HOW BUILDING RESIST EARTHQUAKES

- Factors such as the dynamic characteristics of earthquakes, their duration and the effects of site conditions are all external to a building.
- No matter how well or poorly designed, a building has no control over those effects.
- But as we shall see, a combination of factors such as the form of a building, its materials of construction and dynamic characteristics, as well as the quality of its structural design and construction, greatly influence how a building responds to any shaking it experiences.
- The following sections then explore the key physical properties that affect the severity of seismic forces.
- After appreciating these factors that influence levels of seismic force, the basic requirements for seismic resistance are considered.

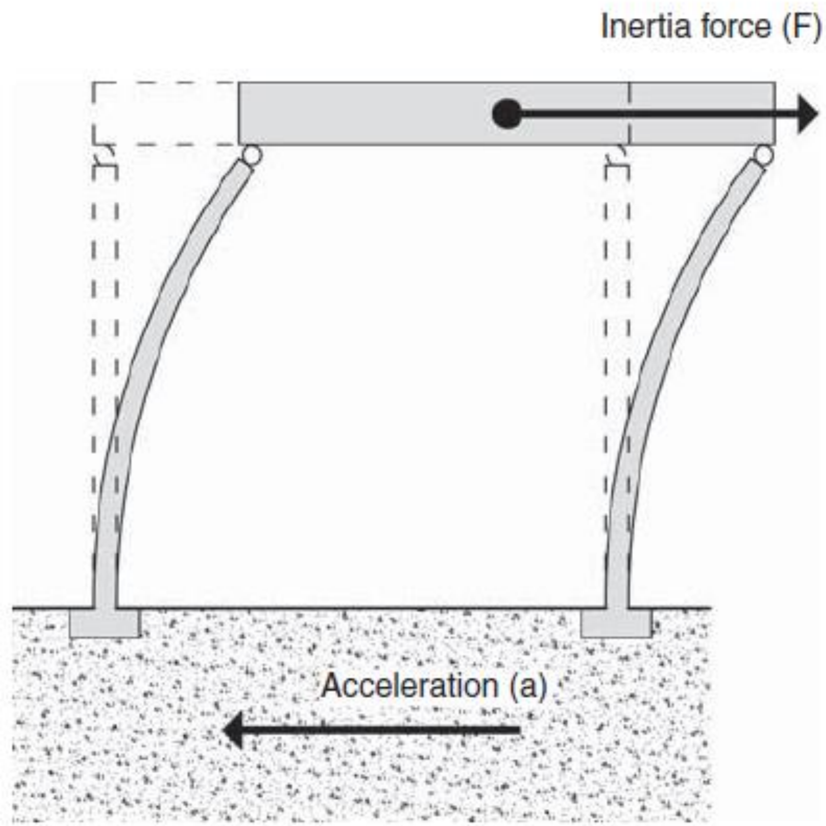
HOW BUILDING RESIST EARTHQUAKES

NATURE OF SEISMIC FORCES

- Seismic forces are inertia forces. When any object, such as a building, experiences acceleration, inertia force is generated when its mass resists the acceleration.
- We experience inertia forces while travelling. Especially when standing in a bus or train, any changes in speed (accelerations) cause us to lose our balance and either force us to change our stance or to hold on more firmly.

HOW BUILDING RESIST EARTHQUAKES

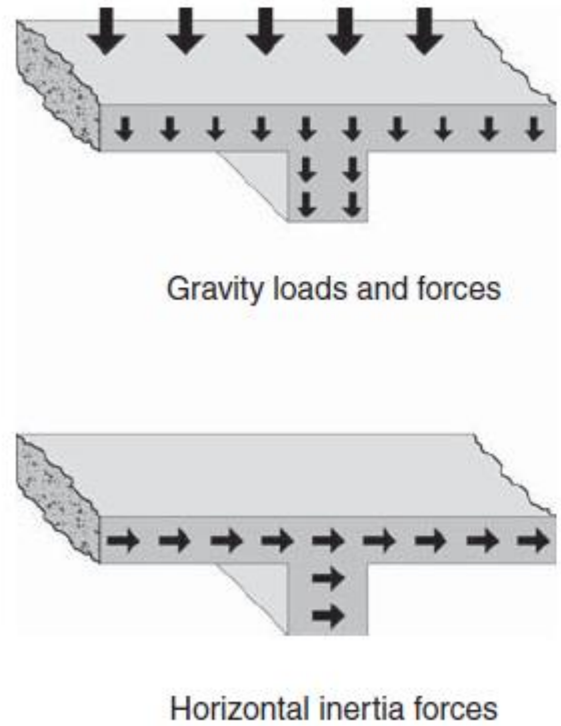
- Newton's Second Law of Motion, **F = Ma** enables the inertia force F to be quantified. M, the mass of an object, is determined by dividing its weight by the acceleration due to gravity, while a is the acceleration it is subject to (Fig. 2.1).
- This is the primary equation for seismic resistant design.
- Inertia forces act within a building. They are internal forces.



▲ 2.1 An inertia force is induced when a building (with cantilever columns) experiences acceleration at its base.

HOW BUILDING RESIST EARTHQUAKES

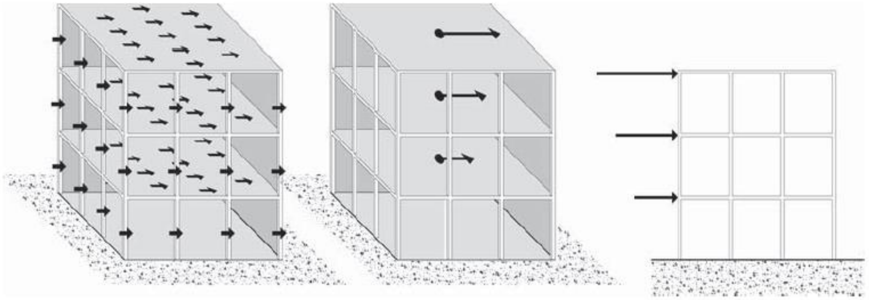
- As the ground under a building shakes sideways, horizontal accelerations transfer up through the superstructure of the building and generate inertia forces throughout it.
- Inertia forces act on every item and every component.
- Every square metre of construction, like a floor slab or wall, possesses weight and therefore mass.
- Just as gravity force that acts vertically is distributed over elements like floor slabs, so is seismic inertia force, except that it acts horizontally (Fig. 2.2).



▲ **2.2** An area of concrete floor showing the difference between gravity forces and horizontal inertia forces.

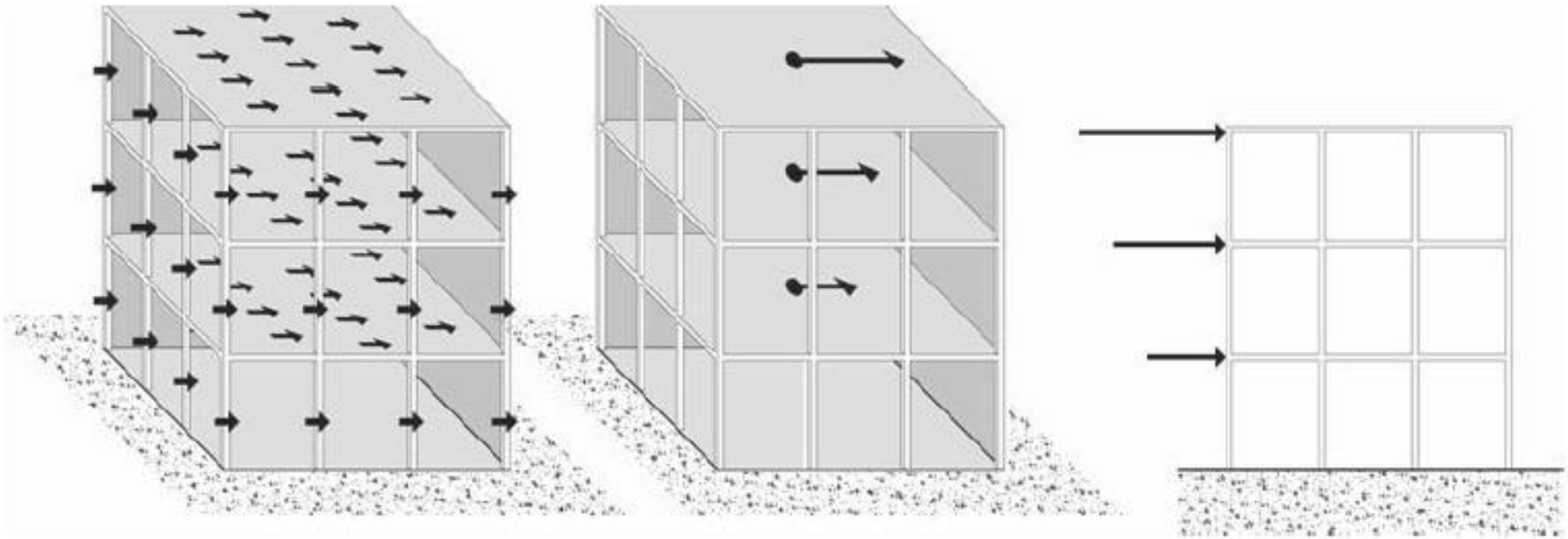
HOW BUILDING RESIST EARTHQUAKES

- The analogy between gravity and inertia forces can be taken further.
- The sum of gravity forces acting on an element can be assumed to act at its centre of mass (CoM), so can the inertia force on any item be considered to act at the same point.
- Since most of the weight in buildings is concentrated in their roofs and floors, for the sake of simplicity designers assume inertia forces act at the CoM of the roof and each floor level (Fig. 2.3). For most buildings the CoM corresponds to the centre of plan.



▲ 2.3 Increasing simplification of how inertia forces on a building are expressed graphically.

HOW BUILDING RESIST EARTHQUAKES



Distributed inertia forces in floors, columns and walls

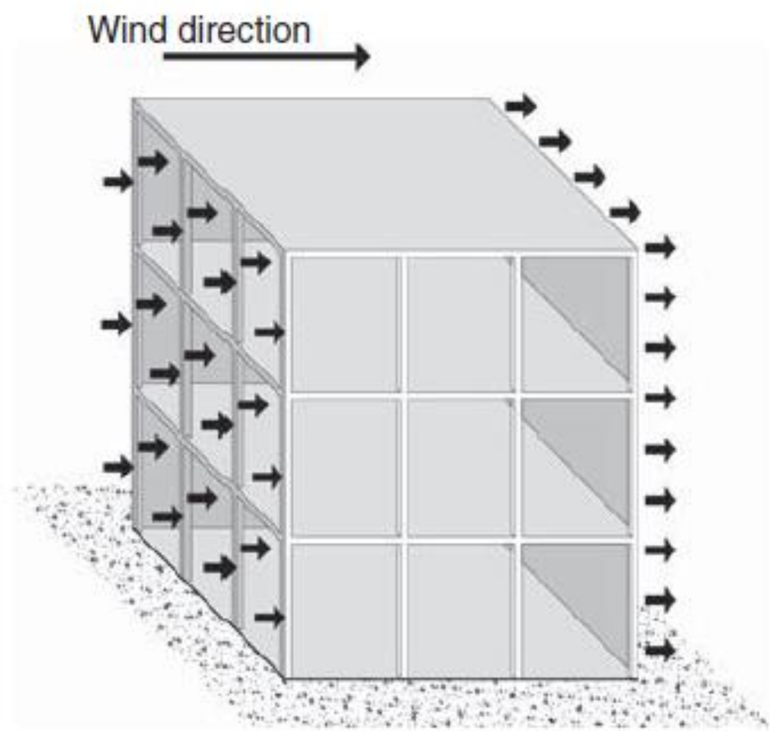
Simplification: inertia forces act at the COM at each level

Further simplification: inertia forces shown acting externally

▲ **2.3** Increasing simplification of how inertia forces on a building are expressed graphically.

HOW BUILDING RESIST EARTHQUAKES

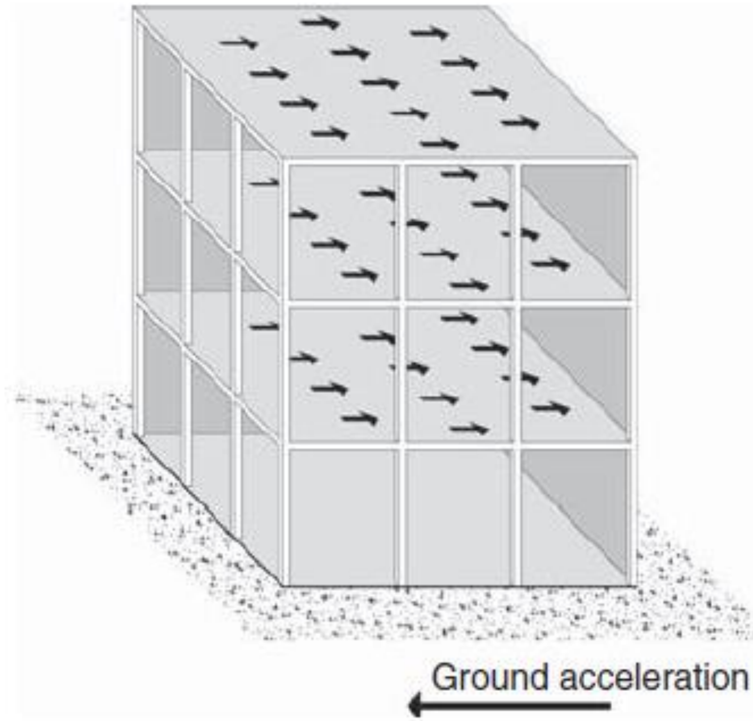
- Wind and inertia forces are different.
- Wind force is external to a building.
- Wind pressure that pushes against a building acts upon external surfaces.
- Its magnitude and centre of loading is determined by the surface area upon which it acts (Fig. 2.4).
- Like inertia forces, wind loading is dynamic, but whereas peak earthquake forces act for just fractions of a second, the duration of a strong wind gust lasts in the order of several seconds.



(a) Wind forces on external surfaces
(Forces acting normal to the wind direction are not shown)

HOW BUILDING RESIST EARTHQUAKES

- Another difference between the two load conditions is that inertia forces are cyclic – they act to-and-fro.
- In spite of these significant differences the feature common to both forces is that they act horizontally.



(b) Inertia forces act within volumes with mass

HOW BUILDING RESIST EARTHQUAKES

- Although near-vertical wind suction forces act on roofs during a wind storm and vertical ground accelerations also occur during an earthquake, these vertical forces usually have little impact on the overall behaviour of buildings.

- The only time a building might need to be explicitly designed for vertical accelerations is where it incorporates some long-spanning floor or roof structures, say in excess of 20 m length, or significant horizontal cantilevers.

HOW BUILDING RESIST EARTHQUAKES

FACTORS AFFECTING THE SEVERITY OF SEISMIC FORCES

1) **Building weight**

- The single most important factor determining the inertia force in a building is its weight.
- Newton's Law states that inertia force is proportional to mass or weight.
- The heavier an object the greater the inertia force for a certain level of acceleration.
- In earthquake prone regions, we should therefore build as light-weight as practicable to reduce seismic vulnerability.
- Wherever possible, lighter elements of construction should be substituted for and replace those that are heavier.

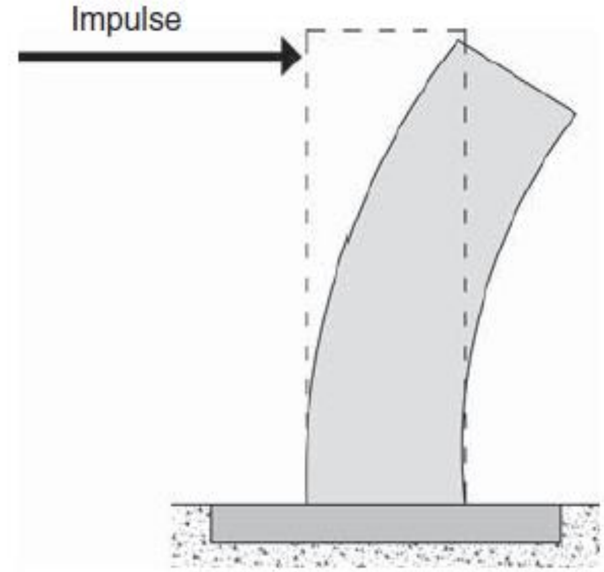
HOW BUILDING RESIST EARTHQUAKES

- Brick or stone masonry, adobe and reinforced concrete are the most widely used materials but heavy in nature.
- Light-weight wood framed construction is an option, but the reality for most people is to inhabit heavy buildings.
- Architects and structural engineers should attempt to build more lightly, bearing in mind economy and other factors like sustainability.
- This intent is applicable for both new buildings and those being renovated or retrofitted.
- There are often opportunities to reduce building weight by, for example, demolishing heavy interior masonry walls and replacing them with light timber or steel framed construction.

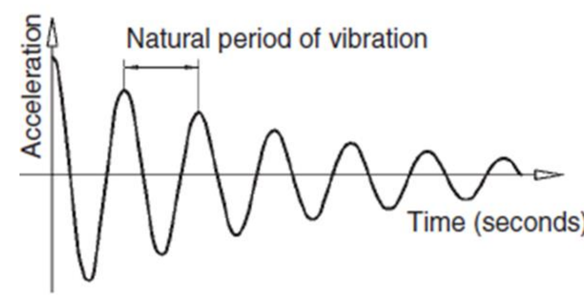
HOW BUILDING RESIST EARTHQUAKES

2) Natural period of vibration

- Hold a reasonably flexible architectural model of a building and give it a sharp horizontal push at roof level.
- The building will vibrate back and forth with a constant period of vibration. As illustrated in Fig. 2.5 , the time taken for one full cycle is called the natural period of vibration, measured in seconds.
- Every model and full-scale building has a natural period of vibration corresponding to what is termed the first mode of vibration.



(a) First mode of vibration

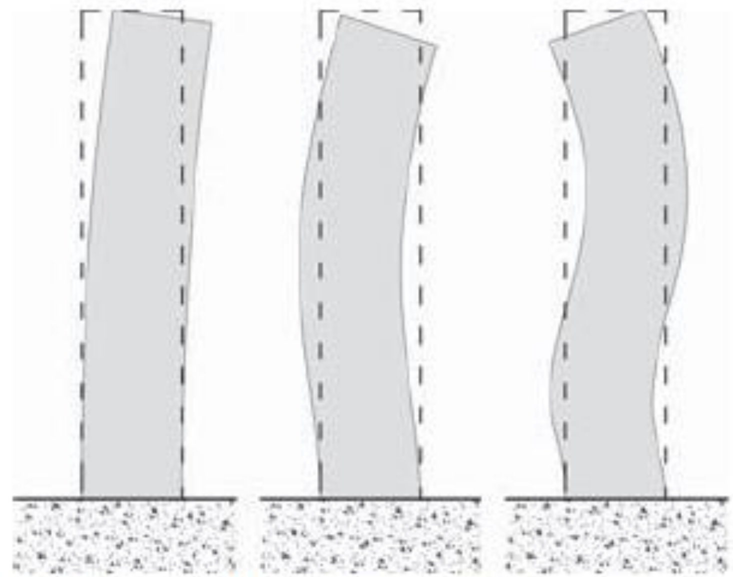


(b) A record of the building acceleration after the impulse

HOW BUILDING RESIST EARTHQUAKES

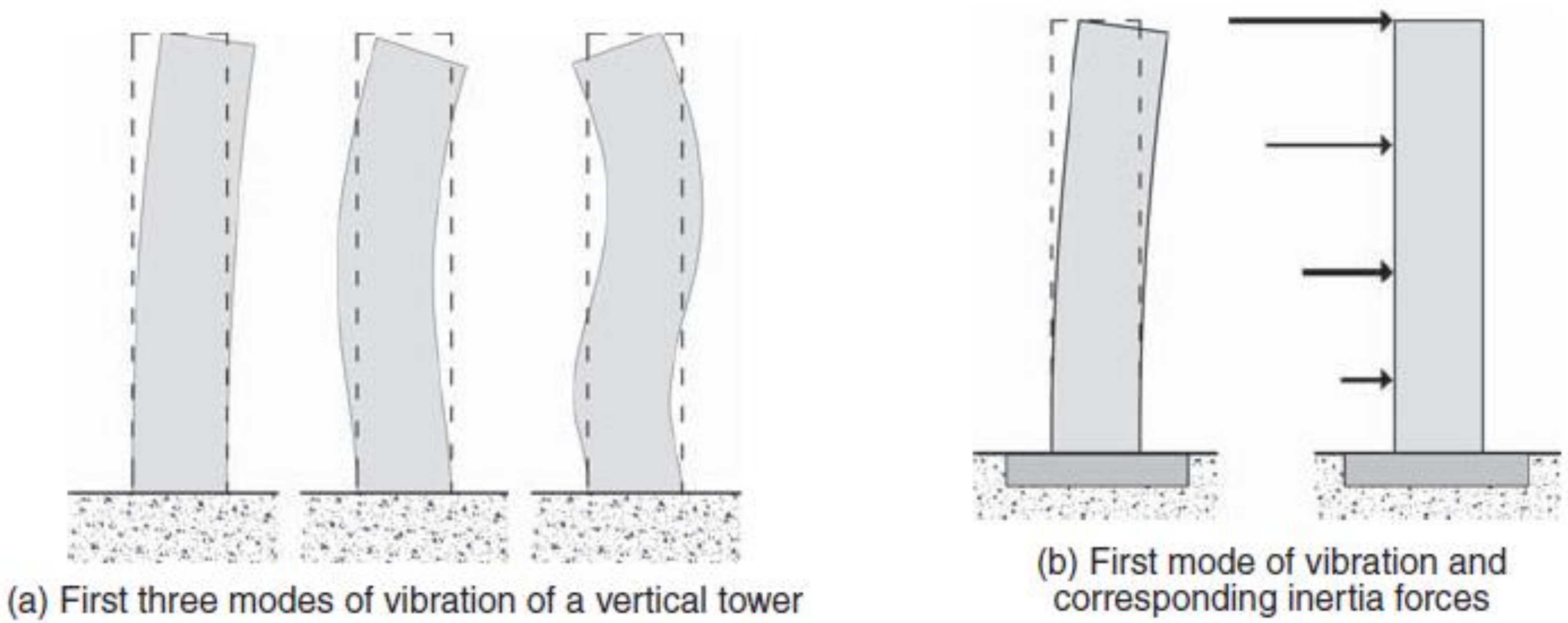
2)**Natural period of vibration**

- Depending on the height of a building there may be periods of vibration as well. They correspond to the second, third and higher modes of vibration (Fig. 2.6(a)).
- There are as many modes of vibration as there are storeys in a building. But usually the effects of the first few modes of vibration only need to be considered by a structural engineer.



(a) First three modes of vibration of a vertical tower

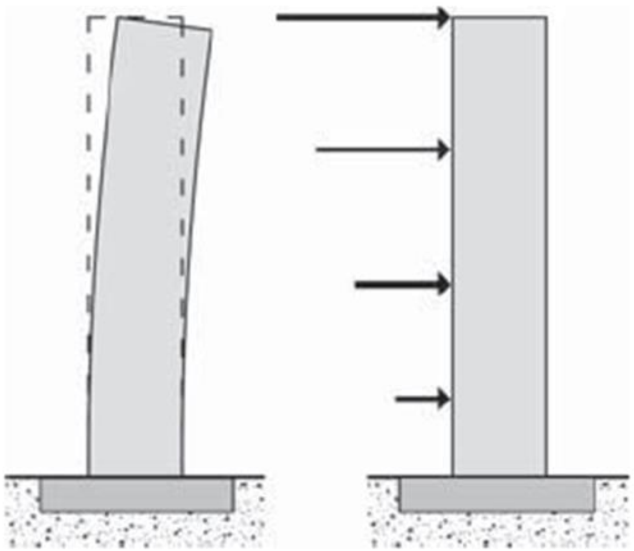
HOW BUILDING RESIST EARTHQUAKES



▲ **2.6** The deflected shapes of the first three modes of vibration (a) and the first mode of vibration as the source of most inertia force (b).

HOW BUILDING RESIST EARTHQUAKES

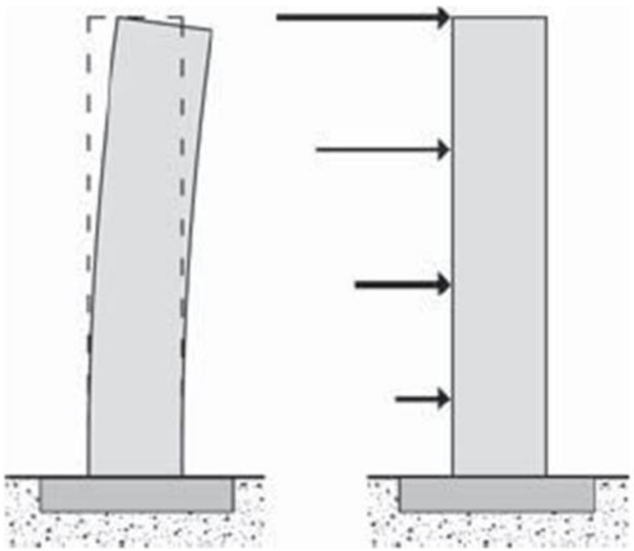
- Higher modes that resonate less strongly with earthquake shaking contain less dynamic energy.
- When earthquake waves with their chaotic period content strike the foundations of a building, its superstructure responds to the various periods of vibration that are all mixed-up together to comprise the shaking.
- Particularly in low- to medium-rise buildings, most of the dynamic energy transmitted into them resonates the first mode and its natural period of vibration; and to a far lesser extent the second and higher modes.



(b) First mode of vibration and corresponding inertia forces

HOW BUILDING RESIST EARTHQUAKES

- Because in the first mode every part of a building moves in the same direction simultaneously resulting in the greatest overall inertia force, it is the most important.
- Its mode shape, rather like an inverted triangle, explains why inertia forces acting at each floor level increase with height (Fig. 2.6(b)).



(b) First mode of vibration and corresponding inertia forces

HOW BUILDING RESIST EARTHQUAKES

- Although the higher modes of vibration do not significantly affect the total inertia force to be resisted by the building at its base, they can cause very high ‘whiplash’ accelerations near the roof of a building.
- These localized yet intense horizontal accelerations often cause of increased damage to non-structural elements in upper storeys.

The natural period of vibration of a building depends upon a number of factors:

- Building height has the greatest influence. The higher a building, the longer its natural period of vibration. A very approximate rule-of-thumb method for calculating the natural period of vibration is to multiply the number of storeys of a building by 0.1.

HOW BUILDING RESIST EARTHQUAKES

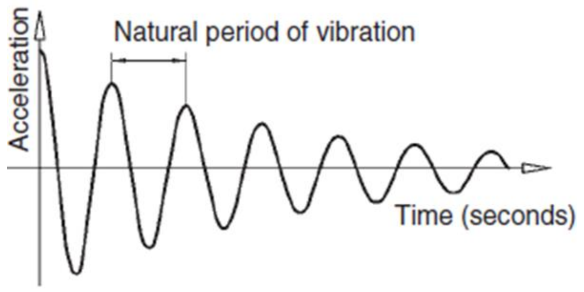
- The natural period of a ten-storey building is therefore approximately 1.0 second.
- The weight of the building. The heavier a building, the longer the natural period, and finally,
- The type of structural system provided to resist seismic forces. The more flexible or less stiff a structure, the longer its natural period.
- A moment frame structure, for example, is usually more flexible than a shear wall structure, so its natural period is longer.
- In practice, natural periods of vibration vary between say 0.05 seconds for a stiff single-storey building to a period of approximately seven seconds for one of the world's tallest buildings at 101 storeys (Fig. 2.7).

▲ **2.7** One of the tallest buildings in the world, Taipei 101, Taiwan.

HOW BUILDING RESIST EARTHQUAKES

Damping

- Damping is another important but less critical dynamic characteristic of a building.
- Fig. 2.5(b) illustrates how damping reduces the magnitude of horizontal vibrations with each successive cycle.
- Damping, mainly caused by internal friction within building elements, causes the amplitude of vibrations to decay.
- The degree of damping in a building depends upon the material of its seismic resisting structure as well as its other construction materials and details.

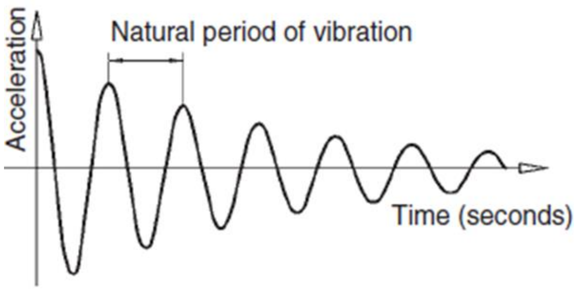


(b) A record of the building acceleration after the impulse

HOW BUILDING RESIST EARTHQUAKES

Damping

- Reinforced concrete structures possess more damping than steel structures, but less than those constructed of wood.
- Damping absorbs earthquake energy and reduces resonance or the build-up of earthquake inertia forces so it is very beneficial.



(b) A record of the building acceleration after the impulse

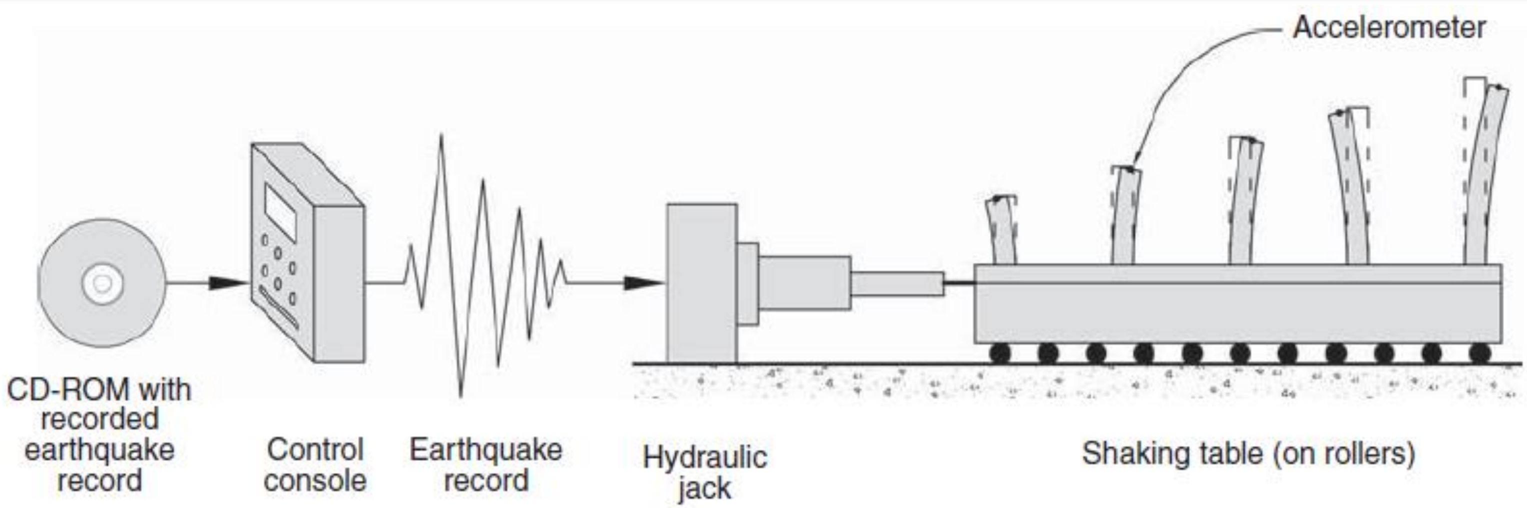
HOW BUILDING RESIST EARTHQUAKES

- Without being aware of it, we regularly experience damping in cars. Shock-absorbers quickly dampen out vertical vibrations caused when a car rides over a bump on the road.
- Damping in buildings has the same but much smaller effect. Apart from high-tech buildings that might have specially designed dampers incorporated into their structural systems, structural engineers do not intentionally attempt to increase damping.
- They just accept it and allow for its beneficial presence in their calculations.
- If the damping in a typical reinforced concrete building is halved, seismic response (peak acceleration) increases by approximately 30 per cent.

HOW BUILDING RESIST EARTHQUAKES

Response spectrum

- The response spectrum is a convenient method for illustrating and quantifying how the natural period of vibration and damping of a building affects its response to earthquake shaking.
- As schematically illustrated in Fig. 2.8 a digitally recorded earthquake accelerogram is the input signal to a dynamic hydraulic ram attached to a shaking table.



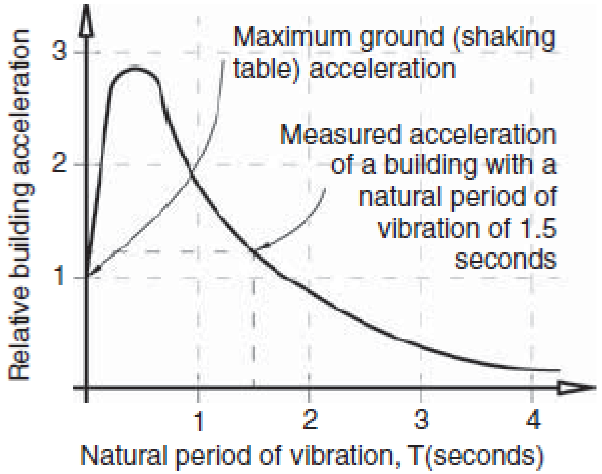
▲ 2.8 Generating a response spectrum from an earthquake record using a shaking table.

HOW BUILDING RESIST EARTHQUAKES

Response spectrum

- Model buildings, each with a longer period of vibration from left to right, are mounted on the table, and an accelerometer is attached to the roof of each to measure its maximum horizontal acceleration.

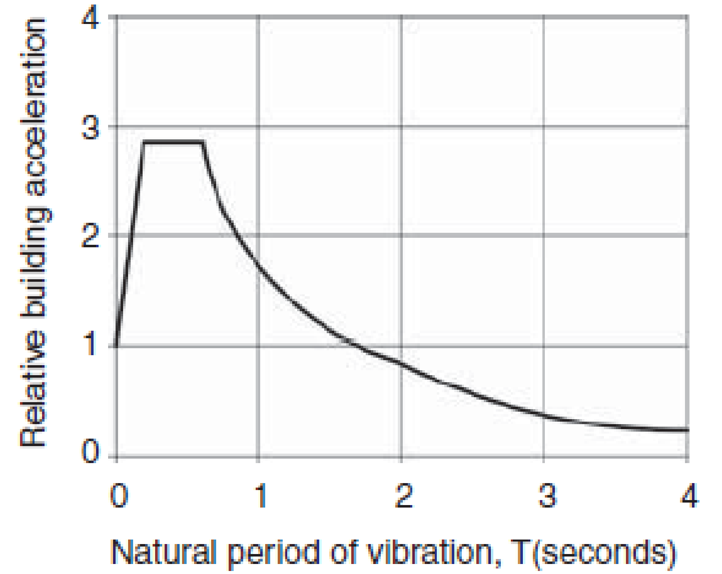
- The buildings possess identical amounts of damping. When the shaking table simulates a recorded earthquake each building vibrates differently and its maximum acceleration is recorded and then plotted on a graph Fig. 2.9(a). Although the procedure outlined above using mechanical equipment like a shaking table could be used in practice, it is far more convenient to model the whole process by computer. All response spectra are computer generated.



(a) Response spectrum for one earthquake record

HOW BUILDING RESIST EARTHQUAKES

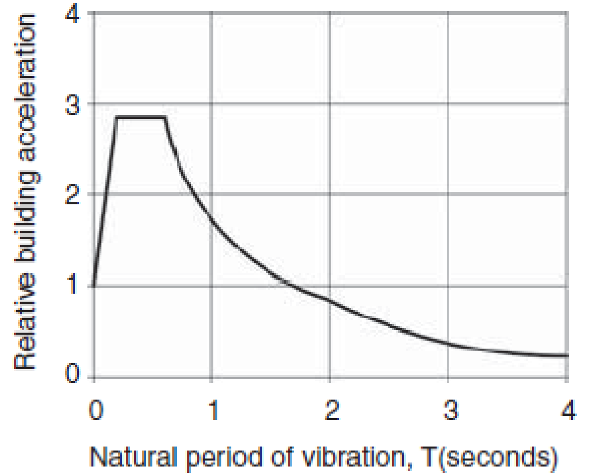
- The shape of a response spectrum illustrates how the natural period of vibration of a building has a huge effect on the maximum horizontal acceleration experienced, and consequently upon the magnitude of inertia force it should be designed for.
- With reference to Fig. 2.9(b) , the maximum acceleration of a building with a natural period of 0.0 seconds is represented by 1.0 unit of acceleration.



(b) A typical loadings code response spectrum for a medium strength soil

HOW BUILDING RESIST EARTHQUAKES

- This point on the spectrum represents the peak ground acceleration. Buildings with certain longer natural periods of vibration amplify ground accelerations.
- For example, buildings with T 0.2 to 0.7 seconds resonate with the cyclic ground accelerations, amplifying them by almost a factor of 3.0. As natural periods become longer, from 0.7 to 1.7 seconds, peak building accelerations reduce towards the same intensity as the peak ground acceleration. Beyond 1.7 seconds the maximum accelerations continue to diminish until at T 4.0 seconds the building acceleration is only 0.3 of the maximum ground acceleration.



(b) A typical loadings code response spectrum for a medium strength soil

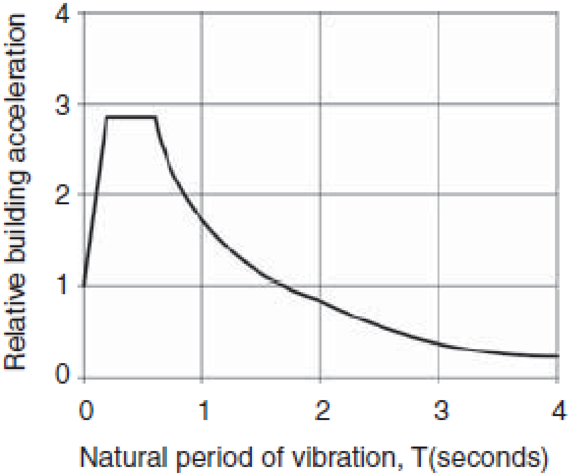
HOW BUILDING RESIST EARTHQUAKES

- So, depending on the value of the natural period of vibration an approximately ten-fold variation in maximum building acceleration is possible.
- A building with T 4.0 seconds (approximately 40 storeys high) need be designed for only 10 per cent of the design force of a building of the same weight with T 0.2 seconds (two storeys). In general, the longer the natural period of vibration, the less the maximum acceleration and seismic design force.

HOW BUILDING RESIST EARTHQUAKES

- Although the shape of a particular response spectrum illustrates some of the fundamentals of seismic design it is not particularly useful for structural engineers.

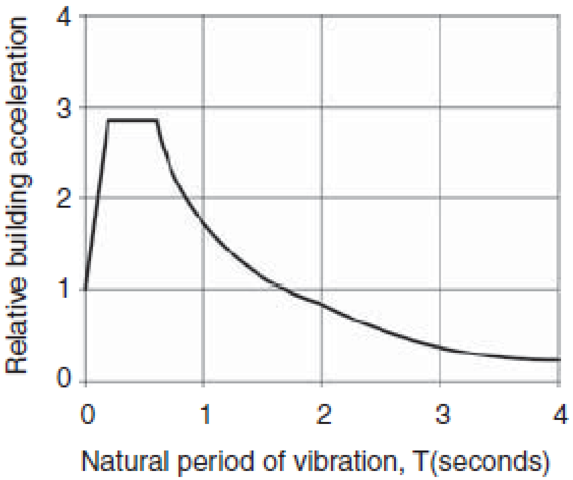
- Ideally they need similar graphs for future damaging earthquakes. Then once they have calculated the natural period of vibration of a building they can determine its maximum acceleration, calculate inertia forces and then design the seismic resisting structure accordingly.



(b) A typical loadings code response spectrum for a medium strength soil

HOW BUILDING RESIST EARTHQUAKES

- To meet this need the best that earthquake engineers can do is to select a suite of past earthquake records as a basis for extrapolating into the future. Response spectra are generated and then averaged to obtain a design response spectrum that is included in a country's earthquake loading code (Fig. 2.9(b)).
- Earthquake recordings from different soil conditions account for how soil modifies bedrock shaking.
- Most loadings codes provide four response spectra to represent rock sites and firm, medium and soft soil sites.

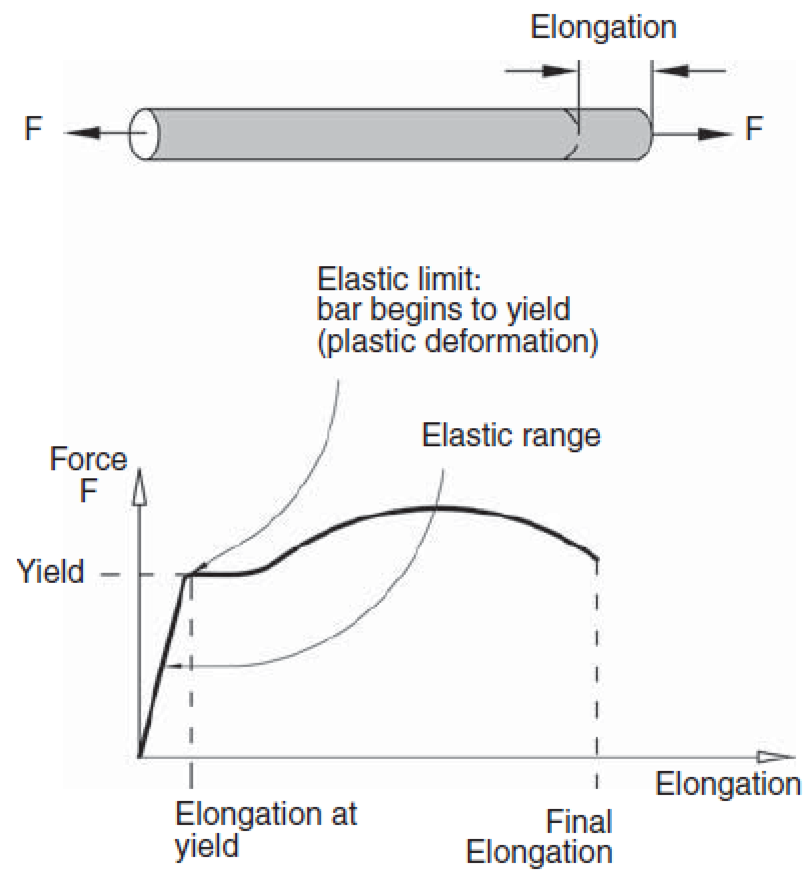


(b) A typical loadings code response spectrum for a medium strength soil

HOW BUILDING RESIST EARTHQUAKES

Ductility

- Ductility has a large influence upon the magnitude of accelerations and seismic forces a building is designed for, just like its natural period of vibration.
- Depending upon the degree of ductility a structure possesses the design seismic force can be reduced to approximately as little as one sixth of an equivalent non-ductile structure.

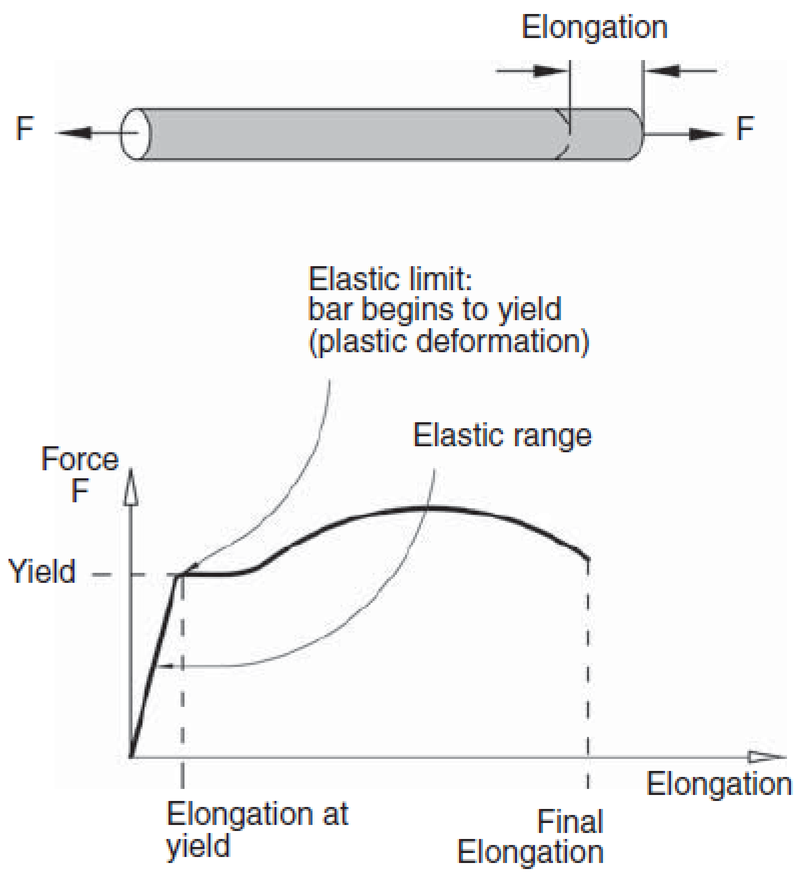


▲ **2.10** A graph of tensile force against elongation of a steel rod.

HOW BUILDING RESIST EARTHQUAKES

Ductility

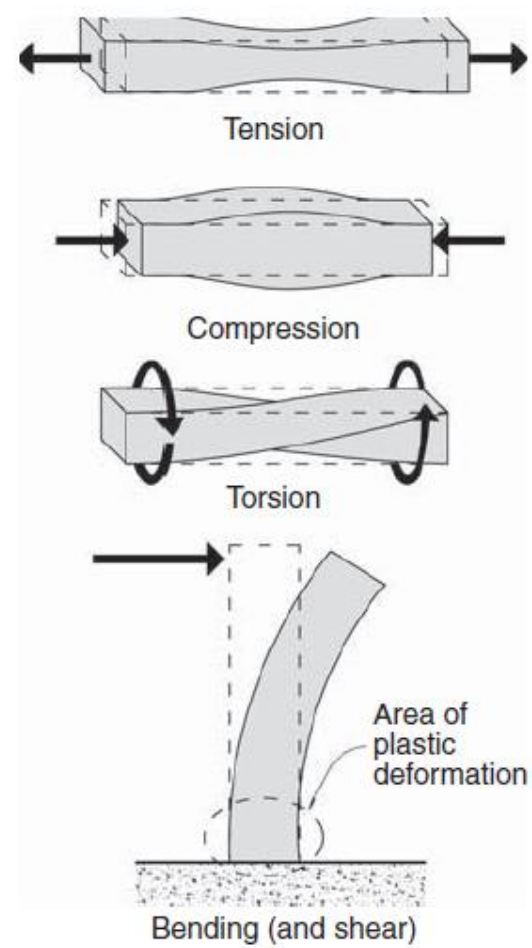
- So what is ductility? Think of it as the opposite of brittleness. When a brittle or non-ductile material like glass or concrete is stretched it suddenly snaps on reaching its elastic limit.
- A ductile material on the other hand like steel, reaches its elastic limit and then deforms plastically.
- It even slightly increases in strength until at a relatively large elongation it breaks (Fig. 2.10).



▲ **2.10** A graph of tensile force against elongation of a steel rod.

HOW BUILDING RESIST EARTHQUAKES

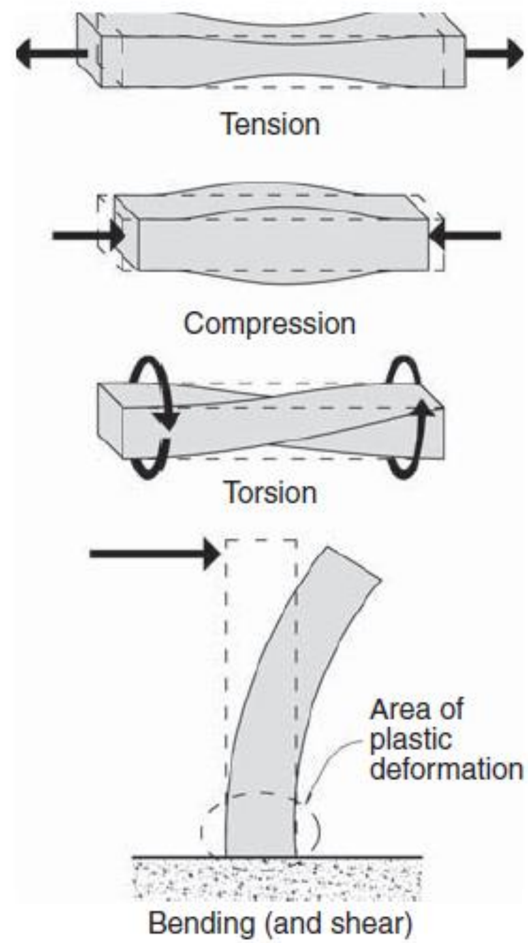
- Ductile (and brittle) performance, possible for all the structural actions illustrated in Fig. 2.11 , can be easily demonstrated.
- Take 400 mm lengths of 3 mm diameter steel wire and 5 x 20 mm wood.
- Hold the wooden member vertically and firmly at its base and apply a horizontal force at its top.
- The wood suddenly snaps due to bending at its base. However, as the horizontal force at the top of a steel wire increases the steel at its base region yields in a ductile fashion.



▲ **2.11** Different structural actions causing ductile deformations in structural elements.

HOW BUILDING RESIST EARTHQUAKES

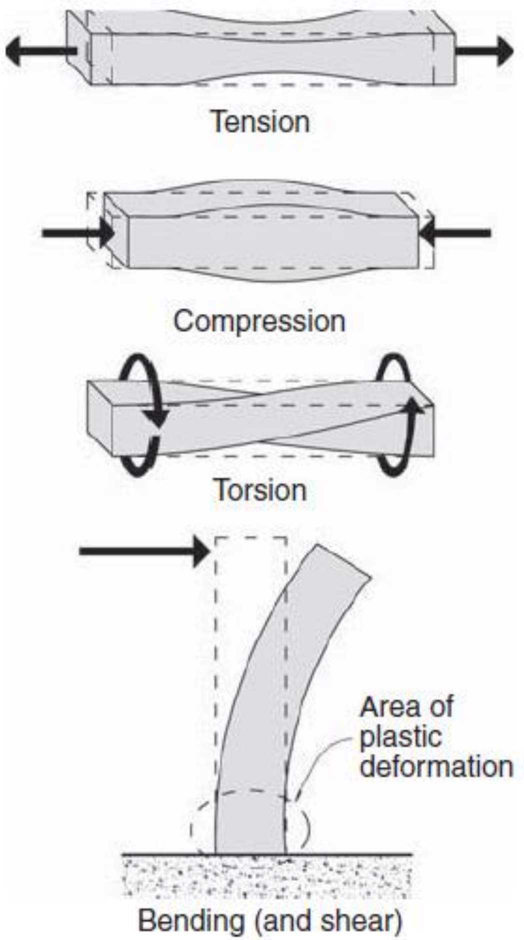
- A plastic hinge forms where the bending moment exceeds the bending strength of the wire.
- Plastic deformation occurs but the wire maintains its bending strength even though it has suffered permanent deformation.
- It requires just as much force to bend the wire back to its original position.



▲ 2.11 Different structural actions causing ductile deformations in structural elements.

HOW BUILDING RESIST EARTHQUAKES

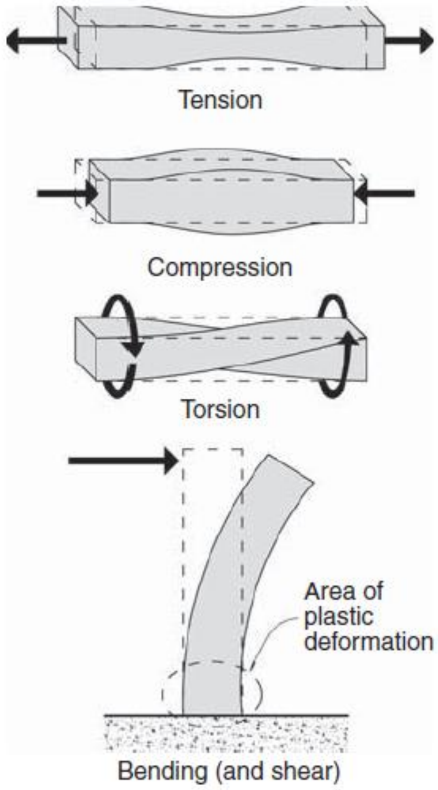
- Ductile structural materials don't necessarily guarantee ductile structures.
- The critical cross-sections of members and their connections need to be properly proportioned and detailed to completely exploit the ductile nature of the material.
- For example, if a steel compression member is too long it suffers non-ductile buckling before being squashed plastically – a ductile overload mechanism.
- If the bolts or welds in its end connections are weaker than the member itself they break prematurely before the steel member yields in a ductile fashion.



▲ **2.11** Different structural actions causing ductile deformations in structural elements.

HOW BUILDING RESIST EARTHQUAKES

- Ductility is one of the most desirable structural qualities of seismic resisting structures.
- If the intensity of earthquake shaking exceeds the strength of a brittle member – be it a beam or column – the member breaks suddenly, possibly leading to building collapse.
- But if the member is ductile, its material will yield, exhibiting plastic behaviour up to a relatively large deflection.
- In the process of being deformed plastically, a ductile member absorbs seismic energy that would otherwise lead to the building experiencing increased accelerations.
- Ductility therefore increases the effective level of damping in a building.



▲ **2.11** Different structural actions causing ductile deformations in structural elements.

HOW BUILDING RESIST EARTHQUAKES

- Non-ductile buildings are designed for up to six times the force of those that are ductile.
- Because a non-ductile structure breaks in an overload situation it must be strong enough to resist the maximum anticipated inertia forces.
- The consequences of overload on a ductile structure are far less severe. Although plastic hinge regions suffer some damage, because they maintain their strength they prevent building collapse.

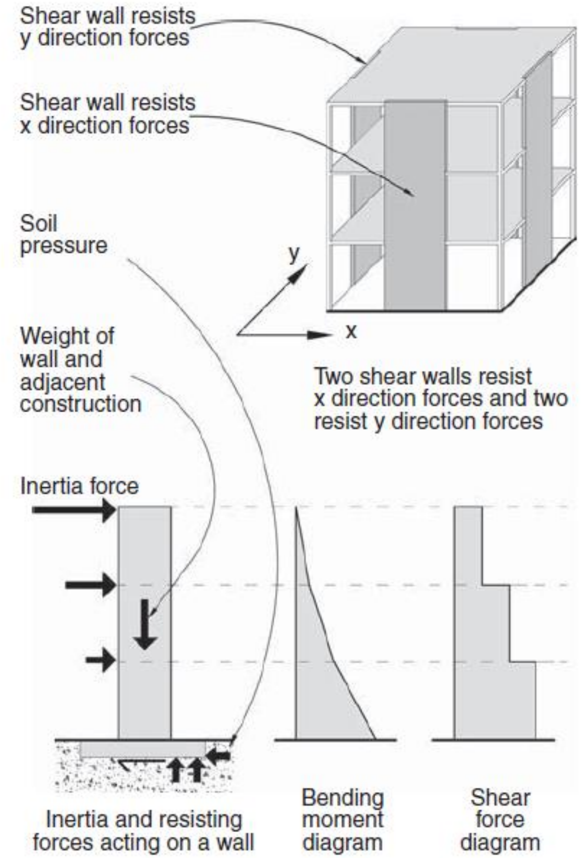
HOW BUILDING RESIST EARTHQUAKES

RESISTING SEISMIC FORCES

- To resist horizontal seismic forces successfully buildings must possess strength and stiffness, and in most cases ductility as well.
- Considers the structural necessities of strength and stiffness.

Strength

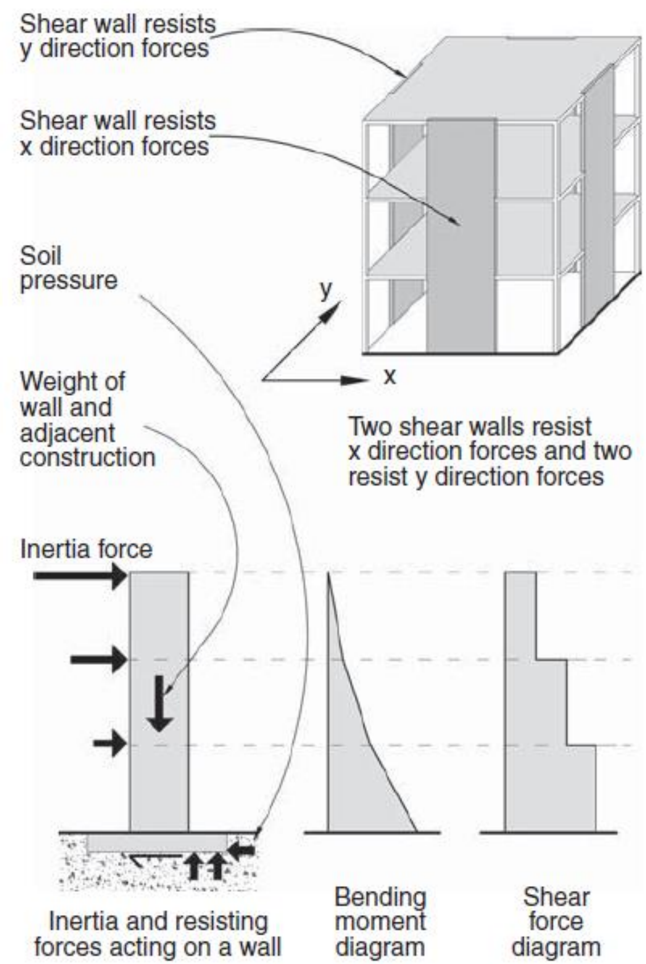
- The superstructure of every building requires sufficient structural strength to resist the bending moments and shear forces caused by seismic forces, and a foundation system capable of preventing overturning and sliding.
- Consider the building shown in Fig. 2.12 .



▲ 2.12 A building with shear walls resisting inertia forces in both orthogonal directions and the wall forces, bending moment and shear force diagrams.

HOW BUILDING RESIST EARTHQUAKES

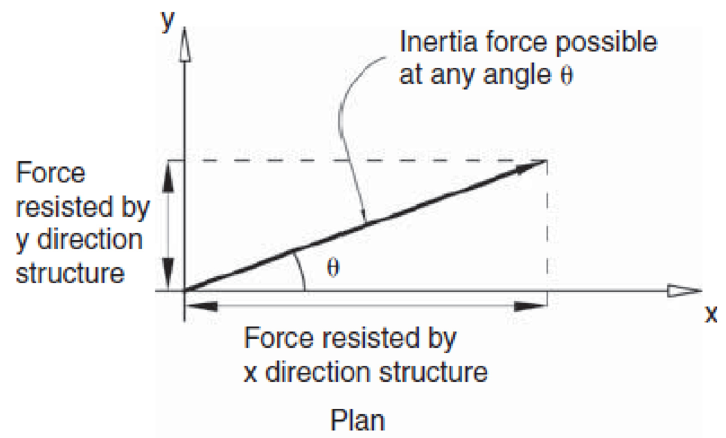
- Two shear walls resist inertia forces in both the x and y directions and transfer them to the foundations.
- The walls are subject to bending moments and shear forces for which they must be designed in order to satisfy the requirements of the seismic design code.
- Bending and shear actions, which increase from the roof level to reach their maximum values at the bases of the walls, are resisted by the foundations and transferred into the ground.

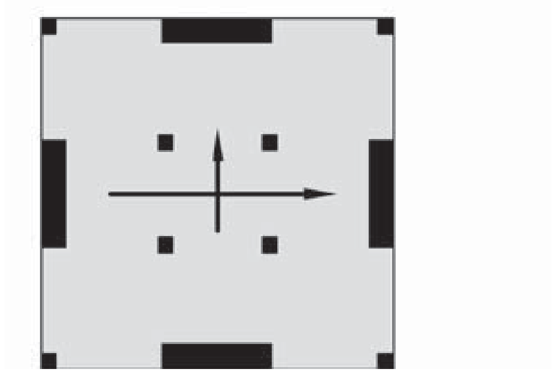


▲ 2.12 A building with shear walls resisting inertia forces in both orthogonal directions and the wall forces, bending moment and shear force diagrams.

HOW BUILDING RESIST EARTHQUAKES

- Due to the alignment of the shear walls which are strong only in the direction of their lengths, horizontal strength is provided in both the x and y directions.
- This provision of bi-directional strength responds to the fact earthquake shaking is directionally random.
- Structure must be prepared for an earthquake attack from any direction. So long as strength is provided in any two orthogonal directions then any angle of attack is covered.



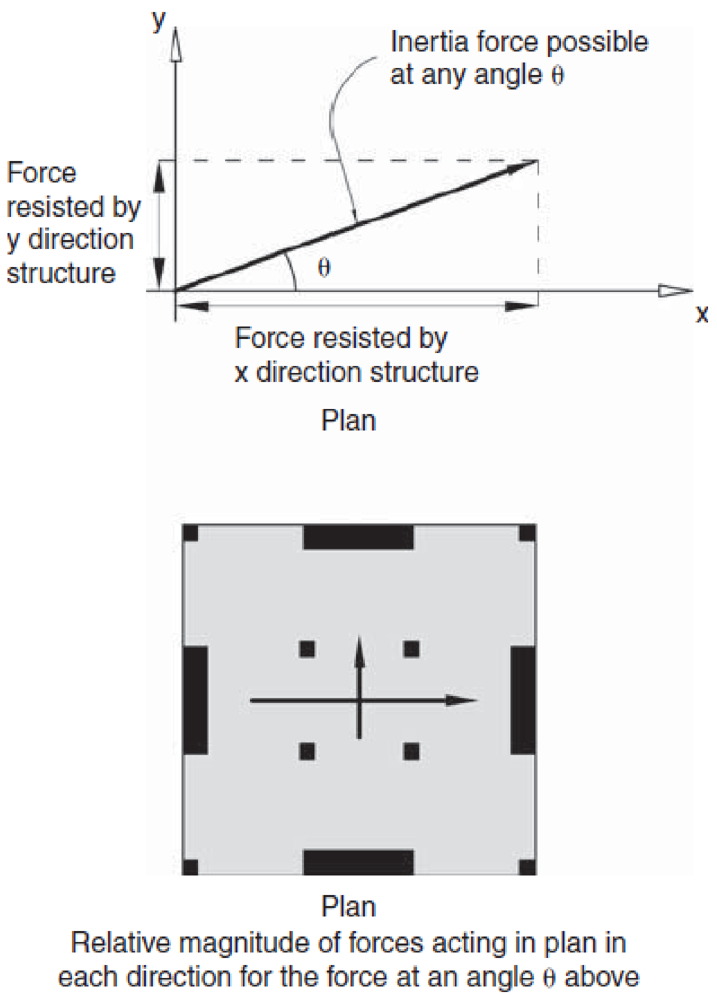


Plan
Relative magnitude of forces acting in plan in each direction for the force at an angle θ above

▲ **2.13** With strength in two orthogonal directions structure can resist earthquake attack from any direction. The building plan is from Fig. 2.12.

HOW BUILDING RESIST EARTHQUAKES

- A seismic force can be resolved into two orthogonal components which are resisted by structure with strength parallel to those directions (Fig. 2.13).
- In a similar way as x and y direction structure resist seismic forces from any direction, structure not parallel to either the x or y axis provides strength along both axes. If the inertia force in Fig. 2.13 is considered to represent the strength of say a shear wall, then that wall contributes considerable strength in the x direction and less in the y direction.

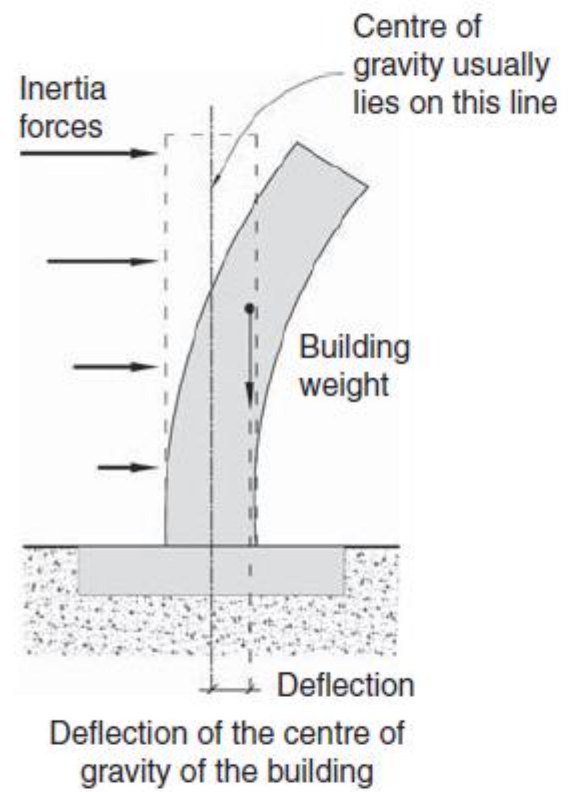


▲ **2.13** With strength in two orthogonal directions structure can resist earthquake attack from any direction. The building plan is from Fig. 2.12.

HOW BUILDING RESIST EARTHQUAKES

Stiffness

- Stiffness is almost as important as strength.
- The stiffer a structure, the less it deflects under seismic force although, as noted previously, a smaller natural period of vibration caused by a stiffer structure will usually result in a structure attracting greater seismic force.
- Even though a building might be strong enough, if its stiffness is so low that it deflects excessively, its non-structural elements will still suffer damage and it will become prone to toppling.

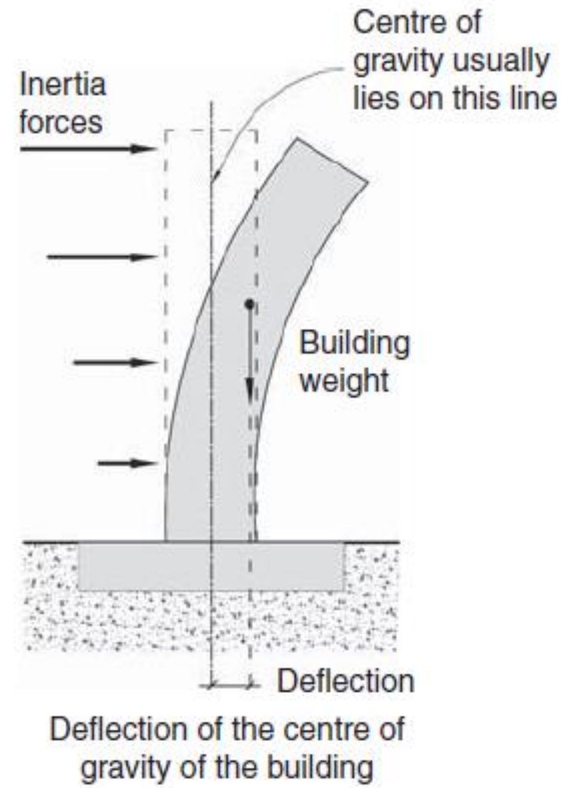


▲ **2.14** The combination of horizontal deflection and building weight increases the risk of toppling.

HOW BUILDING RESIST EARTHQUAKES

Stiffness

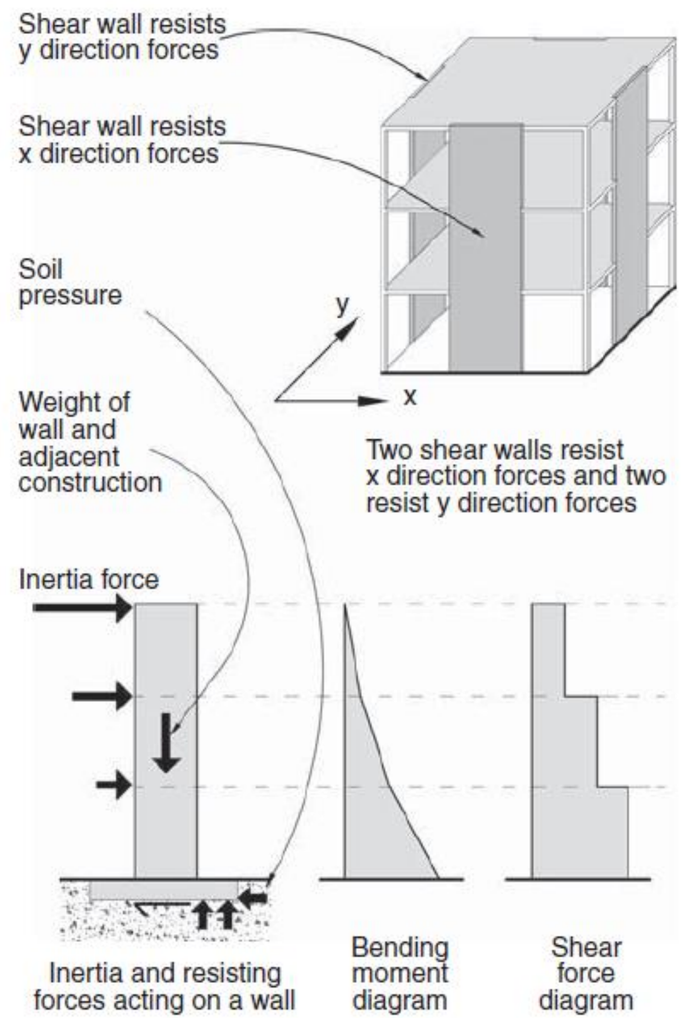
- The more it deflects and its centre of gravity moves horizontally from its normal position, the more its own weight increases its instability (Fig. 2.14).
- For these reasons, design codes limit the maximum seismic deflections of buildings.



▲ **2.14** The combination of horizontal deflection and building weight increases the risk of toppling.

HOW BUILDING RESIST EARTHQUAKES

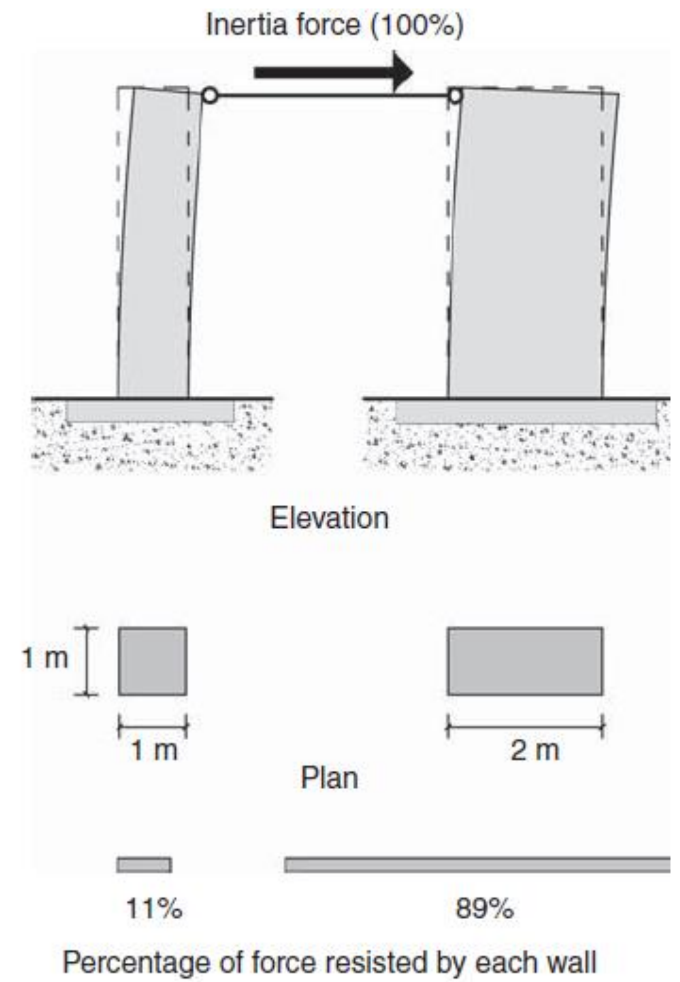
- While the overall structural stiffness of a building is important, so is the relative stiffness of its different primary structural elements.
- In Fig. 2.12 , two identical structural elements resist seismic forces in each direction.
- Each wall resists half the total force. But what happens where the stiffness of vertical elements are different?
- A key structural principle is that structural elements resist force in proportion to their stiffness.



▲ **2.12** A building with shear walls resisting inertia forces in both orthogonal directions and the wall forces, bending moment and shear force diagrams.

HOW BUILDING RESIST EARTHQUAKES

- Where more than one member resists forces the stiffer a member the more force it resists.
- Stiffness is proportional to the moment of inertia of a member.
- Consider Fig. 2.15 . The slender wall, therefore, resists 1/9th or 11 per cent of the force and the longer wall 8/9th or 89 per cent.
- Where two such walls are the only force resisting structures in a certain direction, and they are located in plan along the same line, there is no structural problem.
- But if they are offset, the building experiences torsion.

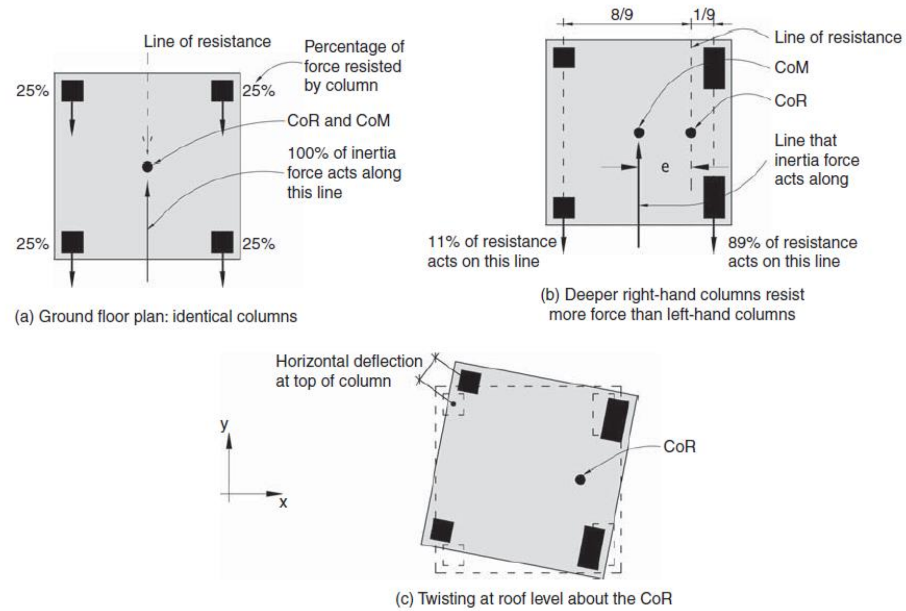


▲ **2.15** Two walls of different stiffness and the force resisted by each.

HOW BUILDING RESIST EARTHQUAKES

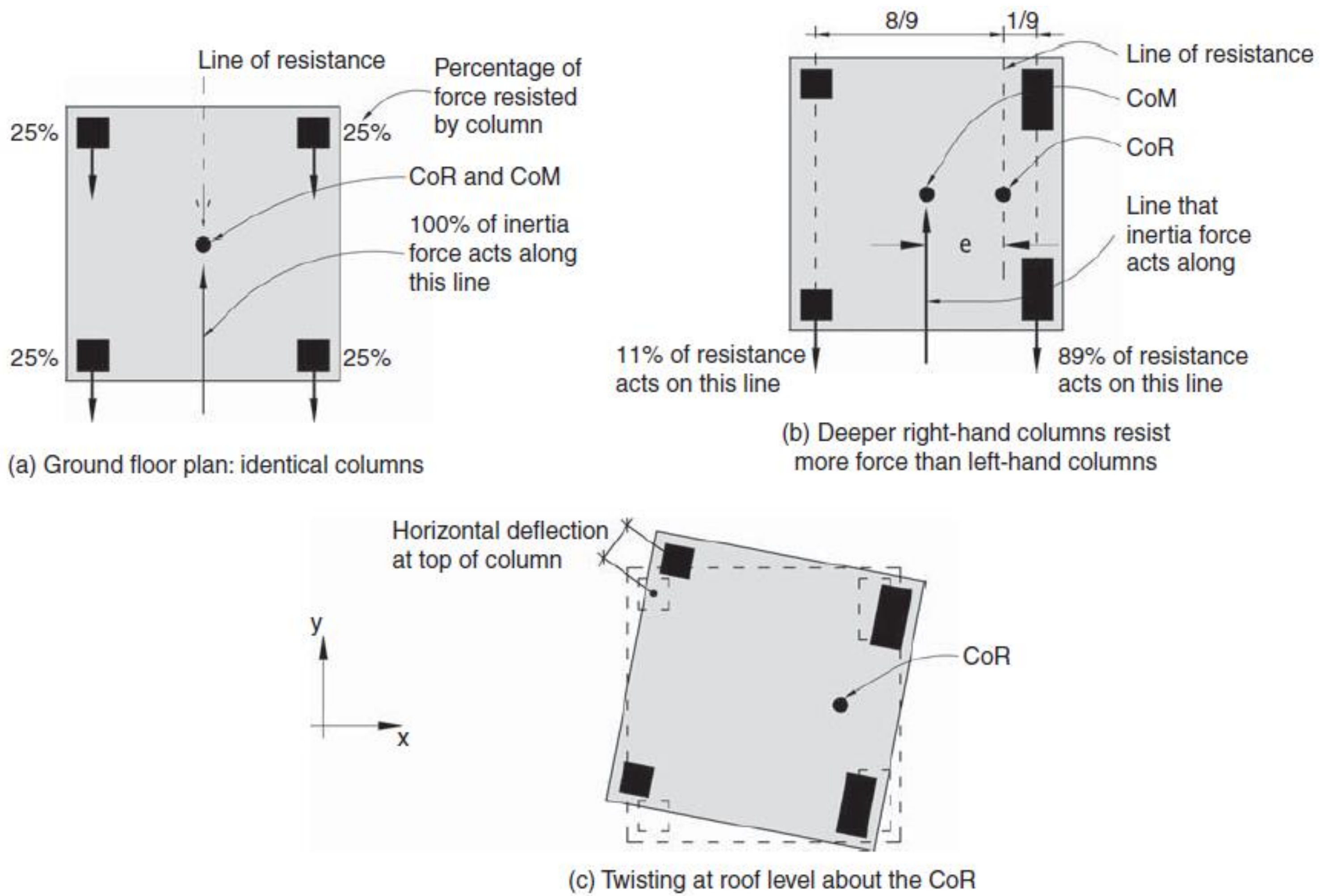
TORSION

- Building torsion occurs either where structural elements are not positioned symmetrically in plan or where the centre of rigidity or resistance (CoR) does not coincide with the CoM.
- Assume the building in Fig. 2.16(a) is single-storey with horizontal forces resisted by four identical square cantilever columns 1 m by 1 m.



▲ **2.16** A symmetrical structure is modified to illustrate torsion and how it causes a building to twist. (Movement of the roof in the y direction is not shown.)

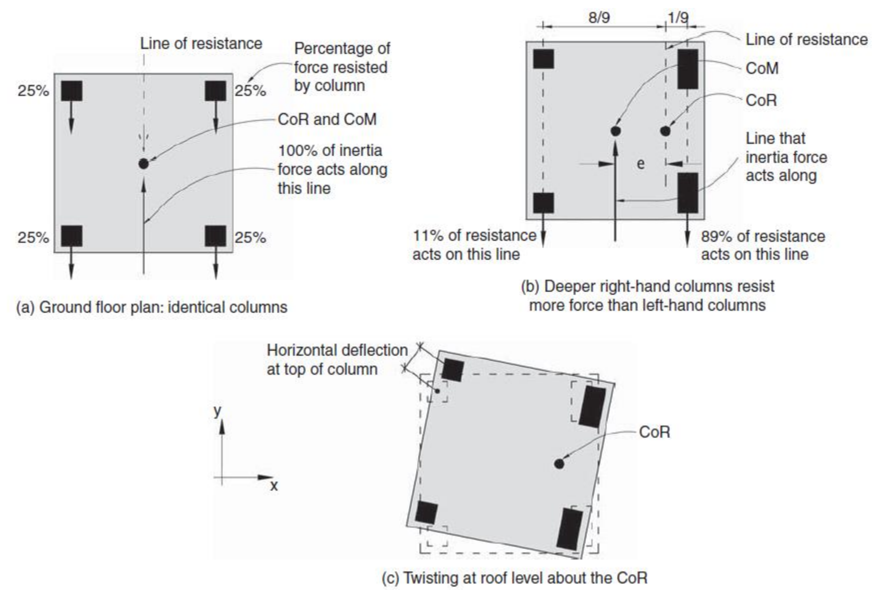
HOW BUILDING RESIST EARTHQUAKES



▲ **2.16** A symmetrical structure is modified to illustrate torsion and how it causes a building to twist. (Movement of the roof in the y direction is not shown.)

HOW BUILDING RESIST EARTHQUAKES

- This force is resisted by the four columns. Because they are of identical stiffness each resists 25 per cent of the total force.
- The sum of all four column resisting forces acts along a line midway between the two column lines.
- The line of force through the CoM therefore coincides with the line of resistance through the CoR.
- The building is subsequently in both y direction and rotational equilibrium.

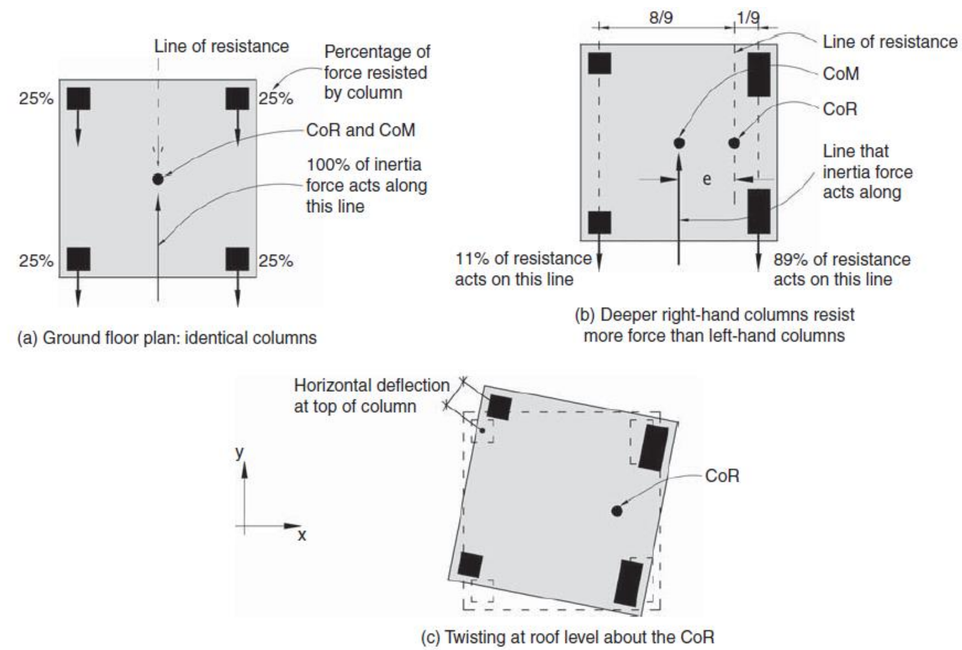


▲ 2.16 A symmetrical structure is modified to illustrate torsion and how it causes a building to twist. (Movement of the roof in the y direction is not shown.)

HOW BUILDING RESIST EARTHQUAKES

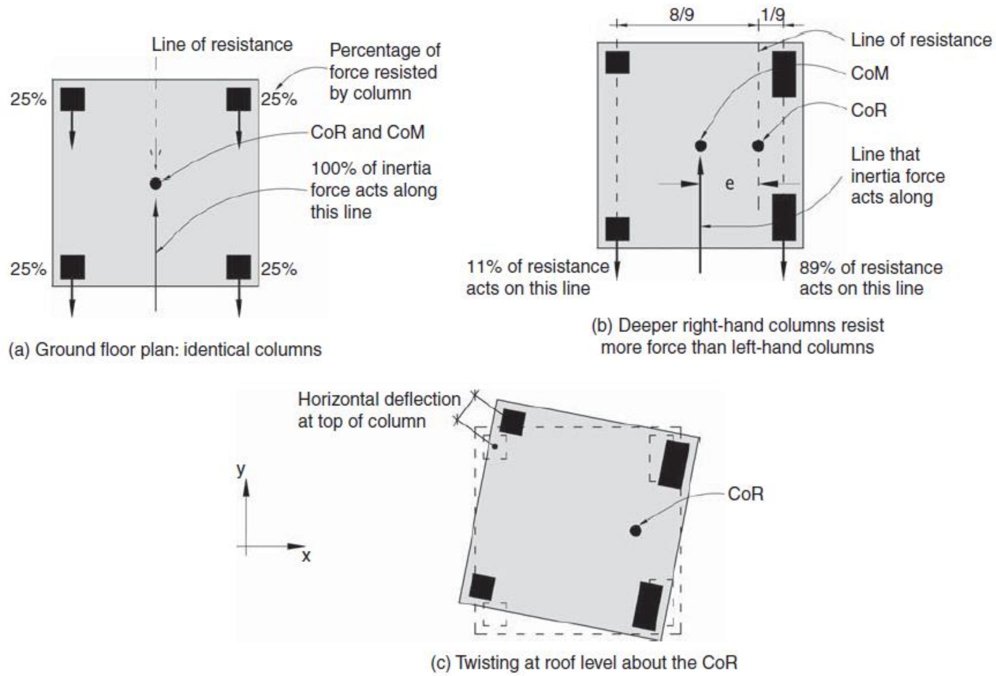
TORSION

- Figure 2.16(b) shows the right-hand columns now 2 m deep when considering their resistance in the y direction.
- The sum of the inertia force still acts at the CoM. (The influence of the increased weight of the larger columns moving the CoM to the right can be neglected because it is so small given the relatively heavy roof.)



▲ 2.16 A symmetrical structure is modified to illustrate torsion and how it causes a building to twist. (Movement of the roof in the y direction is not shown.)

HOW BUILDING RESIST EARTHQUAKES

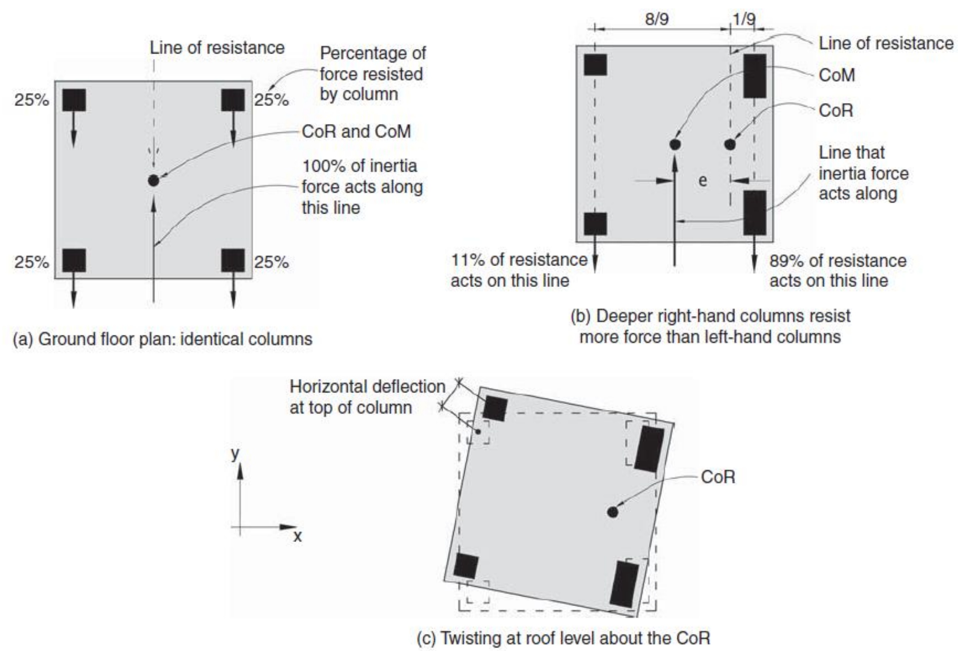


▲ **2.16** A symmetrical structure is modified to illustrate torsion and how it causes a building to twist. (Movement of the roof in the y direction is not shown.)

- However, the CoR moves significantly to the right due to the increased stiffness of the right-hand side columns.
- From the considerations of the previous section the larger columns will resist 89 per cent of the force and the left-hand columns only 11 per cent.

HOW BUILDING RESIST EARTHQUAKES

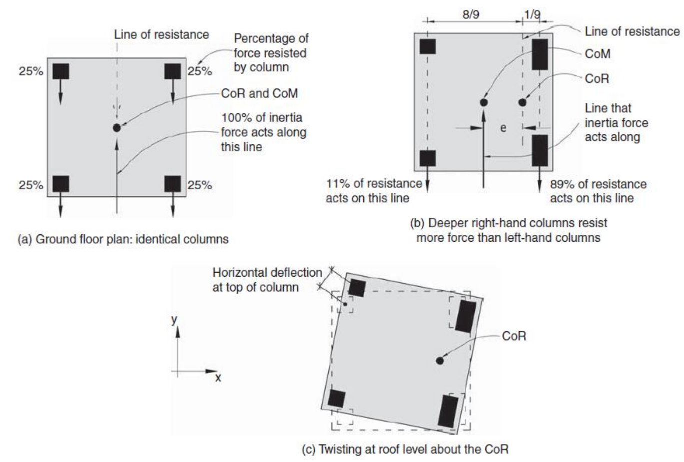
- The position of the CoR therefore lies at 1/9th of the distance between the two sets of column centrelines from the centreline of the right-hand columns.
- The lines of force and resistance are now offset by an eccentricity e (Figure 2.16(b)).
- This causes a torsion moment equal to the inertia force multiplied by "e" that twists the building clockwise in plan.



▲ 2.16 A symmetrical structure is modified to illustrate torsion and how it causes a building to twist. (Movement of the roof in the y direction is not shown.)

HOW BUILDING RESIST EARTHQUAKES

- Twisting occurs about the CoR (Fig. 2.16(c)).
- If the depths of the right-hand columns are further increased in the y direction, then the CoR moves further to the right, almost to the centreline of those columns, and increases the eccentricity to nearly half the building width.
- At this stage all that needs to be said is that torsion is to be avoided as much as possible.
- When a building twists, the columns furthest away from the CoR suffer serious damage due to excessive torsion-induced horizontal deflections.

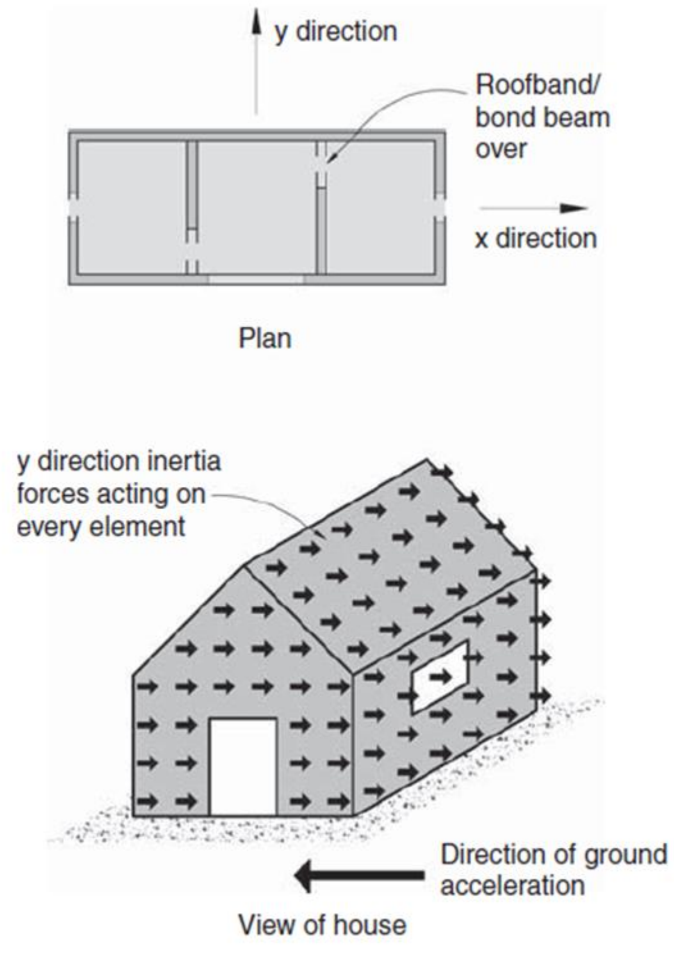


▲ 2.16 A symmetrical structure is modified to illustrate torsion and how it causes a building to twist. (Movement of the roof in the y direction is not shown.)

HOW BUILDING RESIST EARTHQUAKES

FORCE PATHS

- Architects and engineers determine force paths or load paths as they are also called by how they deploy structural elements and how those elements are joined and supported.
- The force path concept is a simple qualitative analytical tool for understanding and describing structural actions.
- A force path describes how forces within a structure are resisted by certain elements and transferred to others.

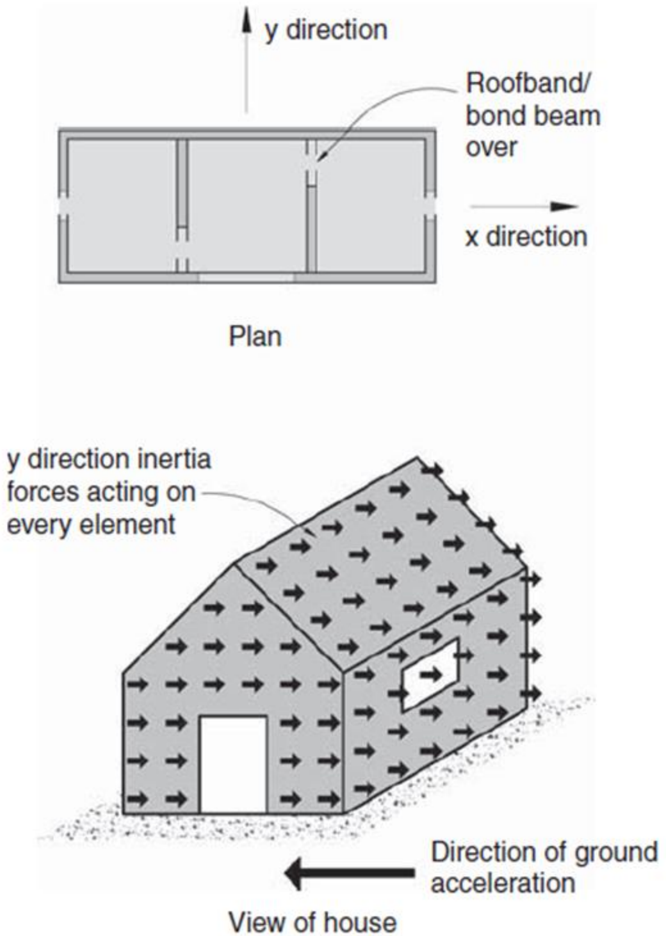


▲ 2.17 A simple building and y direction inertia forces.

HOW BUILDING RESIST EARTHQUAKES

FORCE PATHS

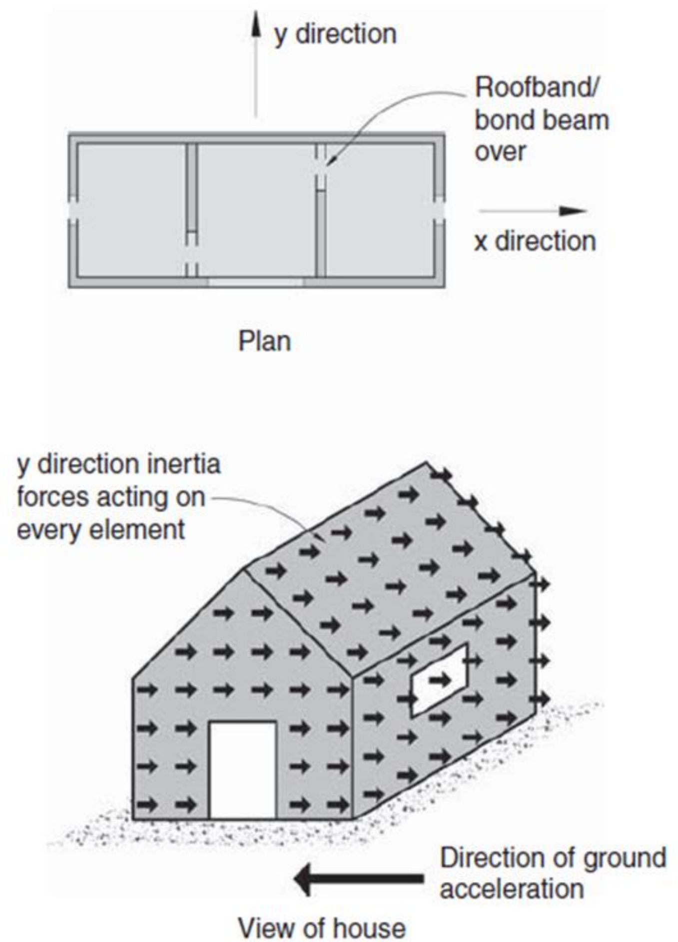
- The ‘ path ’ is the route we visualize forces taking as they travel from the applied forces to the foundations and into the ground beneath.
- The term ‘force path ’ is metaphorical because forces don’t actually move. Rather, they exist within structural members in a state of action and reaction in such a way that every structural element and connection remains in equilibrium.



▲ 2.17 A simple building and y direction inertia forces.

HOW BUILDING RESIST EARTHQUAKES

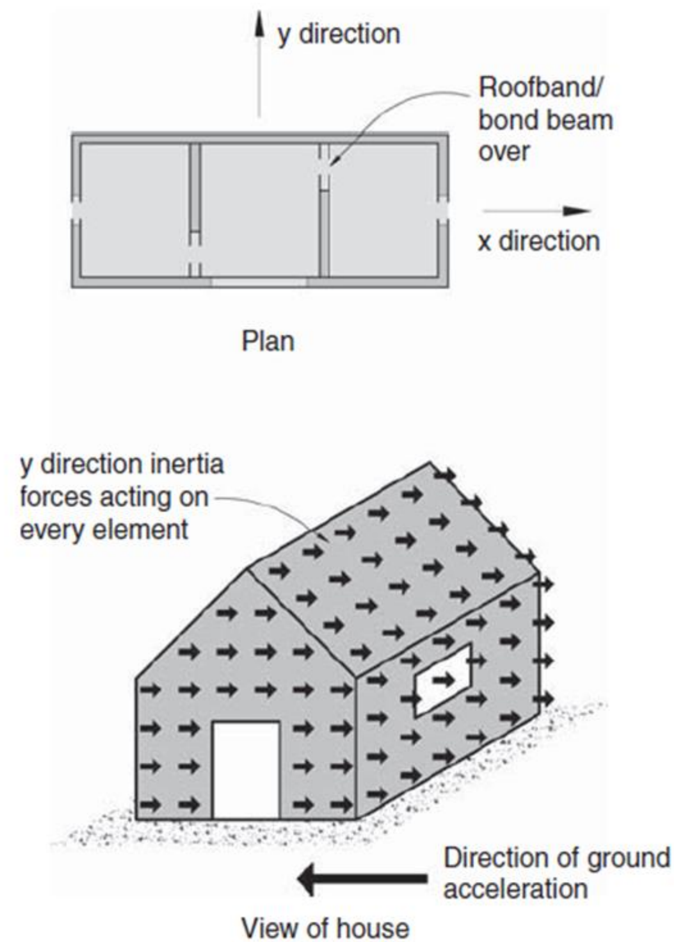
- Every structural element and connection of a force path must be sufficiently strong and stiff to withstand the forces acting within them.
- Structural elements must fulfil two functions;
  - first to resist forces, and
  - second to transfer these forces to other members and eventually into the ground.
- The adequacy of a force path is verified by following it step-by-step, element-by-element.



▲ **2.17** A simple building and y direction inertia forces.

HOW BUILDING RESIST EARTHQUAKES

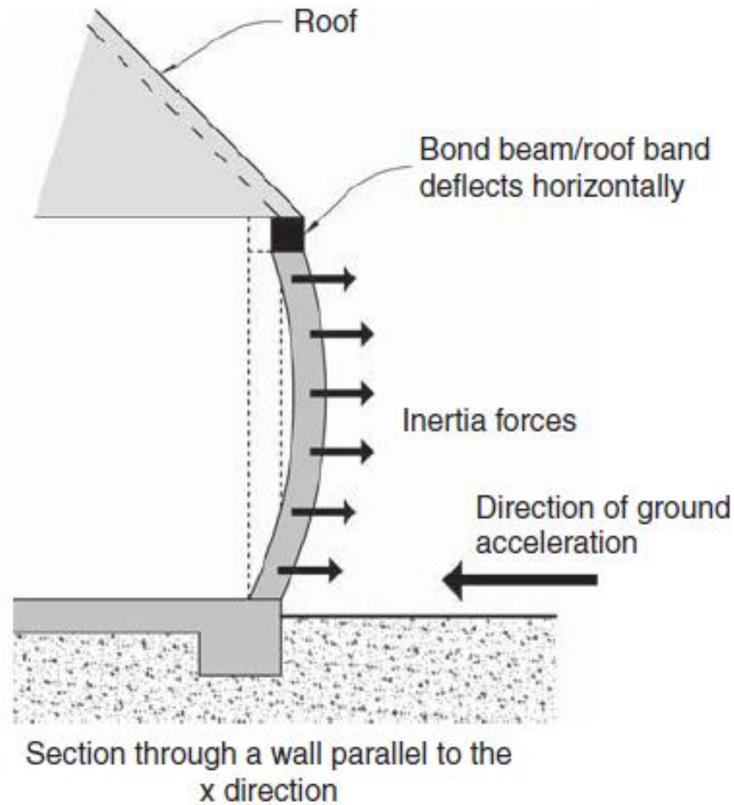
- Three questions are addressed and answered at each step – what resists the force and how, and where is it transferred to?
- Consider the force paths of a simple single-storey building with two interior walls (Fig. 2.17).
- Earthquake accelerations in the y direction induce inertia forces in all building elements namely the roof and walls that need to be transferred to the ground.



▲ 2.17 A simple building and y direction inertia forces.

HOW BUILDING RESIST EARTHQUAKES

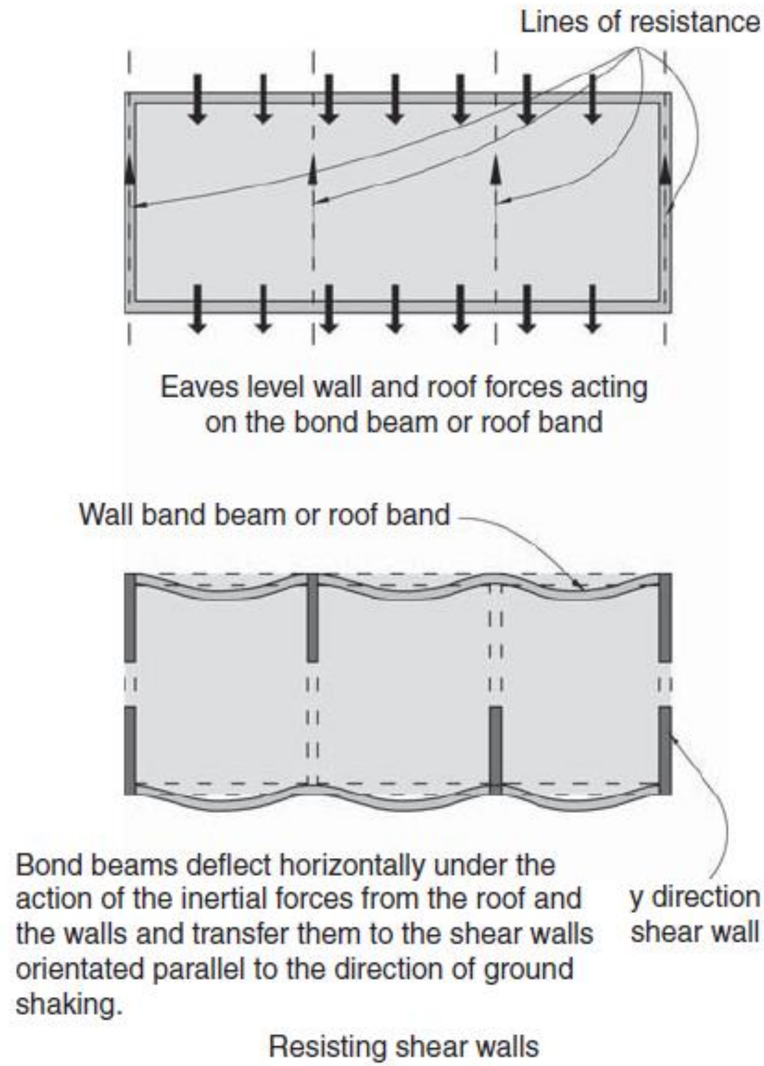
- Walls parallel to the x direction require sufficient bending and shear strength to function as shallow but wide vertical beams. They transfer half of their own inertia forces up to the roof band and the other half down to the foundations (Fig. 2.18).
- Roof forces are resisted and transferred by roof structure down to the bond beam at eaves level. In the absence of a ceiling diaphragm which could also transfer the roof forces horizontally, the bond beam resists and transfers roof and wall inertia forces to the shear walls acting in the y direction.



▲ 2.18 Effects of out-of-plane inertia forces on a wall.

HOW BUILDING RESIST EARTHQUAKES

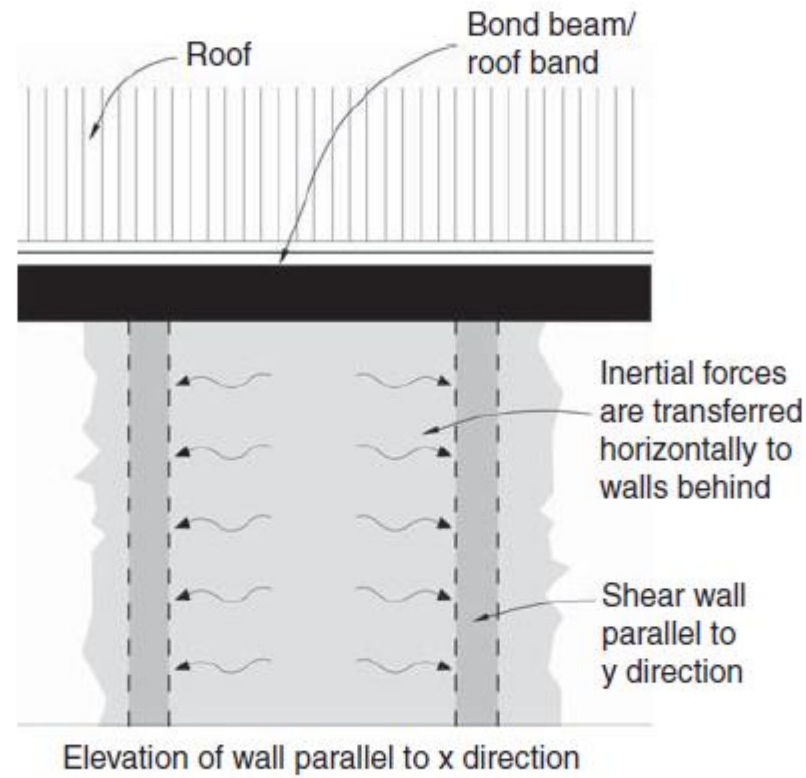
- The bond beam deflects horizontally, functioning as a continuous horizontal beam (Fig. 2.19).
- The walls parallel to the x direction have little or no strength against y direction forces or out-of plane forces except to span vertically between foundations and bond beam.



▲ **2.19** Bond beams or roof bands distribute inertia forces at eaves level to shear walls parallel to the y direction.

HOW BUILDING RESIST EARTHQUAKES

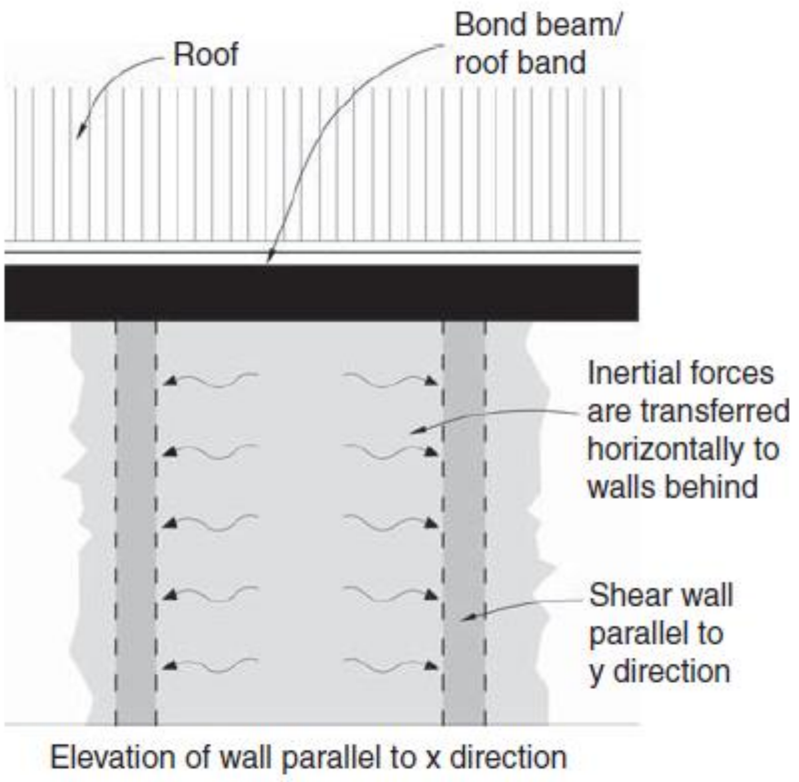
- They are usually not strong enough to cantilever vertically from their bases so they need support from the bond beam.
- If the walls parallel to the y direction were more closely spaced in plan, say 2 m or less apart, then out-of-plane forces acting on the walls at right angles if of concrete or masonry construction can take a shortcut.



▲ **2.20** Force paths for a short length of out-of-plane loaded wall restrained by walls at right-angles.

HOW BUILDING RESIST EARTHQUAKES

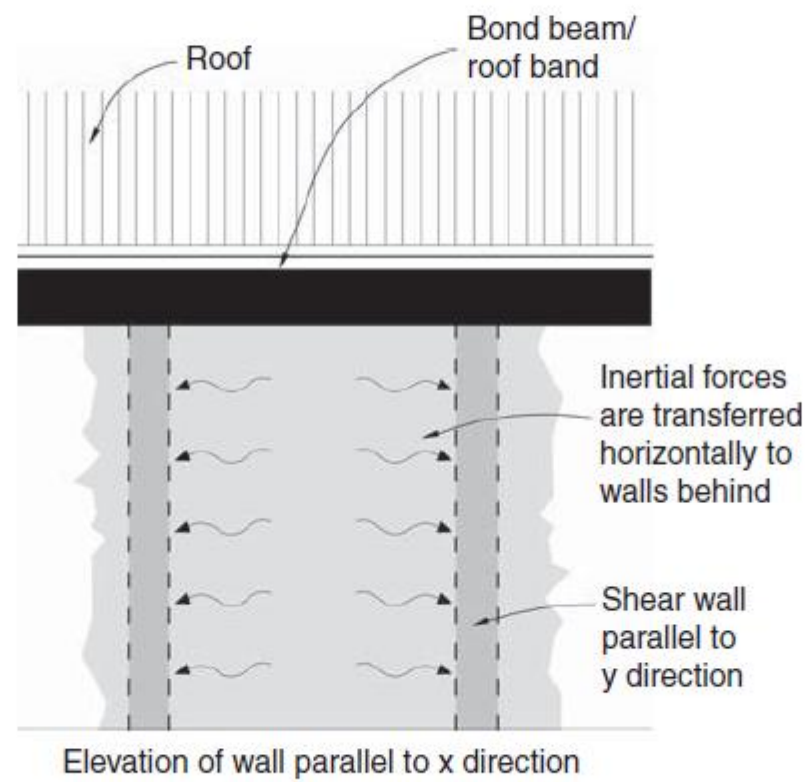
- They travel sideways, directly into those walls parallel to the y direction (Fig. 2.20). In this case the bond beam resists little force from the short out-of-plane laden wall.
- If walls are of light-timber frame construction no matter how closely spaced the cross walls are wall studs will always span vertically and half of the wall inertia force will be transferred upwards to the bond beam.



▲ **2.20** Force paths for a short length of out-of-plane loaded wall restrained by walls at right-angles.

HOW BUILDING RESIST EARTHQUAKES

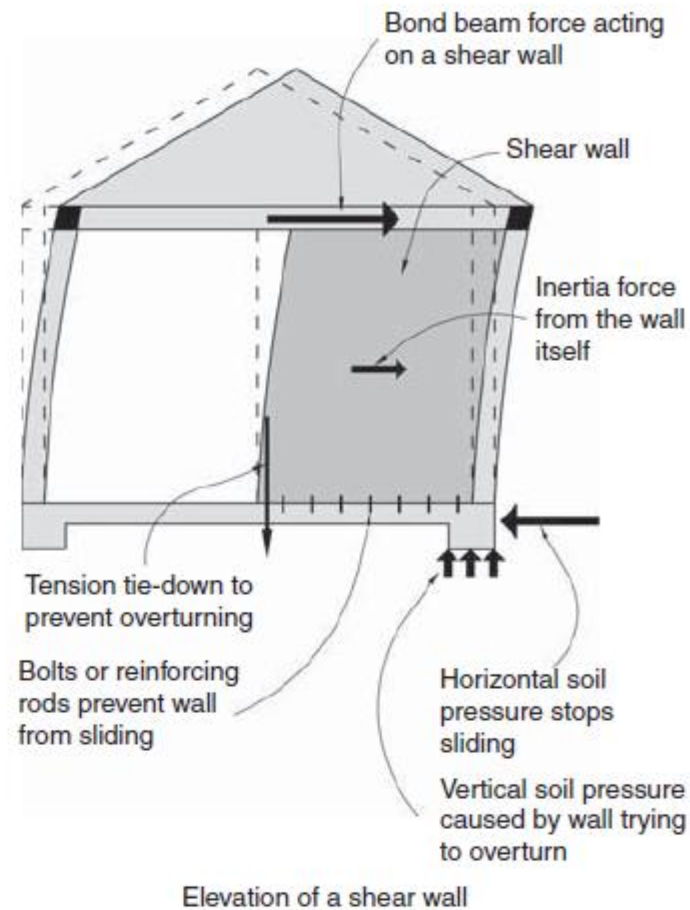
- At this stage of the force path, y direction inertia forces that arise from the roof and walls running in the x direction are transferred by the bond beams to the four lines of shear walls.
- When a wall resists a force parallel to its length, that is an in-plane force, it functions as a shear wall.



▲ **2.20** Force paths for a short length of out-of-plane loaded wall restrained by walls at right-angles.

HOW BUILDING RESIST EARTHQUAKES

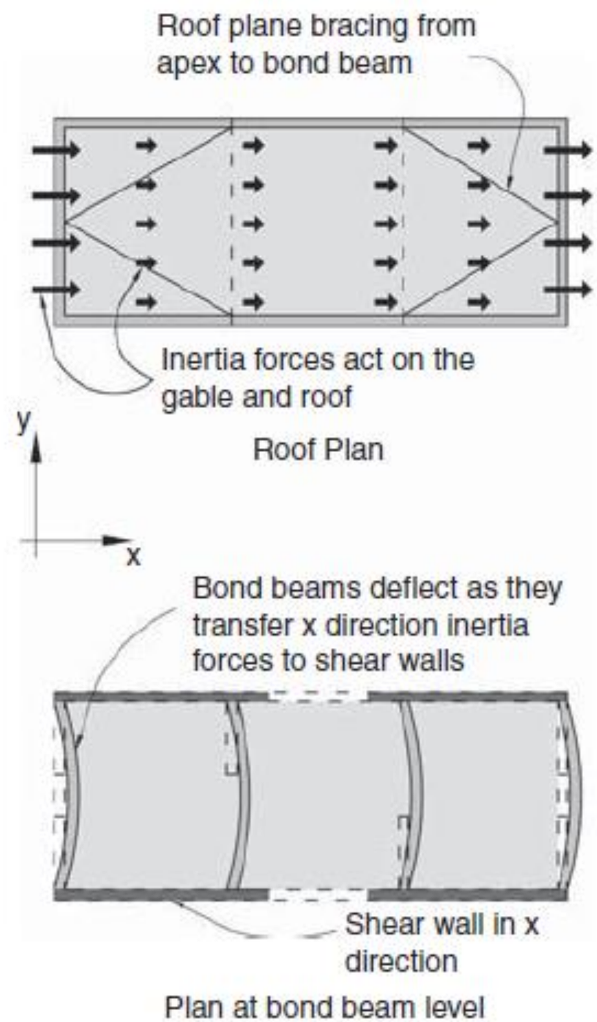
- Bond beams over the y direction walls acting in either tension or compression transfer forces from the roof and walls into these y direction walls.
- Due to their strength in bending and shear they then transfer those forces from the bond beams, plus their own inertia forces, down to the foundations (Fig. 2.21).
- Overturning or toppling of walls is prevented by a combination of their own weight and connection to walls at right angles as well as by ties or bolts extending into the foundations.



▲ **2.21** Inertia forces and resisting actions on a shear wall.

HOW BUILDING RESIST EARTHQUAKES

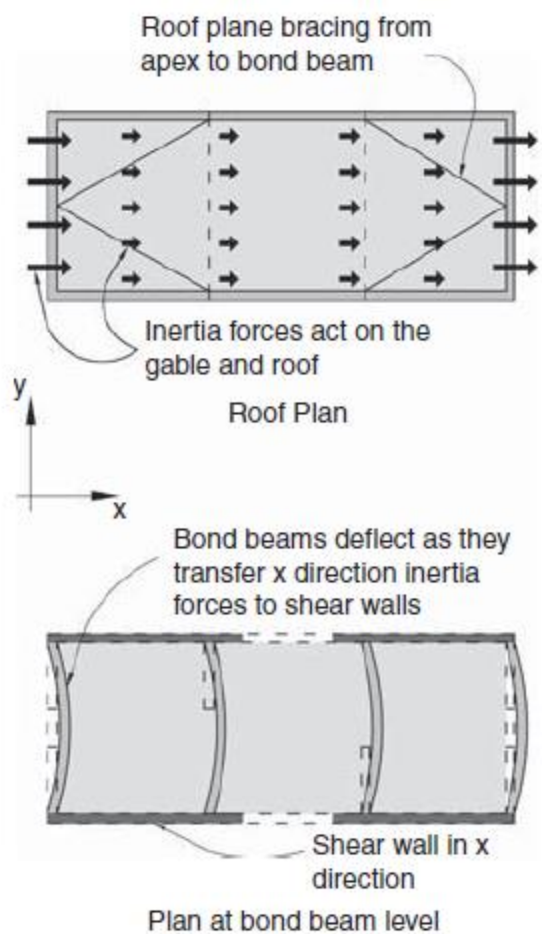
- Finally, consider shaking in the x direction.
- In a real earthquake this happens simultaneously with y direction loading.
- Similar force paths apply except for two differences. First, the gable ends, which are particularly vulnerable against out-of-plane forces due to their height, need to be tied back to roof structure.



▲ **2.22** Bond beams distribute x direction inertia forces at roof level to shear walls.

HOW BUILDING RESIST EARTHQUAKES

- Second, bracing is required in the roof plane to resist inertia forces from the top of the gables as well as the inertia force from the roof itself (Fig. 2.22).
- The bracing transfers these forces through tension and compression stress into the x direction bond beams. From there, forces travel through the four x direction shear walls down to the foundations



▲ **2.22** Bond beams distribute x direction inertia forces at roof level to shear walls.

HOW BUILDING RESIST EARTHQUAKES

- During a quake with its directionally random and cyclic pattern of shaking both force paths are activated at the same time.
- This means that many elements simultaneously resist and transfer two different types of force.
- For example, walls resist out-of-plane forces while also acting as shear walls. Earthquake shaking induces a very complex three-dimensional set of inertia forces into a building but provided adequate force paths are provided as discussed, building occupants will be safe and damage minimized.

ASSIGNMENT

- Search the internet and graphically show the different types of failure in concrete & Steel Structures.