot 10^4 \\ -5.67 \cdot 10^4 & 5.67 \cdot 10^4 \end{bmatrix}$$

c. Dynamic characteristics

Natural frequencies equation

On the system there are **two** modal shapes, like the number of degrees of freedom.

In order that the system $\mathbf{K} \cdot \mathbf{\Phi} - \omega^2 \mathbf{M} \cdot \mathbf{\Phi} = 0$, has two non-zero solutions, apart from the obvious solution $\phi_i = 0$, its determinant has to be zero. Namely,

$$|\boldsymbol{K}-\omega^2\boldsymbol{M}|=0 \quad \rightarrow \quad \begin{vmatrix} 2\cdot 5.67\cdot 10^4-\omega^2 50 & -5.67\cdot 10^4 \\ -5.67\cdot 10^4 & 5.67\cdot 10^4-\omega^2 50 \end{vmatrix}=0 \quad \rightarrow$$

$$(2\cdot 5.67\cdot 10^4-\omega^2 50)\cdot(5.67\cdot 10^4-\omega^2 50)-\ (5.67\cdot 10^4)^2\ =\ 0\quad \rightarrow$$

$$2\cdot 5.67\cdot 10^6-\ 5\cdot 2\cdot 5.67\cdot 10^3\omega^2-5\cdot 5.67\cdot 10^3\omega^2+\omega^4\cdot 5^2-\ 5.67\cdot 10^6=0\,.$$

Putting already $\omega^2 = \lambda$, the previous equation takes the form

$$25\lambda^2-\ 85.05\cdot 10^3\lambda\ +\ 32.15\cdot 10^6\ =\ 0$$

$$\lambda_{1,2}=\frac{85.05\cdot 10^3\ \pm 63.39\cdot 10^3}{50}=\begin{cases} 2.968\cdot 10^3\ =\ \lambda_2 \\ 0.433\cdot 10^3\ =\ \lambda_1 \end{cases}$$

The two natural frequencies are therefore:

$$\boldsymbol{\omega_1}\ =\ \sqrt{\lambda_1}=\boldsymbol{20.81\,rad/sec} \quad \text{and}$$

$$\boldsymbol{\omega_2}\ =\ \sqrt{\lambda_2}=\boldsymbol{54.48\,rad/sec}\,.$$

Natural periods

The natural periods yield from the corresponding frequencies through the basic equation $T_i = 2\pi/\omega_i$.

$$\boldsymbol{T_1}\ =\ \frac{2\pi}{\omega_1}\ =\ \frac{2\cdot 3.14}{20.81}\ =\ \boldsymbol{0.302\ sec} \quad \text{and}$$

$$\boldsymbol{T_2}\ =\ \frac{2\pi}{\omega_2}\ =\ \frac{2\cdot 3.14}{54.48}\ =\ \boldsymbol{0.115\ sec}\,.$$

Modal shapes

For each value of ω_i, (or T_i) the homogeneous system $\mathbf{K}\cdot\mathbf{\Phi} - \omega^2\mathbf{M}\cdot\mathbf{\Phi} = 0$ presents i linearly independent solutions, i.e. natural vectors or modal shapes Φ_i.

Every vector univocally determines a simple infinity of homologous displacements, i.e. a shape of the structure’s deformation (mode), called modal shape.

The characteristic equation for calculating the modal shapes is:

$$[\boldsymbol{K}-\omega^2\boldsymbol{M}]\cdot[\boldsymbol{\varphi_i}]\ =\ [\boldsymbol{0}]\,.$$

<u>First modal shape $\omega = \omega_1$</u>

$$\begin{bmatrix} 2\cdot 5.67\cdot 10^4-\omega_1^2 50 & -5.67\cdot 10^4 \\ -5.67\cdot 10^4 & 5.67\cdot 10^4-\omega_1^2 50 \end{bmatrix}\cdot\begin{bmatrix}\varphi_{11} \\ \varphi_{21}\end{bmatrix}=0$$

$$(2\cdot 5.67\cdot 10^3-\omega_1^2 5)\cdot\varphi_{11}\ -\ 5.67\cdot 10^3\cdot\varphi_{21}\ =0 \quad (1a)$$

$$-5.67 \cdot 10^3 \cdot \varphi_{11} + (5.67 \cdot 10^3 - \omega_1^2 5) \cdot \varphi_{21} = 0 \quad (2a)$$

In equation (1α), if we put the already calculated value **ω₁² = 0.43310 ³** along with $\boldsymbol{\varphi_{11} = 1}$, then, the value for $\boldsymbol{\varphi_{21}}$ will be obtained.

$$2 \cdot 5.67 \cdot 10^3 - 0.433 \cdot 10^3 \cdot 5 - 5.67 \cdot 10^3 \cdot \varphi_{21} = 0 \quad \rightarrow$$

$$\boldsymbol{\varphi_{21}} = \frac{2 \cdot 5.67 - 5 \cdot 0.433}{5.67} = \frac{11.34 - 2.165}{5.67} = \mathbf{1.618}$$

The vector for the **first** modal shape is therefore:

$$\boldsymbol{\varphi_1} = [\varphi_{11} \quad \varphi_{21}] = [\mathbf{1} \quad \mathbf{1.618}].$$

<u>**Second** modal shape ω = ω₂</u>

$$\begin{bmatrix} 2 \cdot 5.67 \cdot 10^4 - \omega_2^2 50 & -5.67 \cdot 10^4 \\ -5.67 \cdot 10^4 & 5.67 \cdot 10^4 - \omega_2^2 50 \end{bmatrix} \cdot \begin{bmatrix} \varphi_{12} \\ \varphi_{22} \end{bmatrix} = 0$$

$$(2 \cdot 5.67 \cdot 10^3 - \omega_2^2 5) \cdot \varphi_{12} - 5.67 \cdot 10^3 \cdot \varphi_{22} = 0 \quad (1b)$$

$$-5.67 \cdot 10^3 \cdot \varphi_{12} + (5.67 \cdot 10^3 - \omega_2^2 5) \cdot \varphi_{22} = 0 \quad (2b)$$

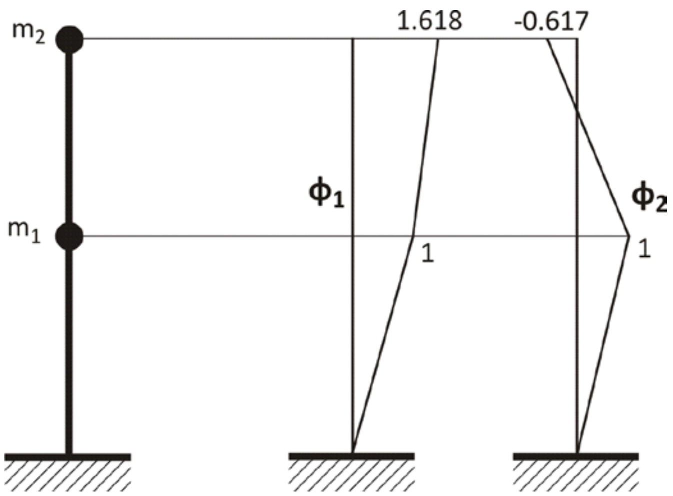
Similarly, in equation (1b), if we put the already calculated value $\boldsymbol{\omega_2^2} = \mathbf{2.968 \cdot 10^3}$ along with $\boldsymbol{\varphi_{12} = 1}$, then, the value for $\boldsymbol{\varphi_{22}}$ will be obtained.

$$2 \cdot 5.67 \cdot 10^3 - 2.968 \cdot 10^3 \cdot 5 - 5.67 \cdot 10^3 \cdot \varphi_{22} = 0 \quad \rightarrow$$

$$\boldsymbol{\varphi_{22}} = \frac{2 \cdot 5.67 - 5 \cdot 2.968}{5.67} = \frac{11.34 - 14.84}{5.67} = \mathbf{-0.617}$$

The vector for the **second** modal shape is therefore:

$$\boldsymbol{\varphi_2} = [\varphi_{11} \quad \varphi_{21}] = [\mathbf{1} \quad \mathbf{-0.617}].$$



Generalized masses

Each generalized mass M_i, plays the role of a “mass” at the i^{th} natural oscillation of the system. For the two floors, we have:

$$M_1 = m_1\varphi_{11}^2 + m_2\varphi_{21}^2 = 50 \cdot 1^2 + 50 \cdot 1.618^2 = 180.9$$

$$M_2 = m_1\varphi_{12}^2 + m_2\varphi_{22}^2 = 50 \cdot 1^2 + 50 \cdot 0.617^2 = 69.03$$

Excitation factors

These are intermediate magnitudes helping to calculating the horizontal forces for each level.

$$L_1 = m_1\varphi_{11} + m_2\varphi_{21} = 50 \cdot 1 + 50 \cdot 1.618 = 130.9$$

$$L_2 = m_1\varphi_{12} + m_2\varphi_{22} = 50 \cdot 1 - 50 \cdot 0.617 = 19.15$$

Participation factors

The participation factors, v_i, are largely decreased by the increase of i.

In general, their value is: $v_i = L_i/M_i$.

$$v_1 = \frac{L_1}{M_1} = \frac{130.9}{180.9} = 0.724$$

$$v_2 = \frac{L_2}{M_2} = \frac{19.15}{69.03} = 0.277$$

Check: $v_1 + v_2 = 1.00$

Acting modal masses

The acting modal mass, M_{ai}, is, for each modal shape, a quantitative criterion of the maximum energy of deformation and constitutes an index of its significance.

In practice it yields the number of significant modal shapes to be taken into account, ignoring all the others. The sum of all the acting modal masses has a constant value, Ms.

In general, the value of the i^{th} modal mass, M_{ai}, is: $M_{ai} = v_i^2 \cdot M_i = L_i^2/M_i$.

$$M_{a1} = \frac{L_1^2}{M_1} = \frac{130.9^2}{180.9} = 94.7$$

$$M_{a2} = \frac{L_2^2}{M_2} = \frac{19.15^2}{69.03} = 5.3$$

Check: $Ms = M_{a1} + M_{a2} = 100$

Modal shapes participation

The non dimensional ratios $e_i = M_{ai}/Ms$, where $\Sigma e_i = 1$, constitute a measure of energy comparison for all the modal shapes. The acting mass, M_{ai}, represents the percentage of the total mass, which is activated at the i^{th} modal shape. It is:

$$e_1 = \frac{M_{a1}}{Ms} = \frac{94.7}{100} = 94.7\ \%$$

$$e_2 = \frac{M_{a2}}{Ms} = \frac{5.3}{100} = 5.3\ \%$$

Modal seismic forces

On the total activated mass Ms we can correspond an activating horizontal seismic force P, which is the resultant of the seismic forces of all the floors.

This resultant is usually called *the base shear force*.

The contribution of each modal shape to the formation of each floor's horizontal seismic force is:

First modal shape, **i = 1**

Making use of the given spectrum, for the already calculated natural period $T_1 = 0.302$ sec of the first modal shape, since $T_1 > 0.3$ sec, the corresponding spectral acceleration, S_{a1}, is:

$$\frac{S_{a1}}{g} = \frac{0.085}{\sqrt[3]{T_1}} \quad \rightarrow \quad S_{a1} = \frac{0.085 \cdot g}{\sqrt[3]{0.302}} = 1.27\ m/sec^2$$

Modal acceleration;

$$\gamma_1 = v_1 \varphi_1 S_{a1} = 0.724 \begin{bmatrix} 1 \\ 1.618 \end{bmatrix} 1.27 = \begin{bmatrix} 0.919 \\ 1.49 \end{bmatrix}$$

Modal horizontal seismic force:

$$\boldsymbol{P}_1 = M \cdot \gamma_1 = \begin{bmatrix} 50 & 0 \\ 0 & 50 \end{bmatrix} \cdot \begin{bmatrix} 0.919 \\ 1.49 \end{bmatrix} = \begin{bmatrix} 50 \cdot 0.919 + 0 \cdot 1.49 \\ 0 \cdot 0.919 + 50 \cdot 1.49 \end{bmatrix} = \begin{bmatrix} \mathbf{46} \\ \mathbf{74,5} \end{bmatrix}$$

Second modal shape, **i = 2**

Again, making use of the given spectrum, for the already calculated natural period T_2 = 0.115 sec of the second modal shape, since T_2 < 0.3 sec, the corresponding spectral acceleration, S_{a2}, is constant:

$$\frac{S_{a2}}{g} = 0.127 \quad \rightarrow \quad S_{a2} = 1.27\, m/sec^2$$

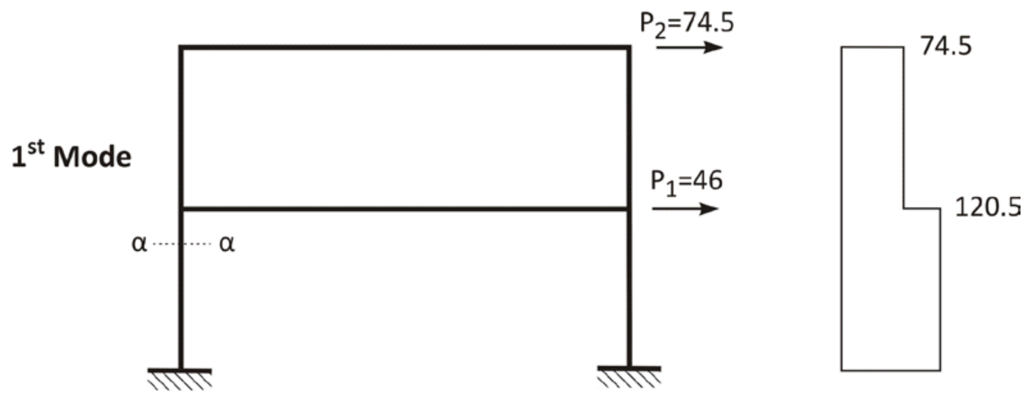
Modal acceleration;

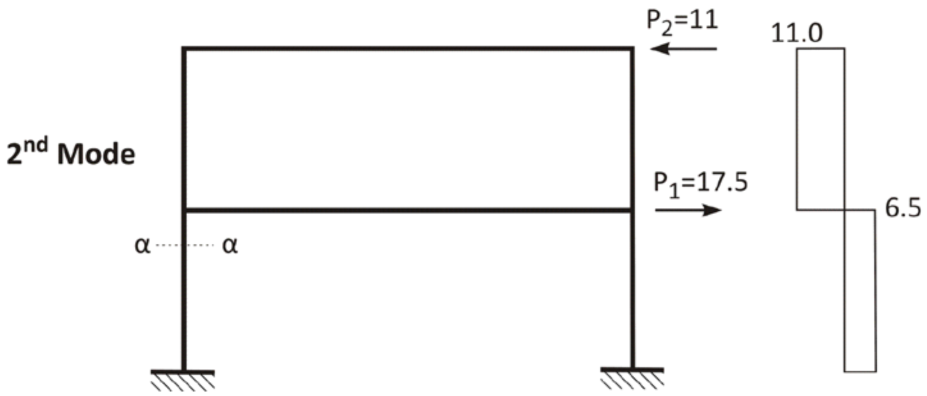
$$\gamma_2 = v_2 \varphi_2 S_{a2} = 0.276 \begin{bmatrix} 1 \\ -0.617 \end{bmatrix} 1.27 = \begin{bmatrix} 0.35 \\ -0.22 \end{bmatrix}$$

Modal horizontal seismic force:

$$\boldsymbol{P}_2 = M \cdot \gamma_2 = \begin{bmatrix} 50 & 0 \\ 0 & 50 \end{bmatrix} \cdot \begin{bmatrix} 0.35 \\ -0.22 \end{bmatrix} = \begin{bmatrix} 50 \cdot 0.35 + 0 \cdot (-0.22) \\ 0 \cdot 0.35 + 50 \cdot (-0.22) \end{bmatrix} = \begin{bmatrix} \mathbf{17.5} \\ \mathbf{-11.0} \end{bmatrix}$$

Modal shear force diagrams





Shear forces and bending moments of columns

The base shear force is: $\mathbf{V_b}$ = 74.5 + 46 = **120.5 kN**, which is equally distributed to each one of the columns.

The modal contribution to shear forces and bending moments is therefore:

$$\mathbf{1^{st}\ Mode:}\quad \boldsymbol{V_a} = \frac{120.5}{2} = \mathbf{60.25\ kN},\quad \boldsymbol{M_a} = V_a \cdot \frac{h}{2} = 60.25 \cdot \frac{4}{2} = \mathbf{120.5\ kNm}$$

$$\mathbf{2^{nd}\ Mode:}\quad \boldsymbol{V_a} = \frac{6.5}{2} = \mathbf{3.25\ kN},\quad \boldsymbol{M_a} = V_a \cdot \frac{h}{2} = 3.25 \cdot \frac{4}{2} = \mathbf{6.5\ kNm}$$

Modal superposition

$$\boldsymbol{maxV_a} = \sqrt{V_{a1}^2 + V_{a2}^2} = \sqrt{60.25^2 + 3.25^2} = \mathbf{60.34\ kN}$$

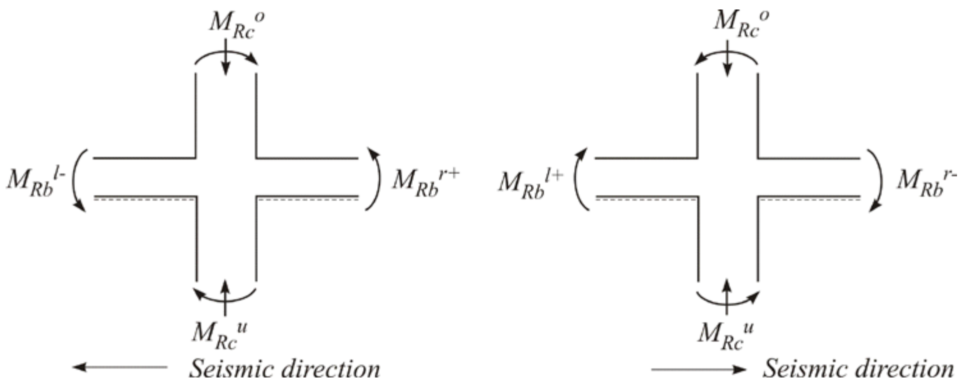
$$\boldsymbol{maxM_a} = \sqrt{M_{a1}^2 + M_{a2}^2} = \sqrt{120.5^2 + 6.5^2} = \mathbf{120.66\ kN}$$

Capacity design of joints (between beams and columns)

As a procedure, the capacity design aims at providing the structure the maximum possible absorption of energy without a partial or total collapse.

A basic principal of earthquake design of joints, is, that during a very strong seismic event, the first elements to fail must be exclusively beams, followed by a possible failure of columns.

This principal can be ensured by designing frames with "**strong columns and weak beams**"; this is quantified by a demand, stating that the sum of the **column's** flexural capacity *under the simultaneous action of compressional load*, should be **greater** than the sum of the corresponding **beams'** flexural capacity. The term *flexural capacity* is here equivalent to the *bending moment when first yield is initiating*.



Following the figure's configuration and applying the above principal, it must be:

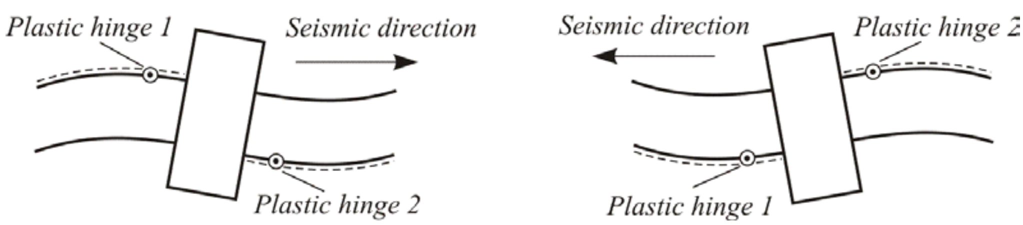
$$|M_{Rc}^{o}| + |M_{Rc}^{u}| \geq \gamma_{Rd} \cdot \left(|M_{Rb}^{l-}| + |M_{Rb}^{r+}|\right) \quad \text{and}$$

$$|M_{Rc}^{o}| + |M_{Rc}^{u}| \geq \gamma_{Rd} \cdot \left(|M_{Rb}^{l+}| + |M_{Rb}^{r-}|\right)$$

or $\Sigma|M_{Rc}| \geq \gamma_{Rd} \cdot \Sigma|M_{Rb}|$, where $\gamma_{Rd} = 1.40$

The dimensioning of columns will appear after applying the design moments, which must yield from the following procedure:

1. For each seismic direction we apply on the ends of the joint opposite moments in order to form the following mechanisms:



2. The failure moments are calculated from the existing real reinforcement of beams at both ends of the joint. Of course the dimensioning of all the beams gathered on the joint has been preceded.
3. The joint capacity magnification factor, α_{CD}, is calculated through the relation:

$$\alpha_{CD} = \gamma_{Rd} \cdot \frac{\Sigma M_{Rb}}{|\Sigma M_{Eb}|}\,, \qquad \text{where} \qquad \gamma_{RD} = 1.40 \qquad \text{and}$$

ΣM_{Rb} is the sum of the **beams' flexural capacity** gathered on the joint, as a result of the column's bending moment, **M_{EC}**, yielding from seismic analysis and <u>following the corresponding seismic direction to generate M_{EC}</u> and

ΣM_{Eb} is the sum of the **beams' seismic moments** derived from the **analysis**, following always the same corresponding seismic direction.

4. The flexural capacity of the column, **$M_{CD,c}$** , is now derived from the column's seismic moment, M_{Ec}, through the relation

$$M_{CD,c} = \alpha_{CD} \cdot M_{Ec}\ .$$

The seismic moment, M_{Ec}, as highlighted before, yields through the analysis.

5. At joints where the bending moment of the overhead vertical element, $M_{EC,1}$ is greater than the sum of moments derived from the beams, namely

$$|M_{EC,1}| > |\Sigma M_{Eb}|\,,$$

the flexural capacity is obtained from the relation **$M_{CD,C} = 1.40 M_{EC} \geq M_{SC}$**, where M_{SC} is the moment yielding from the **s**eismic **c**ombination.

The coefficient α_{CD} should not be taken greater than the behavior factor, q, used to determine the seismic action; i.e. **$\alpha_{cd} \leq q$** .

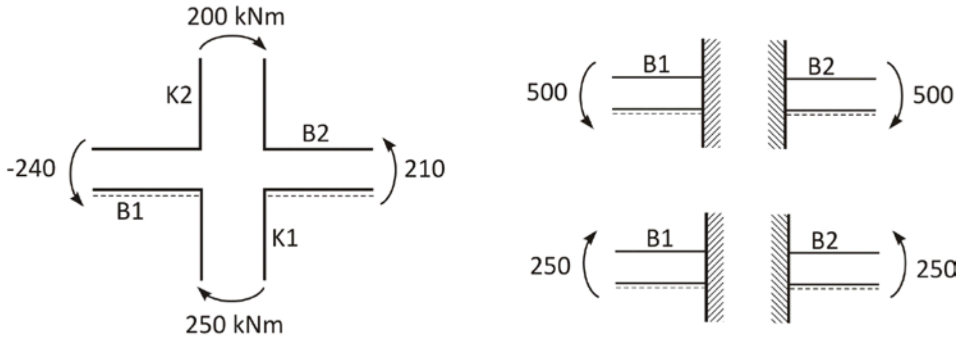
6. The flexural capacity can be avoided in the following cases:
   a) Columns of a single-storey building
   b) Columns belonging to double-storey buildings that present a normal plan
   c) Columns belonging to the upper floor of a multi-storey-building.

Example

A framed structure has been designed according to Greek seismic code EAK 2000 for a behavior factor q = 3.5. From the seismic analysis carried out for an internal joint, the derived bending moments are depicted on figure (a).

Initially the beams were dimensionalized, and, according to the reinforcement placed to them, the capacity moments, shown in figure (b), were calculated according to the seismic direction yielding from the moment action of the column.

Calculate the moments through which the columns K1 and K2 will be dimensionalized, according to the capacity design procedure.



(a) Seismic moments   **(b)** Capacity moments of beams

Data: 1) $\gamma_{Rd} = 1.40$

2) Bending moments at the beam ends from non-seismic-loads (dead and live): $M_{B1} = M_{B2} = -200$ kNm.

Solution

Since the capacity moments of beams (fig. b) are equal and symmetric, the seismic direction does not play any role. However, according to the seismic **directions** of bending moments shown in figure (a), the sum of the beams' flexural capacity, ΣM_{Rb} and the corresponding sum of the beams' seismic moments, ΣM_{Eb} , is respectively:

$$\Sigma M_{Rb} = 500 + 250 = 750 \text{ kNm}$$

$$\Sigma M_{Eb} = 240 + 210 = 450 \text{ kNm}$$

Indeed, due to the **rightwards** rotation of the joint from columns, for each one of the beams B1 and B2, **we keep**, of fig. (b), **only the capacity moments that resist the corresponding seismic moments of columns** at (a), i.e. 500 for B1 and 250 for B2.

The joint capacity magnification factor, α_{CD}, is therefore:

$$a_{CD} = \gamma_{Rd} \cdot \frac{\Sigma M_{Rb}}{|\Sigma M_{Eb}|} = 1.40 \cdot \frac{750}{450} = 2.33 < 3.50 = q$$

and consequently the bending moments through which the columns K1 and K2 will be dimensionalized are:

For column K1, presenting $M_{Ec} = 250$ kNm, it is: $\mathbf{M_{CD,c}} = 2.33 \cdot 250 =$ **583.33 kNm**

For column K2, presenting M_{Ec} = 200 kNm,   it is: $\mathbf{M_{CD,c}}$ = 2.33·200 = **466.67 kNm**

B.N. The **given static beam moments** of -200 kNm, **do not affect the column's flexural capacity**. They are taken into account only in the beams' dimensionalization.

Seismic pathology

A serious seismic event puts all the structures through a hard test. As a result all the weaknesses generated in the structure, due to either code imperfections or analysis and design errors, or even bad construction are readily apparent.

This is why strong earthquakes usually lead to improvements or even drastic changes to the design codes along with modifications on the design and execution of the construction works.

It is difficult to classify the damage caused by an earthquake. This is due to dynamic character of the seismic action and the inelastic response of the structure.

It is therefore obvious that an earthquake design must be realized by people carrying a deep knowledge of the seismic phenomenon along with its parameters that affect the response of structures.

In this section an attempt will be made to a damage classification on individual structural elements. A valuable guide to this attempt will be the lessons derived from the damages of structures after real earthquakes.

Damage to columns

There are two types of damage caused to columns by an earthquake:

1. damage due to cyclic **flexure** and <u>low shear</u> under strong axial compression,
2. damage due to cyclic **shear** and <u>low flexure</u> under strong axial compression.

1.The **first** type of damage comes out with a **flexural failure at both the top and bottom** of the column. It occurs in columns of moderate to high slenderness ratio, ie:

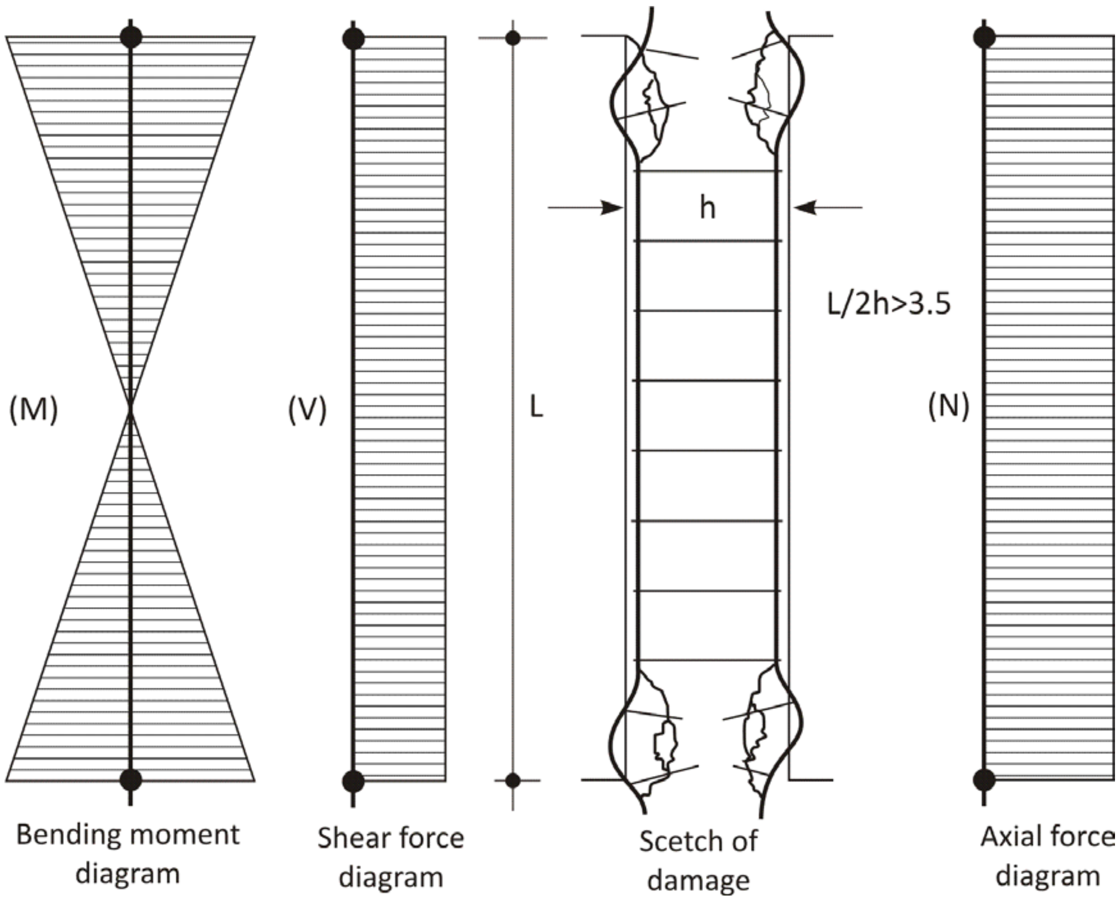
$$a = \frac{M}{Vh} = \frac{0.5VL}{Vh} = \frac{L}{2h} > 3.5$$

The combination of high bending moment with axial load at the ends of the column, leads to the crushing of the concrete's compression zone. The smaller the number of ties in these areas, the higher their vulnerability to this type of damage.

The crushing of the compression zone appears initially by spalling off the concrete cover to the reinforcement. Then the concrete core expands, causing hoop fracture and therefore buckling to the bars in compression.

The fraction of the ties and the disintegration of the concrete lead to shortening of the column under the axial load. This type of damage is very serious because the column not only loses its stiffnes; it also loses its ability to carry vertical loads. As a result there is a redistribution of stresses in the structure.

This is a very common type of damage covering on average one quarter of the totally damaged buildings.



Basic reasons for this type of damage are: low quality of concrete, rare hoops, strong girders etc.

2. The **second** type of damage is of the **shear type** and appears in the form of X–shaped cracks in the weakest zone of the column. It occurs to columns with moderate to small slenderness ratio, i.e.

$$a = \frac{M}{Vh} = \frac{0.5VL}{Vh} = \frac{L}{2h} < 3.5$$

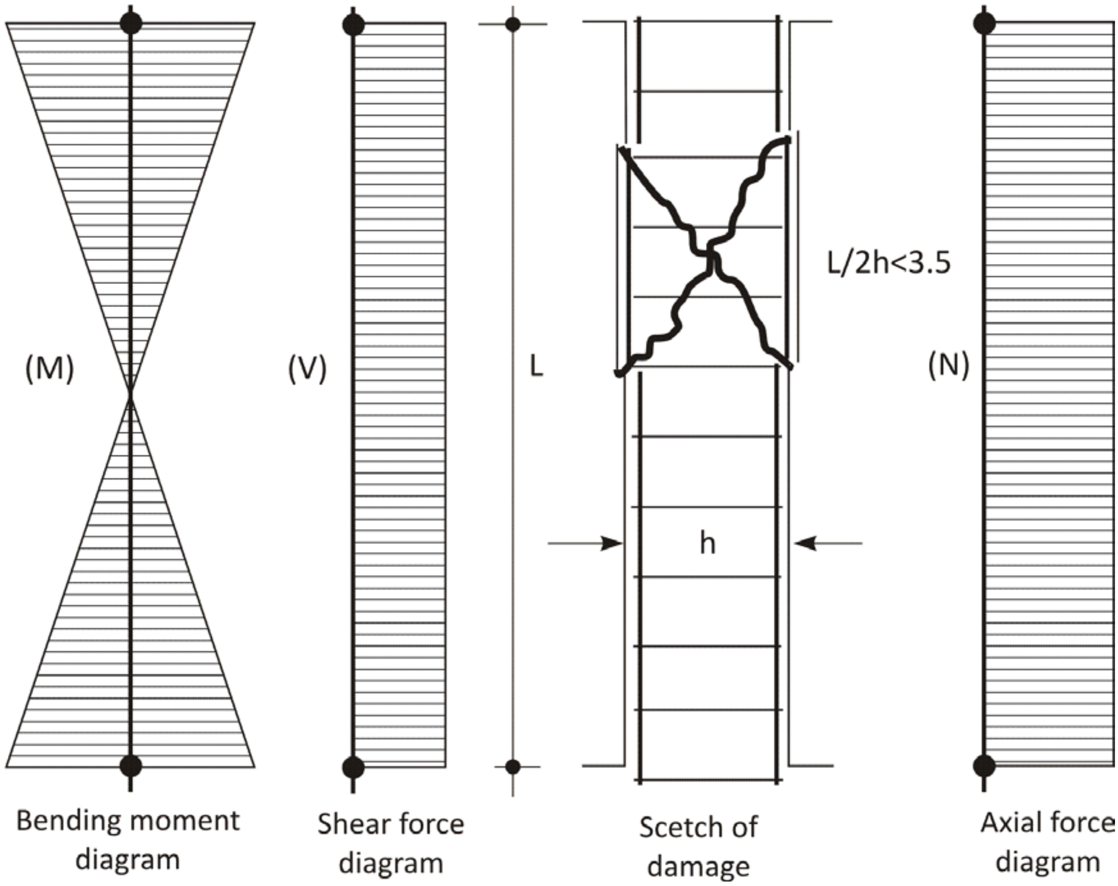
For the usual value of $L = 3$ m, it yields that $h > 0.43$ m.

The main reason for this type of damage is that the flexural capacity of the column is higher than its shear capacity and therefore shear failure prevails (see next figure).

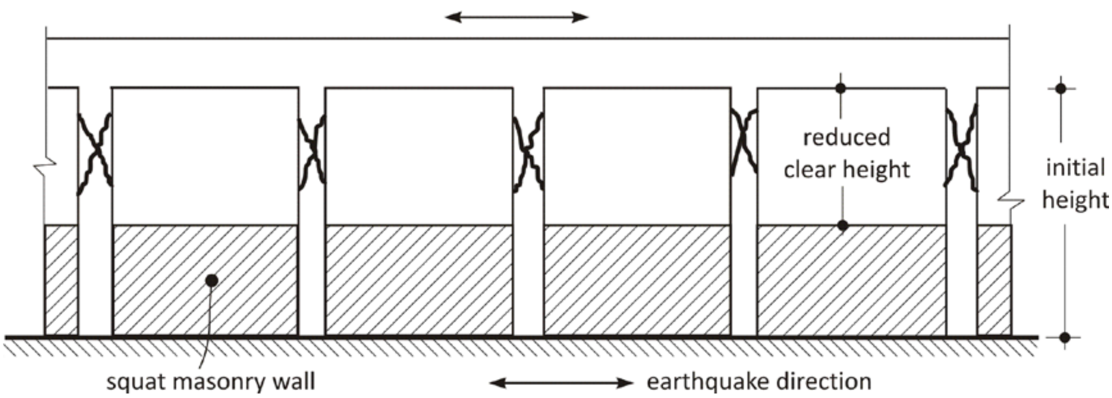
The frequency of this type of damage is lower than the failure at the top and bottom of the column.

It usually occurs at columns on the ground floor, where, due to the large cross-sectional dimensions of columns, the slenderness ratio is low.

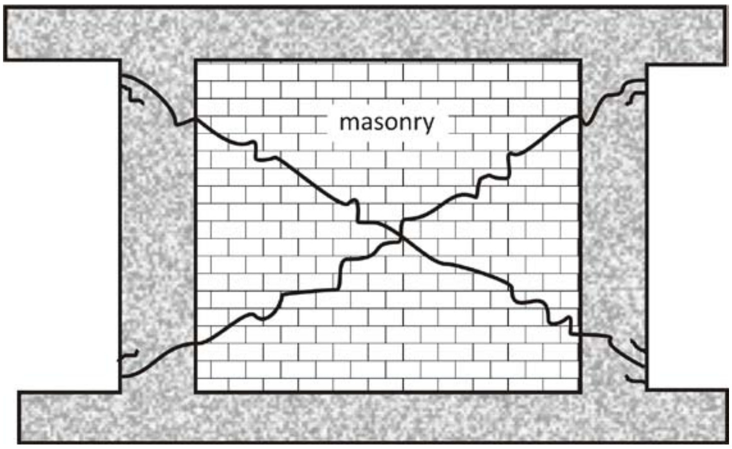
It also appears in short columns which have either been designed as short, or have been reduced to short due to adjacent masonry construction which was not accounted for in the design (see figure at the bottom of the page).



For the structure, this type of column damage is very dangerous because it alters or even destroys the vertical elements.



Sometimes, in the case of one-sided masonry-in-filled frames, masonry failure is followed by shear failure of the adjacent columns.



Damage to beams

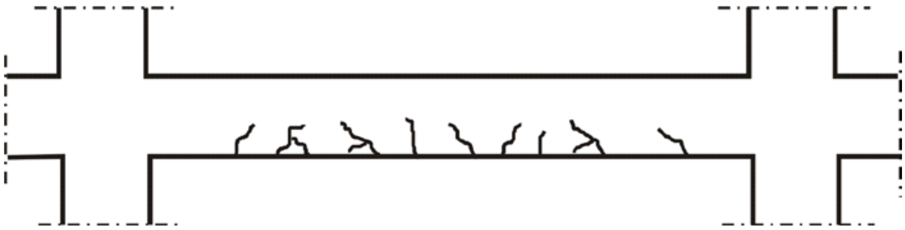
In reinforced concrete beams, this type of damage may occur in the following way:

1. cracks perpendicular to the beam axis along the tension zone of the span;
2. cracks near the supports due to shear failure;
3. flexural cracks on the upper or lower face of the beam at the supports;
4. shear or flexural cracks at the points where secondary beams are supported by the beam under consideration;

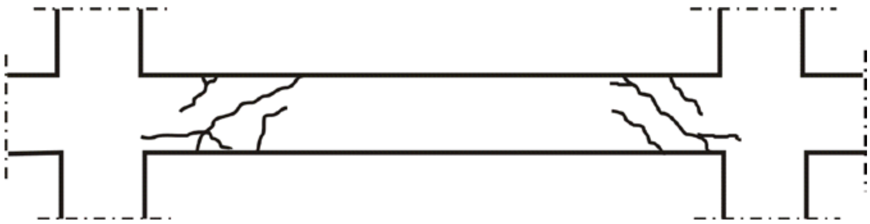
Although damage to beams, is the most common type of damage in R/C buildings – covering approximately one third of the total damages – it does not jeopardize the safety of the structure.

1. Cracks in the tension zone of the span constitute the most common damage type, covering approximately four out of five cases of the total beam-damages. Although the seismic forces do not increase the bending moment in the

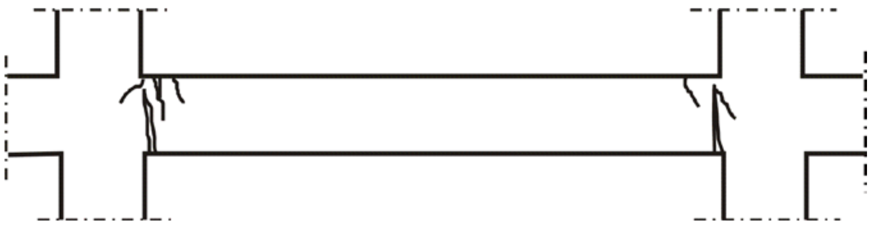
span, the vertical components simply make visible the microcracks due to bending on the tension zone, creating thus the impression of earthquake damage.



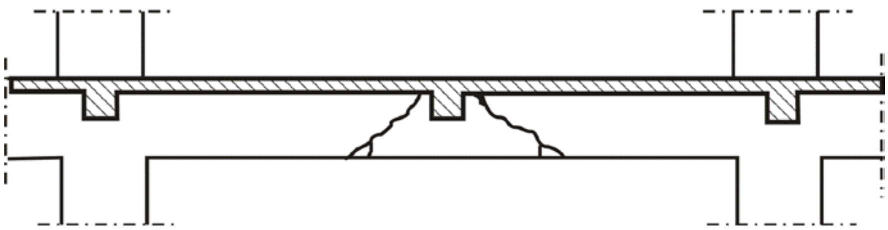
2. The bending-shear failure near supports is the second most frequent type of damage (43%) in beams. It is more serious than the previous one. However, only in very few cases, does it jeopardize the overall stability of structures.



3. The flexural cracks on the upper and lower face of the beam at the supports can be readily explained if we statically consider the horizontal forces. This type is rarer than the shear one (28%). In most cases, wide cracking of the lower face is due to bad anchorage of the bottom reinforcement into the supports.



4. The shear or flexural failure at points of secondary beams occurs frequently due to the vertical component of the earthquake, which, amplifies the concentrated load.

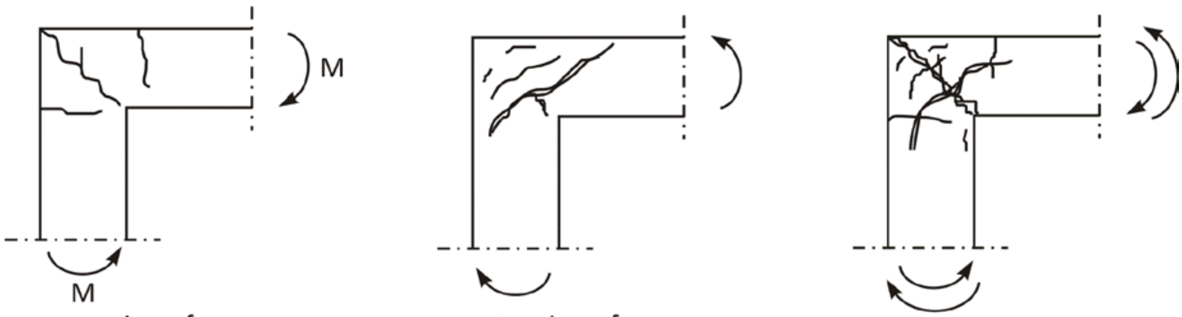


Damage to beam-column joints

This type of damage, is extremely dangerous for the structure, even at the early stages of cracking, and has to be carefully treated.

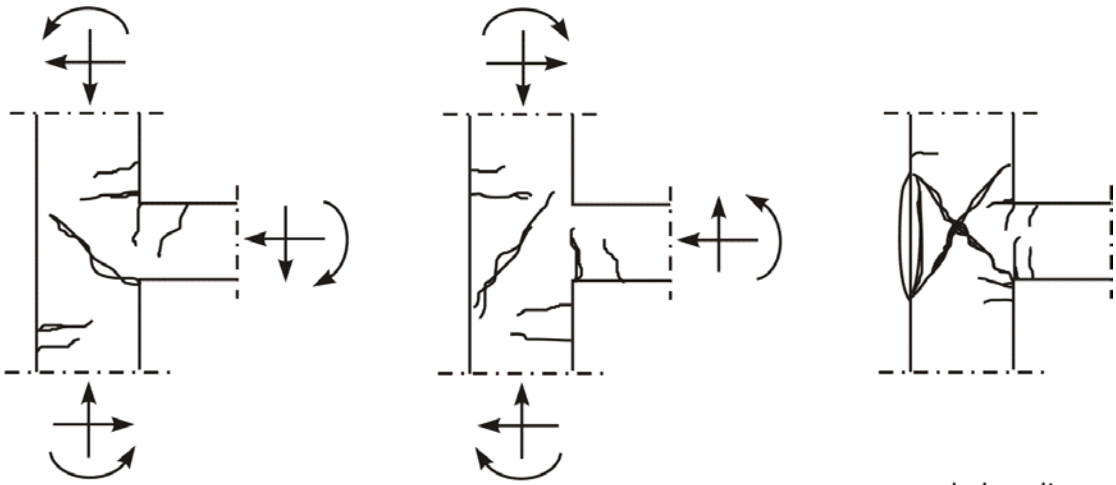
The reason is that it reduces the stiffness of the structural element, thus leading to uncontrollable redistribution of internal forces and stresses. Common failures of this type are:

1. Failure of a corner joint



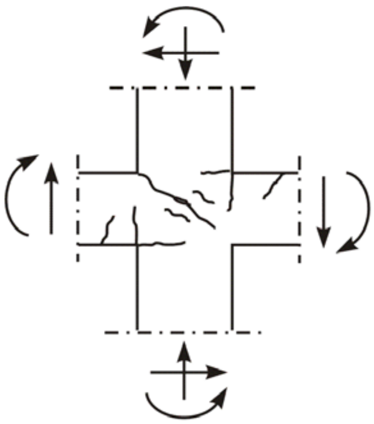
compression of inner fibers | tension of inner fibers | cycle bending moment loading

2. Failure of exterior joint in a multi-storey building

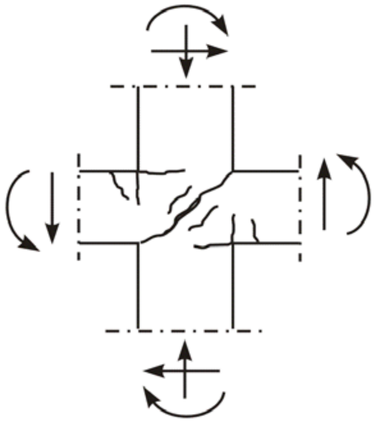


compression of lower fibers | compression of upper fibers | cycle bending moment loading

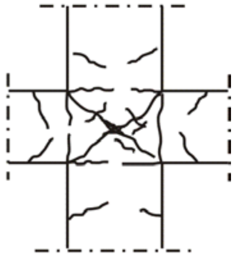
3. Failure of a cross-shaped interior joint



seismic action
from right to left



seismic action
from left to right



cyclic
seismic action

Damage to slabs

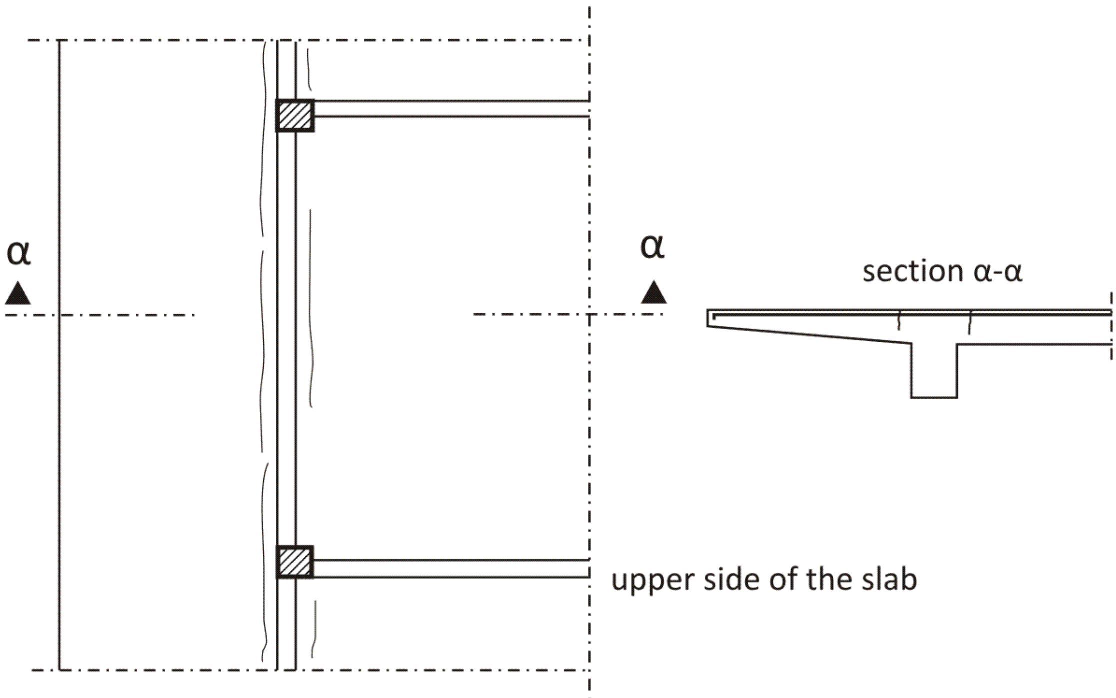
Common types of damage occurring in slabs are:

1. Cracks parallel or transverse to the reinforcement at random locations. These cracks are the most frequent type of damage.

They are due to the already existing microcracks – formed usually from temperature changes or shrinkage – becoming visible after the seismic excitation. Rarely they appear after a differential settlement of columns.

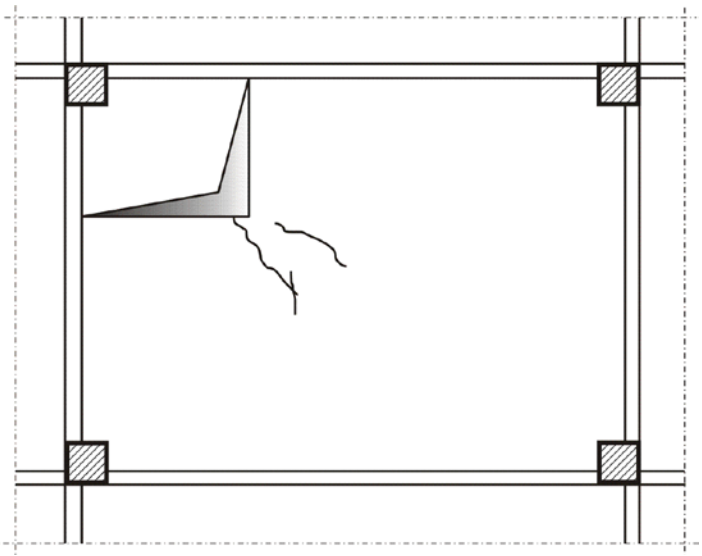
2. Cracks at critical sections of large spans or cantilevers, transverse to the main reinforcement.

They are due to the vertical component of the earthquake action.



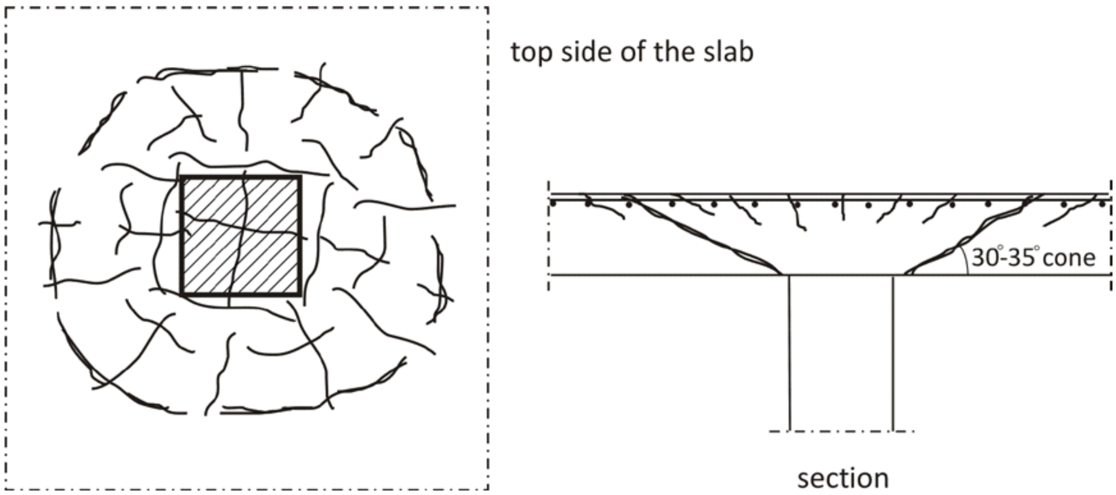
3. Cracks forming at floor discontinuities, like corners of large openings which accommodate internal stairways, light shafts etc.

They are also due to the vertical component of the earthquake action.



4. Cracks in areas where large seismic loads are concentrated, especially in a flat plate system, where a column is connected to the center of flat.

This type of damage is related to punching shear failure. From the safety point of view this sort of construction is vulnerable to a seismic action and, once it is not covered by the codes, it must be avoided.



Damage at a slab to column connection

Appendix

A. What should I do before, during, and after an earthquake

What to do before an erthquake

Make sure you have a fire extinguisher, first aid kit, a battery-powered radio, a flashlight, and extra batteries at home.

1. Learn first aid.
2. Learn how to turn off the gas, water, and electricity.
3. Make up a plan of where to meet your family after an earthquake.
4. Don't leave heavy objects on shelves (they'll fall during a quake).
5. Anchor heavy furniture, cupboards, and appliances to the walls or floor.
6. Learn the earthquake plan at your school or workplace.

What to do during an Earthquake

1. **Stay calm!** If you're indoors, stay inside. If you're outside, stay outside.
2. If you're indoors, stand against a wall near the center of the building, stand in a doorway, or crawl under heavy furniture (a desk or table). Stay away from windows and outside doors.
3. If you're outdoors, stay in the open away from power lines or anything that might fall. Stay away from buildings (stuff might fall off the building or the building could fall on you).
4. Don't use matches, candles, or any flame. Broken gas lines and fire don't mix.
5. If you're in a car, stop the car and stay inside the car until the earthquake stops.
6. Don't use elevators (they'll get stuck anyway).

What to do after an earthquake

1. Check yourself and others for injuries. Provide first aid for anyone who needs it.
2. Check water, gas, and electric lines for damage. If any are damaged, shut off the valves. Check for the smell of gas. If you smell it, open all the windows and doors, leave immediately, and report it to the authorities (use someone else's phone).
3. Turn on the radio. Don't use the phone unless it's an emergency.
4. Stay out of damaged buildings.
5. Be careful around broken glass and debris. Wear boots or sturdy shoes to keep from cutting your feet.
6. Be careful of chimneys (they may fall on you).
7. Stay away from beaches. Tsunamis and seiches sometimes hit after the ground has stopped shaking.
8. Stay away from damaged areas.
9. If you're at school or work, follow the emergency plan or the instructions of the person in charge.
10. Expect aftershocks.

B. Alphabetical Earthquake Terminology

Following are basic terms used in seismology.

Aftershock:

An earthquake that follows a larger earthquake or main shock and originates at or near the focus of the larger earthquake. Generally, major earthquakes are followed by a larger number of aftershocks, decreasing in frequency with time.

Amplitude:

The maximum height of a wave crest or depth of a trough.

Array:

An ordered arrangement of seismometers or geophones, the data from which feeds into a central receiver.

Arrival:

The appearance of seismic energy on a seismic record.

Arrival time:

The time at which a particular wave-phase arrives at a detector.

Aseismic:

Unassociated with an earthquake.

Asthenosphere:

The layer of mantle underlying the lithosphere which is close to its melting point and therefore much less rigid than the lithosphere.

Body wave:

A seismic wave that travels through the interior of the earth and is not related to a boundary surface.

Continental Crust:

Outermost solid layer of the earth that forms the continents and is composed of igneous, metamorphic, and sedimentary rocks. Overall, the continental crust is broadly granitic in composition. Contrast with oceanic crust.

Continental Drift:

The theory, first advanced by Alfred Wegener, that the earth's continents were originally one land mass called Pangaea. About 200 million years ago Pangaea split off and the pieces migrated (drifted) to form the present-day continents. The predecessor of plate tectonics.

Convergent Plate Boundary:

See subduction, and subduction zone.

Crust:

The outer layer of the earth's surface.

Dilatancy:

An increase in the bulk volume of rock during deformation. Possibly related to the migration of water into microfractures or pores.

Divergent Plate Boundary:

The boundary between two crustal plates that are pulling apart (e.g. sea floor spreading).

Earthquake:

Shaking of the earth caused by a sudden movement of rock beneath its surface.

Earthquake swarm:

A series of minor earthquakes, none of which may be identified as the main shock, occurring within a limited area and time.

Elastic wave:

A wave that is propagated by some kind of elastic deformation, that is, a deformation that disappears when the forces are removed. A seismic wave is a type of elastic wave.

Epicenter:

That point on the earth's surface directly above the hypocenter of an earthquake.

Fault:

A weak region in the earth's crust where the rock layers have ruptured and slipped.

First arrival:

The first recorded signal attributed to seismic wave travel from a known source.

Focal zone:

The rupture zone of an earthquake. In the case of a great earthquake, the focal zone may extend several hundred kilometers in length.

Focus:

That region, considered as a point within the earth, from which originates the first motion of an earthquake and its elastic waves.

Foreshock:

A small tremor that commonly precedes a larger earthquake or main shock by seconds to weeks and that originates at or near the focus of the larger earthquake.

Harmonic Tremor:

A continuous release of seismic energy typically associated with the underground movement of magma, often preceding volcanic eruptions. It contrasts distinctly with the sudden release and rapid decrease of seismic energy associated with the more common type of earthquake caused by slippage along a fault.

Hypocenter:

The calculated location of the focus of an earthquake.

Igneous:

As in igneous rock. A rock formed when magma, or molten rock, cools and solidifies.

If it cools slowly, the rock will have a coarse crystalline texture.

If it cools quickly, it will have a fine crystalline texture.

If it cools very quickly ("quenched"), it forms a glass, which has no crystalline structure. The three main types of rocks are sedimentary, igneous and metamorphic.

Intensity:

A measure of the effects of an earthquake at a particular place on humans and/or structures. The intensity at a point depends not only upon the strength of the earthquake (magnitude) but also upon the distance from the earthquake to the epicenter and the local geology at that point.

Isoseismal line:

A line connecting points on the earth's surface at which earthquake intensity is the same. It is usually a closed curve around the epicenter.

Leaking mode:

A surface seismic wave which is imperfectly trapped so that its energy leaks or escapes across a layer boundary causing some attenuation.

Lg Wave:

A surface wave that travels through the continental crust.

Liquefaction:

The process in which a solid (such as soil) takes on the characteristics of a liquid as a result of an increase in pore pressure and a reduction in stress. In other words, solid ground turns to jelly.

Lithosphere:

The rigid crust and uppermost mantle of the earth. Thickness is on the order of 62 miles (100 kilometers). Stronger than the underlying asthenosphere.

Love wave:

A major type of surface wave having a horizontal motion that is shear or transverse to the direction of propagation. It is named after A.E.H. Love, the English mathematician who discovered it.

Low-velocity zone:

Any layer in the earth in which seismic wave velocities are lower than in the layers above and below. More commonly the "slow" layer just beneath the lithosphere.

Magma:

Molten rock beneath the surface of the earth. Molten rock erupted at the surface is called "lava."

Magnitude:

A quantitative measure of the strength of an earthquake.

Magnitude is calculated from ground motion as measured by seismograph and incorporates the distance of the seismograph from the earthquake epicenter so that, theoretically, the magnitude calculated for an earthquake would be the same from any seismograph station recording that earthquake.

This is a logarithmic value originally defined by Wadati (1931) and Richter (1935).

An increase of one unit of magnitude (for example, from 4.6 to 5.6) represents a 10-fold increase in wave amplitude on a seismogram or approximately a 30-fold increase in the energy released. In other words, a magnitude 6.7 earthquake releases over 900 times (30 times 30) the energy of a 4.7 earthquake - or it takes about 900 magnitude 4.7 earthquakes to equal the energy released in a single 6.7 earthquake!

There is no beginning nor end to this scale. However, rock mechanics seem to preclude earthquakes smaller than about -1 or larger than about 9.5. A magnitude -1.0 event releases about 900 times less energy than a magnitude 1.0 quake.

Except in special circumstances, earthquakes below magnitude 2.5 are not generally felt by humans. See also Richter scale.

Major earthquake:

An earthquake having a magnitude of 7 or greater on the Richter scale.

Mantle:

The layer of rock that lies between the outer crust and the core of the earth. It is approximately 1,802 miles (2,900 kilometers) thick and is the largest of the earth's major layers.

Metamorphic:

As in metamorphic rock. A rock formed from any other type of rock by elevated temperatures and pressures, but which has not undergone complete melting. Two common examples of metamorphic rocks are slate (usually formed from shale), and

marble (formed from limestone). The three main types of rocks are sedimentary, igneous and metamorphic.

Micro earthquake:

An earthquake having a magnitude of 2 or less on the Richter scale.

Microseism:

A more or less continuous motion in the earth that is unrelated to an earthquake and that has a period of 1.0 to 9.0 seconds. It is caused by a variety of natural and artificial agents.

Modified Mercalli Scale:

Mercalli intensity scale modified for North American conditions. A scale, composed of 12 increasing levels of intensity that range from imperceptible shaking to catastrophic destruction, designated by Roman numerals. It does not have a mathematical basis; instead it is an arbitrary ranking based on observed effects. Contrast with Richter scale, a type of magnitude scale.

Mohorovicic discontinuity:

The boundary surface or sharp seismic-velocity discontinuity that separates the earth's crust from the underlying mantle.

Oceanic crust:

The outermost solid layer of Earth that underlies the oceans. Composed of the igneous rocks basalt and gabbro, and therefore basaltic in composition. Contrast with continental crust.

P (Primary) wave:

Also called compressional or longitudinal waves, P waves are the fastest seismic waves produced by an earthquake. They oscillate the ground back and forth along the direction of wave travel, in much the same way as sound waves, which,(also compressional), move the air back and forth as the waves travel from the sound source to a sound receiver.

Pangaea:

The supercontinent composed of all the present-day continents, which existed about 200 million years ago. Continental drift refers to the breakup of Pangaea into the present configuration of continents.

Phase:

The onset of a displacement or oscillation on a seismogram indicating the arrival of a different type of seismic wave.

Plate:

Pieces of crust and brittle uppermost mantle, perhaps 100 kilometers thick and hundreds or thousands of kilometers wide, that cover the earth's surface. The plates move very slowly over, or possibly with, a viscous layer in the mantle at rates of a few centimeters per year.

Plate boundary:

The place where two or more plates in the earth's crust meet.

Plate tectonics:

A widely accepted theory that relates most of the geologic features near the earth's surface to the movement and interaction of relatively thin rock plates. The theory predicts that most earthquakes occur when plates move past each other.

Rayleigh wave:

A type of surface wave having a retrograde, elliptical motion at the earth's surface, similar to the waves caused when a stone is dropped into a pond.

These are the slowest, but often the largest and most destructive, of the wave types caused by an earthquake. They are usually felt as a rolling or rocking motion and in the case of major earthquakes, can be seen as they approach.

Named after Lord Rayleigh, the English physicist who predicted its existence.

Recurrence interval:

The approximate average length of time between earthquakes in a specific seismically active area.

Richter magnitude scale:

The system used to measure the strength or magnitude of an earthquake.

The Richter magnitude scale was developed in 1935 by Charles F. Richter of the California Institute of Technology as a collection of mathematical formulas to compare the size of earthquakes.

A similar scale was developed in 1931 by Wadati, so it is more appropriate to call such scales "Wadati-Richter" scales. The magnitude of an earthquake is determined from the logarithm of the amplitude of waves recorded by seismographs. Adjustments are included for the variation in the distance between the various seismographs and the epicenters of the earthquakes.

On the Richter scale, magnitude is expressed in whole numbers and decimal fractions. For example, a magnitude 5.3 might be computed for a moderate earthquake, and a strong earthquake might be rated as magnitude 6.3. Because of the logarithmic basis of the scale, each whole number increase in magnitude represents a tenfold increase in measured amplitude; as an estimate of energy, each whole number step in the magnitude scale corresponds to the release of about 30 times more energy than the amount associated with the preceding whole number value.

Rift system:

The oceanic ridges formed where tectonic plates are separating and new crust is being created; also refers to the on-land counterparts such as the East African Rift.

Ring of Fire:

A 40,000 kilometer (24,855 mile) band of seismicity including mountain-building, earthquakes, and volcanoes, stretching up the west coasts of South and Central America and from the North American continent to the Aleutians, Japan, China, the Philippines, Indonesia, and Australasia.

Rupture zone:

The area of the earth through which faulting occurred during an earthquake. For very small earthquakes, this zone could be the size of a pinhead, but in the case of a great earthquake, the rupture zone may extend several hundred kilometers in length and tens of kilometers in width.

S (secondary or shear) wave:

A seismic body wave that involves particle motion from side to side, perpendicular to the direction of wave propagation. S-waves are slower than P-waves and cannot travel through a liquid such as water or molten rock.

Seafloor Spreading:

The mechanism by which new oceanic crust is created at oceanic ridges and slowly spreads away as the plates separate.

Sedimentary:

As in sedimentary rock. A rock made up of sediments, or rock fragments, laid down in water or deposited by wind or ice. The fragments can be microscopic, like the clays in a shale, or large, like the boulders in a coarse conglomerate. Sandstone, shale, and limestone are common sedimentary rocks. About 70% of the earth's crust is covered with sedimentary rocks (covering igneous or metamorphic rocks).

The three main types of rocks are sedimentary, igneous and metamorphic.

Seiche:

A free or standing wave oscillation of the surface of water in an enclosed basin that is initiated by local atmospheric changes, tidal currents, or earthquakes. Similar to water sloshing in a bathtub.

Seismic:

Of or having to do with earthquakes.

Seismic belt:

An elongated earthquake zone, for example, circum-Pacific, Mediterranean, RockyMountain. About 75% of the world's earthquakes occur in the circum-Pacific seismic belt.

Seismic constant:

In building codes dealing with earthquake hazards, an arbitrarily-set acceleration value (in units of gravity) that a building must withstand.

Seismicity:

Earthquake activity.

Seismic sea wave:

A tsunami generated by an undersea earthquake.

Seismic zone:

A region in which earthquakes are known to occur.

Seismogram:

A written record of an earthquake, recorded by a seismograph.

Seismograph:

An instrument that records the motions of the earth, especially earthquakes.

Seismograph station:

A site at which one or more seismographs are set up and routinely monitored.

Seismologist:

A scientist who studies earthquakes.

Seismology:

The study of earthquakes and earthquake waves.

Seismometer:

The part of a seismograph which actually senses ground motion, ground velocity or ground acceleration.

Strike-slip fault:

A nearly vertical fault with side-slipping displacement.

Subduction:

The process in which one lithospheric plate collides with and is forced down under another plate and drawn back into the earth's mantle.

Subduction zone:

The zone of convergence of two tectonic plates, one of which is subducted beneath the other. An elongated region along which a plate descends relative to another plate, for example, the descent of the Nazca plate beneath the South American plate along the Peru-Chile Trench.

Surface waves:

Waves that move over the surface of the earth.

Rayleigh and Love waves are surface waves.

Tectonic:

Pertaining to the forces involved in the deformation of the earth's crust, or the structures or features produced by such deformation.

Transform Fault:

A plate boundary where one plate slides past another; essentially a large strike-slip fault.

Tremor:

Low amplitude, continuous earthquake activity commonly associated with magma movement.

Tsunami:

One or a series of great sea waves produced by a submarine earthquake, volcanic eruption, or large landslide. (Referred to incorrectly by many as a tidal wave, but these waves have nothing to do with tides).

The word tsunami is Japanese for "**harbor wave**."

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