EARTHQUAKE DESIGN PHILOSOPHY

Earthquake design philosophy may be summarized as follows:

- Under minor but frequent shaking, the main members of the building that carry vertical and horizontal forces should not be damaged; however building parts that do not carry load may sustain repairable damage.

- Under moderate but occasional shaking, the main members may sustain repairable damage, while the other parts of the building may be damaged such that they may even have to be replaced after the earthquake; and Under strong but rare shaking, the main members.

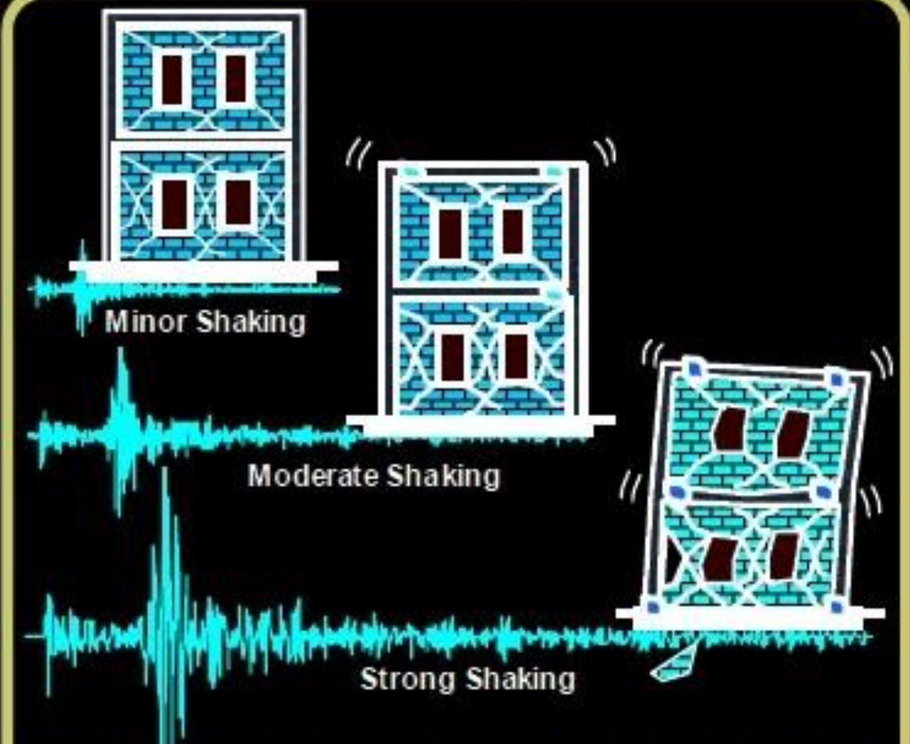

Figure 1: Performance objectives under different intensities of earthquake shaking – *seeking low repairable damage under minor shaking and collapse-prevention under strong shaking.*

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- Thus, after minor shaking, the building will be fully operational within a short time and the repair costs will be small.

- And, after moderate shaking, the building will be operational once the repair and strengthening of the damaged main members is completed.

- But, after a strong earthquake, the building may become dysfunctional for further use, but will stand so that people can be evacuated and property recovered.

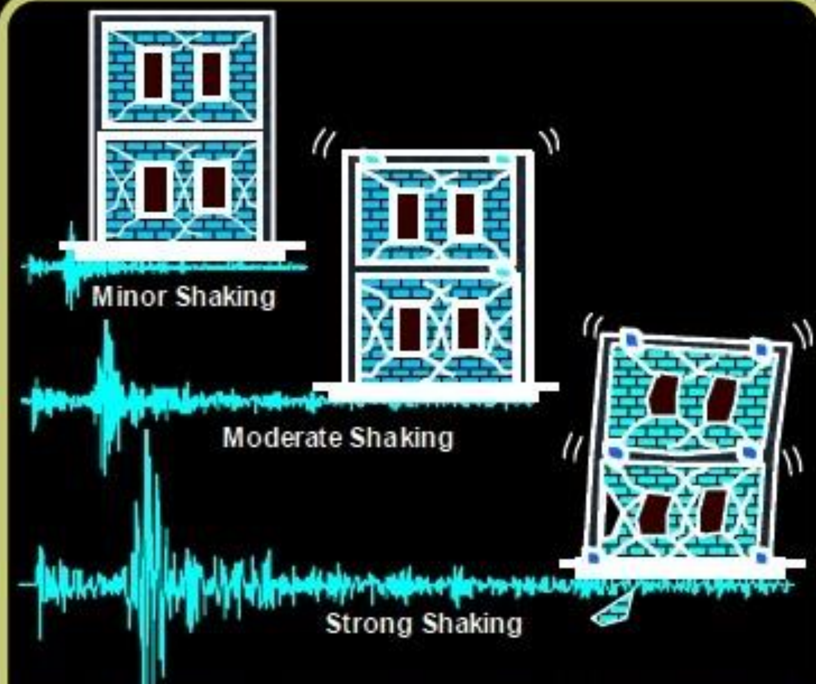


Figure 1: Performance objectives under different intensities of earthquake shaking – *seeking low repairable damage under minor shaking and collapse-prevention under strong shaking.*

Architectural Features affecting Building during Earthquake

The importance of the configuration of a building was aptly summarised by Late Henry Degenkolb, a noted Earthquake Engineer of USA, as:

"If we have a poor configuration to start with, all the engineer can do is to provide a Band-Aid - improve a basically poor solution as best as he can. Conversely, if we start-off with a good configuration and reasonable framing system, even a poor engineer cannot harm its ultimate performance too much."

Size of Buildings

- In tall buildings with large height-to-base size ratio, the horizontal movement of the floors during ground shaking is large.

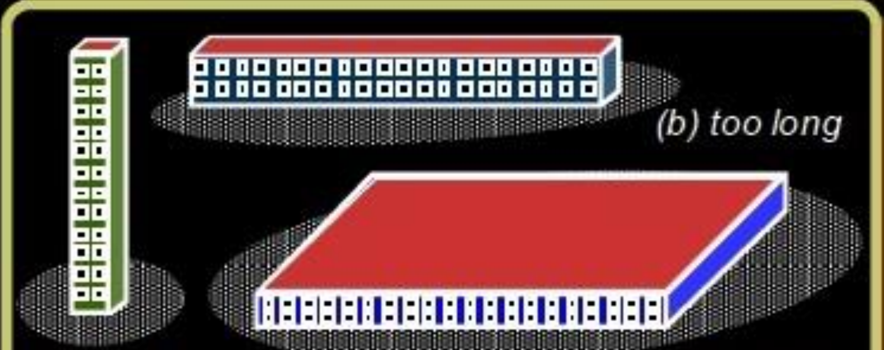


Figure 1: Buildings with one of their overall sizes much larger or much smaller than the other two, do not perform well during earthquakes.

- In short but very long buildings, the damaging effects during earthquake shaking are many.
- And, in buildings with large plan area like warehouses, the horizontal seismic forces can be excessive to be carried by columns and walls.

HORIZONTAL LAYOUT OF BUILDINGS

- Buildings with simple geometry in plan have performed well during strong earthquakes.
- Buildings with re-entrant corners, like those U, V, H and + shaped in plan, have sustained significant damage.
- Many times, the bad effects of these interior corners in the plan of buildings are avoided by making the buildings in two parts.
- For example, an L-shaped plan can be broken up into two rectangular plan shapes using a separation joint at the junction.

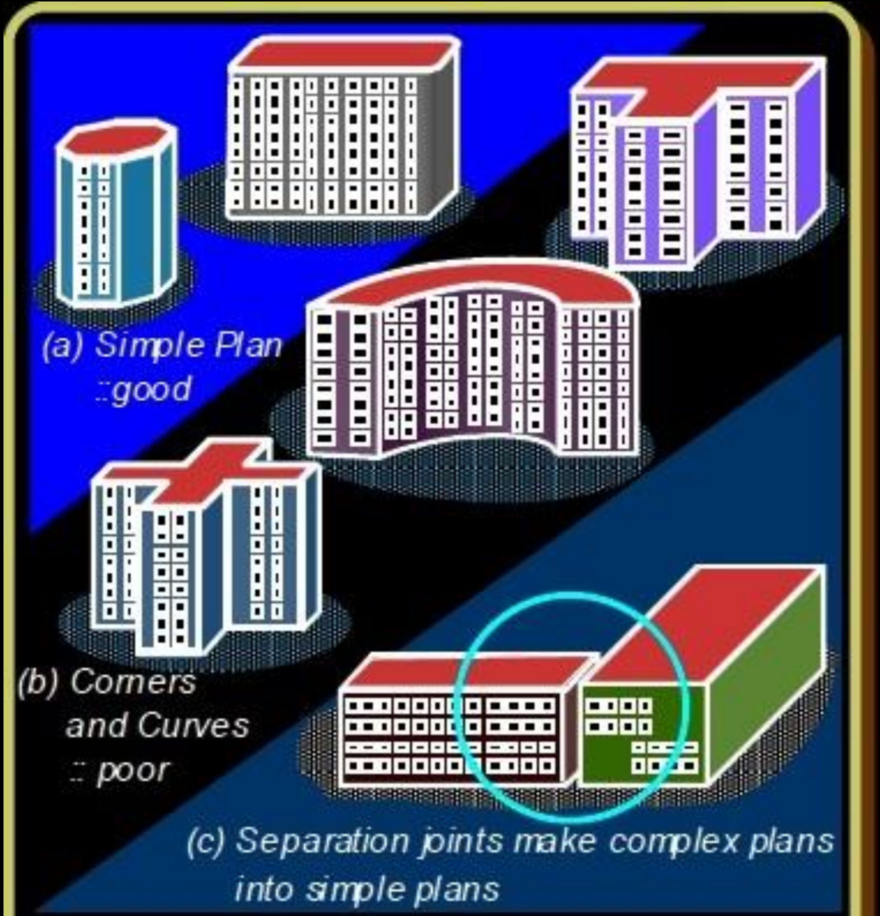
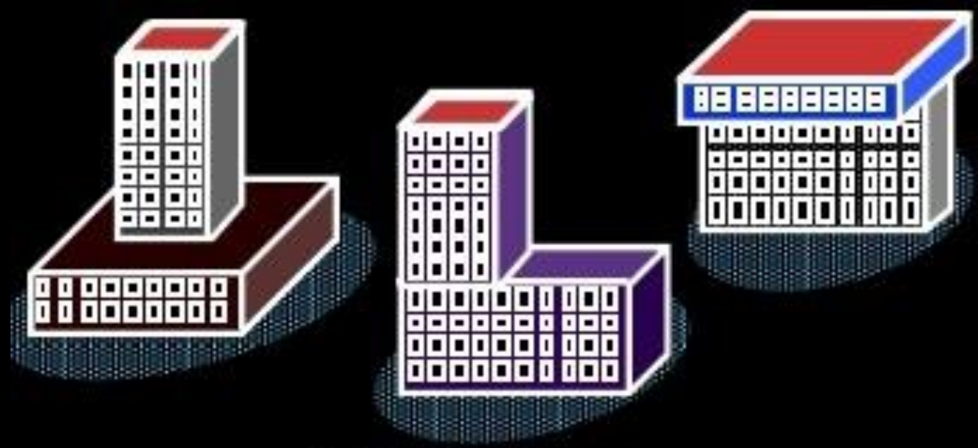


Figure 2: Simple plan shape buildings do well during earthquakes.

VERTICAL LAYOUT OF BUILDINGS

- The earthquake forces developed at different floor levels in a building need to be brought down along the height to the ground by the shortest path.
- Any deviation or discontinuity in this load transfer path results in poor performance of the building.
- Buildings with vertical setbacks (like the hotel buildings with a few storey wider than the rest) cause a sudden jump in earthquake forces at the level of discontinuity.



(a) Setbacks

- Buildings that have fewer columns or walls in a particular Storey or with unusually tall Storey, tend to damage or collapse which is initiated in that Storey.

- Many buildings with an open ground Storey intended for parking collapsed or were severely damaged.

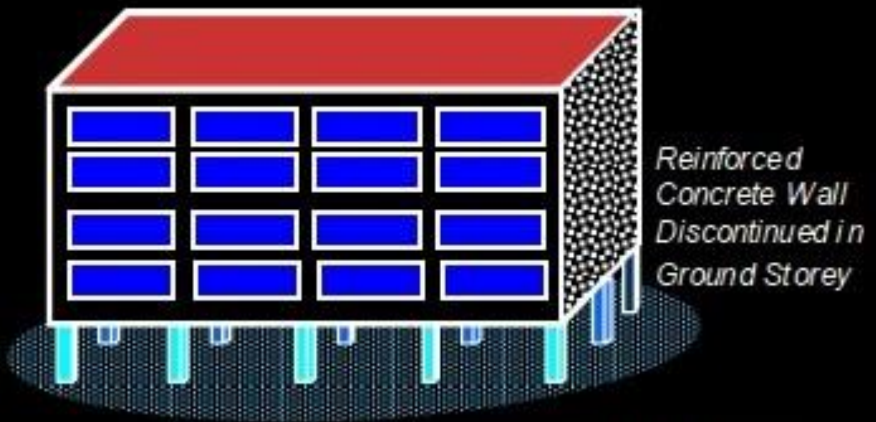
- Buildings on sloppy ground have unequal height columns along the slope, which causes ill effects like twisting and damage in shorter columns .

(c) Slopy Ground

- Buildings with columns that hang or float on beams at an intermediate Storey and do not go all the way to the foundation, have discontinuities in the load transfer path.

(d) Hanging or Floating Columns

- Some buildings have reinforced concrete walls to carry the earthquake loads to the foundation.
- Buildings, in which these walls do not go all the way to the ground but stop at an upper level, are liable to get severely damaged during earthquakes.



(e) Discontinuing Structural Members

ADJACENCY OF BUILDINGS

- When two buildings are too close to each other, they may pound on each other during strong shaking.
- With increase in building height, this collision can be a greater problem.
- When building heights do not match , the roof of the shorter building may pound at the mid-height of the column of the taller one; this can be very dangerous.

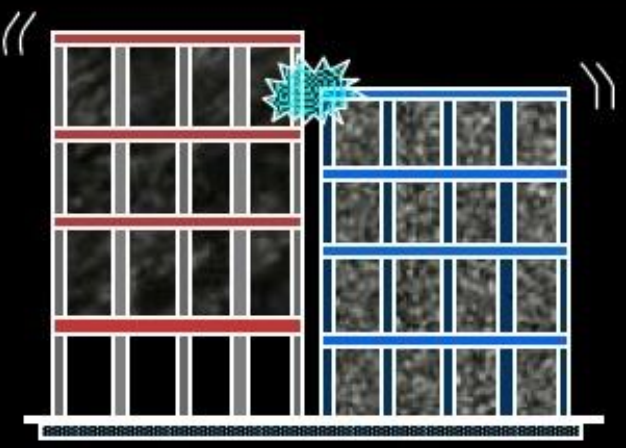


Figure 4: Pounding can occur between adjoining buildings due to horizontal vibrations of the two buildings.

EARTHQUAKE PHILOSOPHY

- Severity of ground shaking at a given location during an earthquake can be **minor** or **moderate** or **strong.**
- Relatively speaking, minor shaking occurs frequently, moderate shaking occasionally and strong shaking rarely.
- For instance, on average annually about 800 earthquakes of magnitude 5.0-5.9 occur in the world while the number is only about 18 for magnitude range 7.0-7.9**.**
- So, should we design and construct a building to resist that **rare** earthquake shaking that may come only once in 500 years or even once in 2000 years at the chosen project site, even though the life of the building itself may be only 50 or 100 years?
- **Since it costs money to provide additional earthquake safety in buildings.**

Group	Magnitude	Annual Average Number
Great	8 and higher	1
Major	7-7.9	18
Strong	6-6.9	120
Moderate	5-5.9	800
Light	4-4.9	6200
Minor	3-3.9	49000
Very Minor	< 3	M2-3 1000/day M1-2 8000/day

- A conflict arises **Should we do away with the design of buildings for earthquake effects?** Or **Should we design the buildings to be earthquake proof wherein there is no damage during the strong but rare earthquake shaking?**
- Clearly, the former approach can lead to a major disaster and **the second approach is too expensive.**
- Hence, the design philosophy should lie somewhere in between these two extremes.

EARTHQUAKE-RESISTANT BUILDINGS

- The engineers do not attempt to make **earthquake proof buildings** that **will not** get damaged even during the rare but strong earthquake; such buildings will be too robust and also too expensive.

- Instead, the engineering intention is to make buildings **earthquake resistant;** such buildings resist the effects of ground shaking, although they may get damaged severely but would not collapse during the strong earthquake.

- Thus, safety of people and contents is assured in earthquake-resistant buildings, and thereby a disaster is avoided. This is a major objective of seismic design codes throughout the world.

- Design of buildings to resist earthquakes involves **controlling the damage to acceptable levels at a reasonable cost.**

- Contrary to the common thinking that any crack in the building after an earthquake means the building is unsafe for habitation, engineers designing earthquake-resistant buildings recognize that some damage is unavoidable. Some of these cracks **are ,**while others **are not.**

- For instance, in a reinforced concrete frame building with masonry filler walls between columns, the cracks between vertical columns and masonry filler walls are acceptable.

- but diagonal cracks running through the columns are not.

- In general, qualified technical professionals are knowledgeable of the causes and severity of damage in earthquake-resistant buildings.

Diagonal cracks in columns

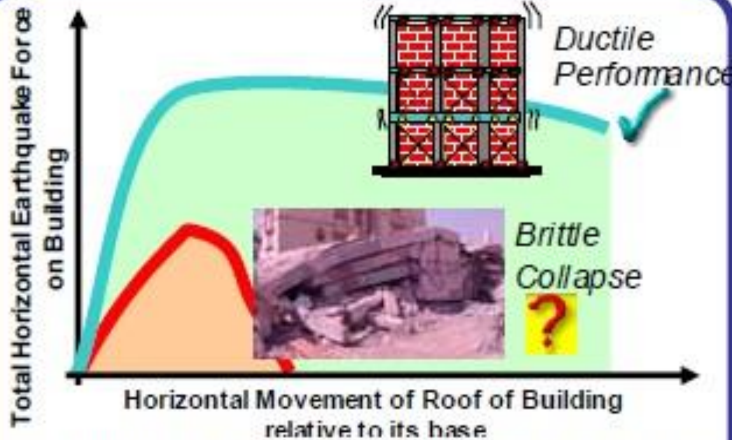
- So, the task now is to identify acceptable forms of damage and desirable building behavior during earthquakes.

- Consider **white chalk** used to write on blackboards and **steel pins** with solid heads used to hold sheets of paper together. Yes… a chalk **breaks easily'.**

- On the contrary, a steel pin **allows it to be bent back-and-forth.** Engineers define the property that allows steel pins to bend back-and-forth by large amounts, as **ductility;** chalk is a **brittle** material.

- Earthquake-resistant buildings, particularly their main elements, need to be built with ductility in them.

- Such buildings have the ability to sway back-and-forth during an earthquake, and to withstand earthquake effects with some damage, but without collapse.



(a) **Building performances during earthquakes: two extremes –** *the ductile and the brittle.*

Photo from: Housner & Jennings, Earthquake Design Criteria, EERI, USA

(b) **Brittle failure of a reinforced concrete column**

Figure 3: Ductile and brittle structures – *seismic design attempts to avoid structures of the latter kind.*

- In case of masonry structure bricks are good in case of compressive load but can hardly take tensile load.
- Concrete is also used widely. It also has greater compressive strength but less amount of tensile strength
- Steel is used in masonry and concrete buildings as reinforcement bars of diameter ranging from 6mm to 40mm.
- Reinforcing steel can carry both tensile and compressive loads. Moreover, steel is a **ductile material.**
- This important property of ductility enables steel bars to undergo large elongation before breaking.

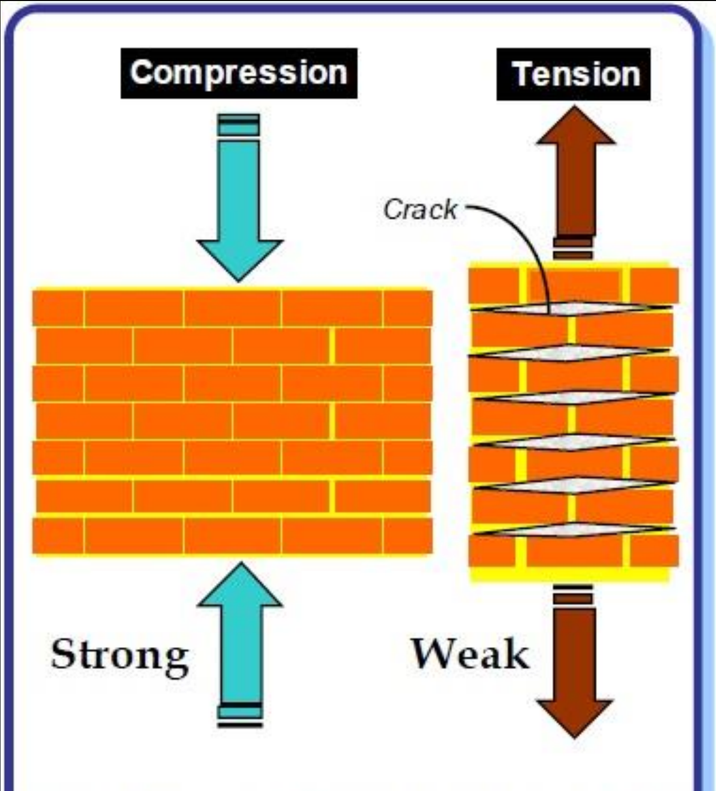


Figure 1: Masonry is strong in compression but weak in tension.

- Concrete is used in buildings along with steel reinforcement bars. This composite material is called **reinforced cement concrete (RCC)** or simply **reinforced concrete (RC).**

- The amount and location of steel in a member should be such that the failure of the member is by steel reaching its strength in tension before concrete reaches its strength in compression.

- This type of failure is **ductile failure,** and hence is preferred over a failure where concrete fails first in compression. Therefore, contrary to common thinking, providing too much steel in RC buildings can be harmful even!!

- Let us take two bars of same length and cross sectional area - one made of a ductile material and another of a brittle material. Now, pull these two bars until they break!!

- You will notice that the ductile bar elongates by a large amount before it breaks, while the brittle bar breaks suddenly on reaching its maximum strength at a relatively small elongation .

- Amongst the materials used in building construction, steel is **ductile,** while masonry and concrete are **brittle.**

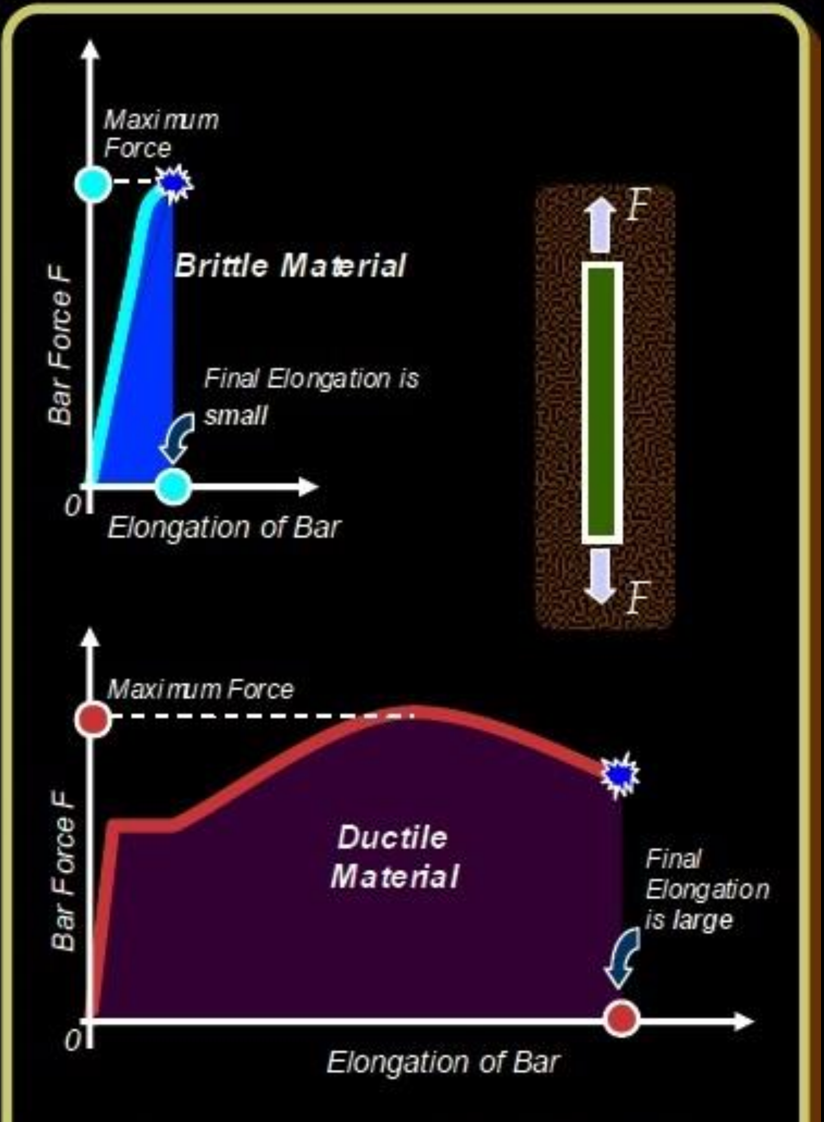


Figure 2: Tension Test on Materials – *ductile versus brittle materials.*

CAPACITY DESIGN CONCEPT

- Now, let us make a chain with links made of **brittle** and **ductile** materials.

- Now, hold the last link at either end of the chain and apply a force F.

- Since the same force F is being transferred through all the links, the force in each link is the same, **i.e.,** F.

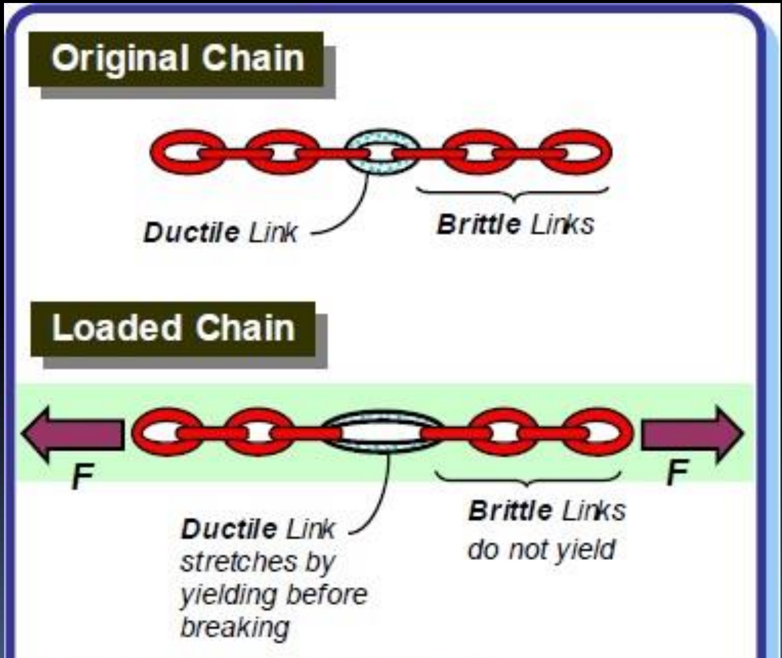


Figure 3: Ductile chain design.

- As more and more force is applied, eventually the chain will break when the **weakest link** in it breaks.

- If the ductile link is the **weak** one **(i.e.,** its capacity to take load is less), then the chain will show large final elongation.

- Instead, if the brittle link is the weak one, then the chain will fail suddenly and show small final elongation.

- Therefore, if we want to have such a **ductile** chain, we have to make the ductile link to be the **weakest** link.

EARTHQUAKE RESISTANT DESIGN OF BUILDINGS

- Buildings should be designed like the ductile chain. It consists of horizontal and vertical members, namely **beams** and **columns.**
- The seismic inertia forces generated at its floor levels are transferred through the various **beams** and **columns** to the ground. The correct building components need to be made ductile.
- The failure of a column can affect the stability of the whole building, but the failure of a beam causes localized effect.
- Therefore, it is better to make **beams** to be the ductile weak links than **columns.**
- This method of designing RC buildings is called the **strong-column weak-beam** design method.

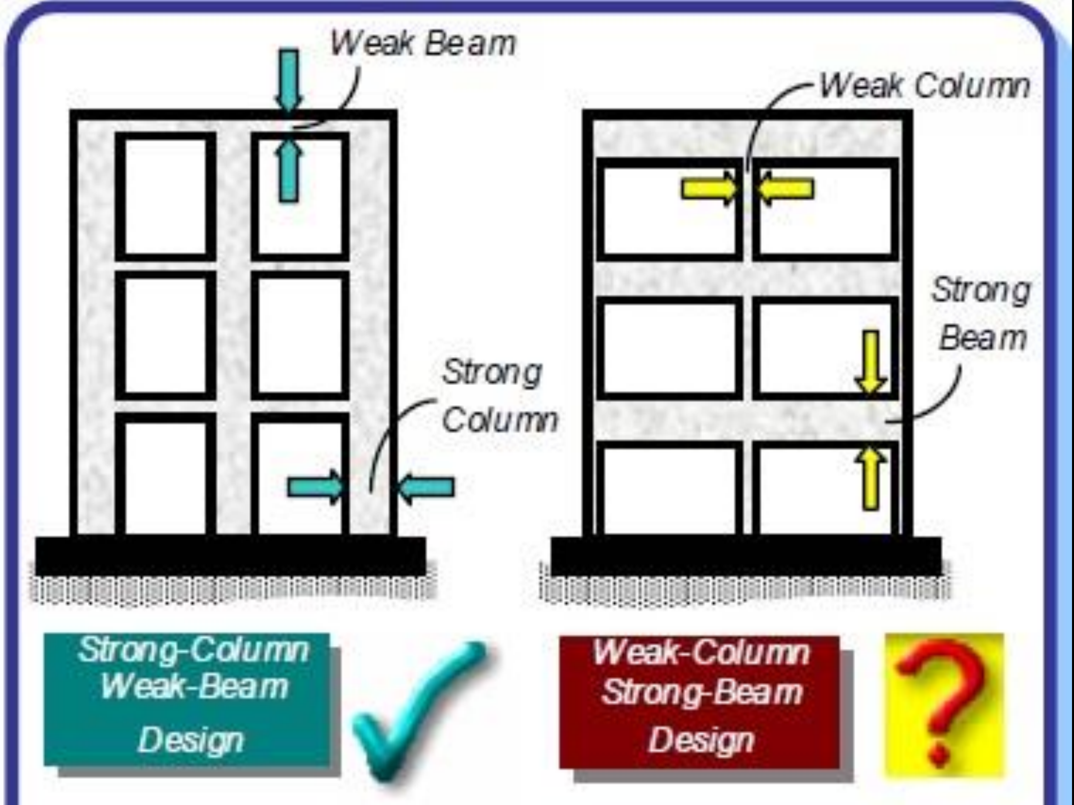
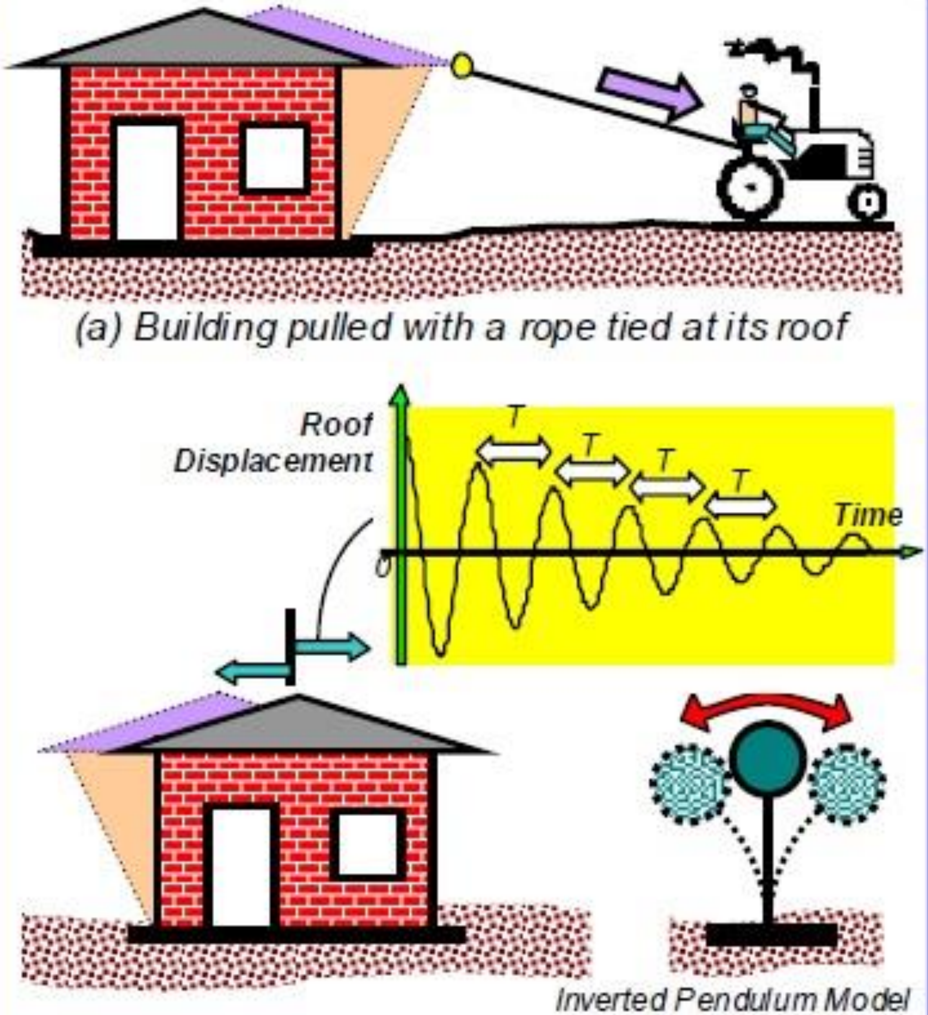


Figure 4: Reinforced Concrete Building Design: *the beams must be the weakest links and not the columns – this can be achieved by appropriately sizing the members and providing correct amount of steel reinforcement in them.*



(a) Building pulled with a rope tied at its roof

(b) Oscillation of building on cutting the rope

Figure 1: Free vibration response of a building: *the back-and-forth motion is periodic.*

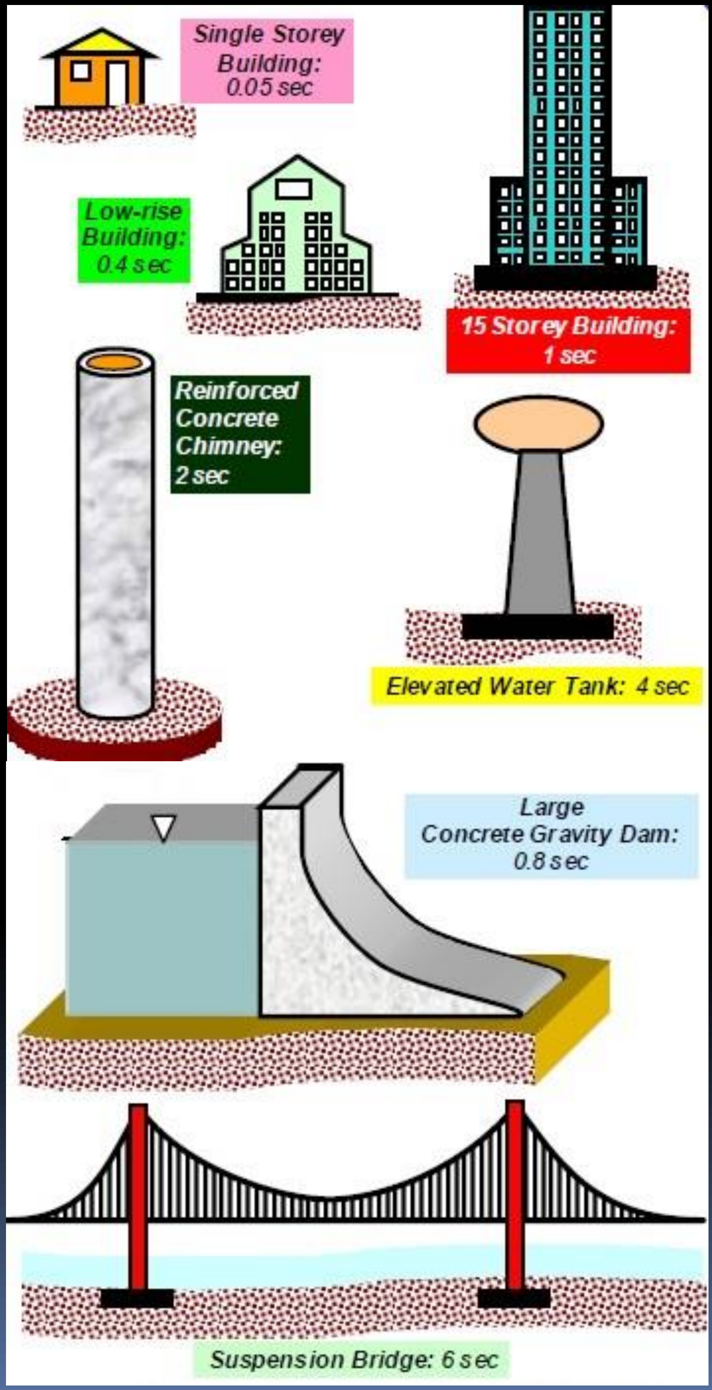
- Take a fat coir rope and tie one end of it to the roof of a building and its other end to a motorized vehicle (tractor).

- Next, start the tractor and pull the building; it will move in the direction of pull For the same amount of pull force, the movement is larger for a more flexible building.

- Now, cut the rope! The building will oscillate back-and-forth horizontally and after some time come back to the original position; these oscillations are periodic.

- The time taken **(in seconds)** for each complete cycle of oscillation **(i.e.,** one complete **back-and-forth** motion) is the same and is called **Fundamental Natural Period T** of the building. Value of **T** depends on the building flexibility and mass; more the flexibility, the longer is the T, and more the mass, the longer is the **T.**

- In general, taller buildings are more flexible and have larger mass, and therefore have a longer T.
- On the contrary, low- to medium-rise buildings generally have shorter T (less than 0.4 sec).
- Fundamental natural period T is an inherent property of a building.
- Any alterations made to the building will change its T.
- Fundamental natural periods **T** of normal single Storey to **20** Storey buildings are usually in the range **0.05-2.00 sec.**
- Some examples of natural periods of different structures are shown in Figure.



IMPORTANCE OF FLEXIBILITY IN BUILDING

- The ground shaking during an earthquake contains a mixture of many sinusoidal waves of different frequencies, ranging from short to long periods .
- The time taken by the wave to complete one cycle of motion is called **period of the earthquake wave.**
- In general, earthquake shaking of the ground has waves whose periods vary in the range **0.03-33sec.**

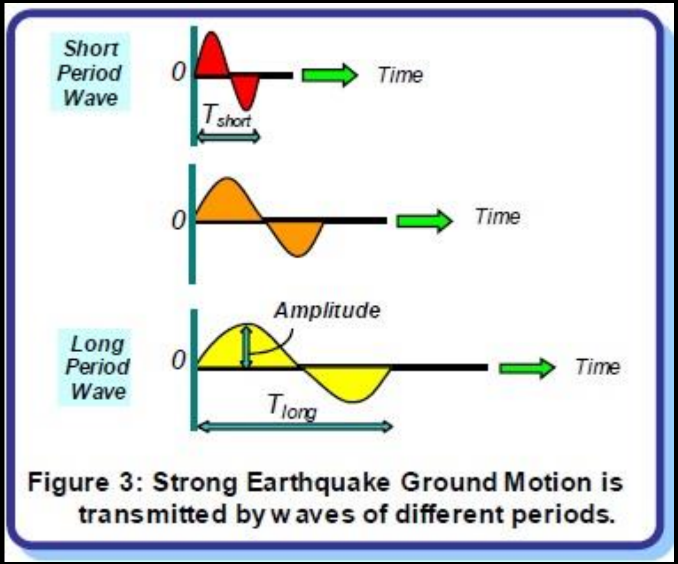


Figure 3: Strong Earthquake Ground Motion is transmitted by waves of different periods.

- Even within this range, some earthquake waves are stronger than the others.
- Intensity of earthquake waves at a particular building location depends on a number of factors, including the **magnitude** of the earthquake, the **epicentral distance,** and the type of ground that the earthquake waves travelled through before reaching the location of interest.

- In a typical city, there are buildings of many different sizes and shapes.

- One way of categorizing them is by their **fundamental natural period T.** The ground motion under these buildings varies across the city.

- If the ground is shaken back-and-forth by earthquake waves that have short periods, then **short period buildings** will have large response.

- Similarly, if the earthquake ground motion has long period waves, then **long period buildings** will have larger response.

- Thus, depending on the value of T of the buildings and on the characteristics of earthquake ground motion (i.e., the periods and amplitude of the earthquake waves), some buildings will be shaken more than the others.

- Flexible buildings undergo larger relative horizontal displacements, which may result in damage to various nonstructural building components and the contents.

- For example, some items in buildings, like glass windows, cannot take large lateral movements, and are therefore damaged severely or crushed.
- Unsecured shelves might topple, especially at upper stories of multi-storied buildings.
- These damages may not affect safety of buildings, but may cause economic losses, injuries and panic among its residents.

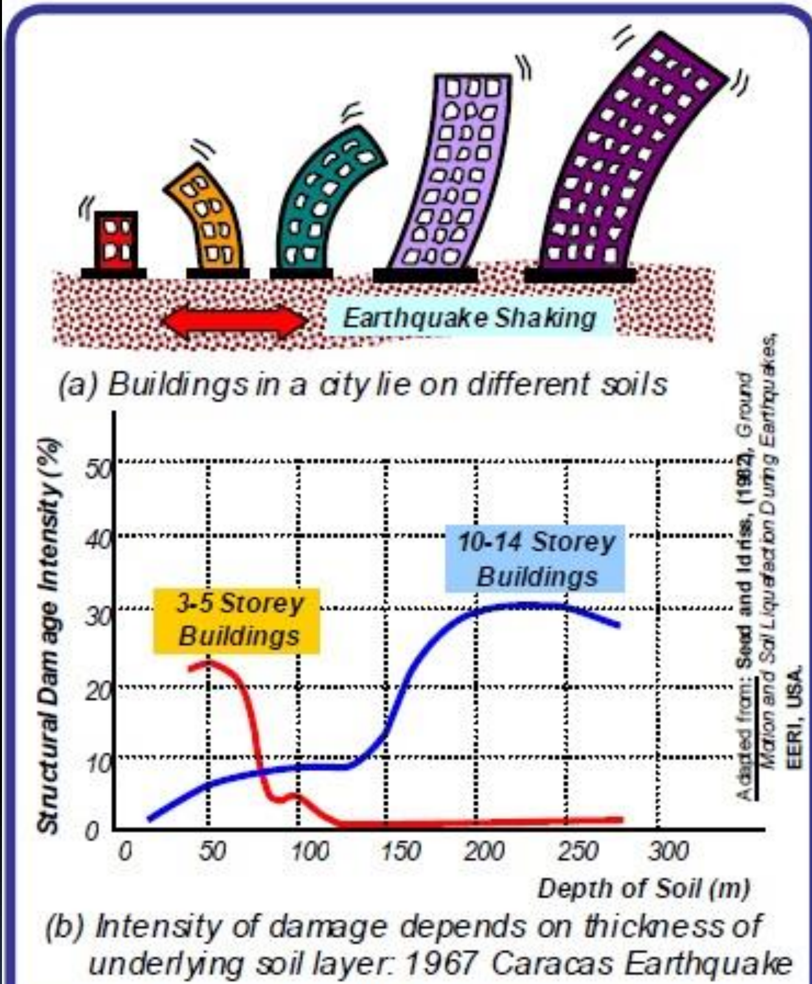


Figure 4: Different Buildings Respond Differently to Same Ground Vibration.

FOUR VIRTUES OF EARTHQUAKE RESISTANT STRUCTURE

- For a building to perform satisfactorily during earthquakes, it must meet the philosophy of *earthquake-resistant* design.

Characteristics of Buildings

- There are four aspects of buildings that architects and design engineers work with to create the earthquake-resistant design of a building, namely ***seismic structural configuration, lateral stiffness, lateral strength*** **and *ductility*.**
- In addition to other aspects like form, aesthetics, functionality and comfort of building.
- Lateral stiffness, lateral strength and ductility of buildings can be ensured by strictly following most seismic design codes.
- But, good seismic structural configuration can be ensured by following coherent architectural features that result in good structural behaviour.

Seismic Structural Configuration

- *Seismic structural configuration* entails three main aspects, namely (a) geometry, shape and size of the building, (b) location and size of structural elements, and (c) location and size of significant non-structural elements.

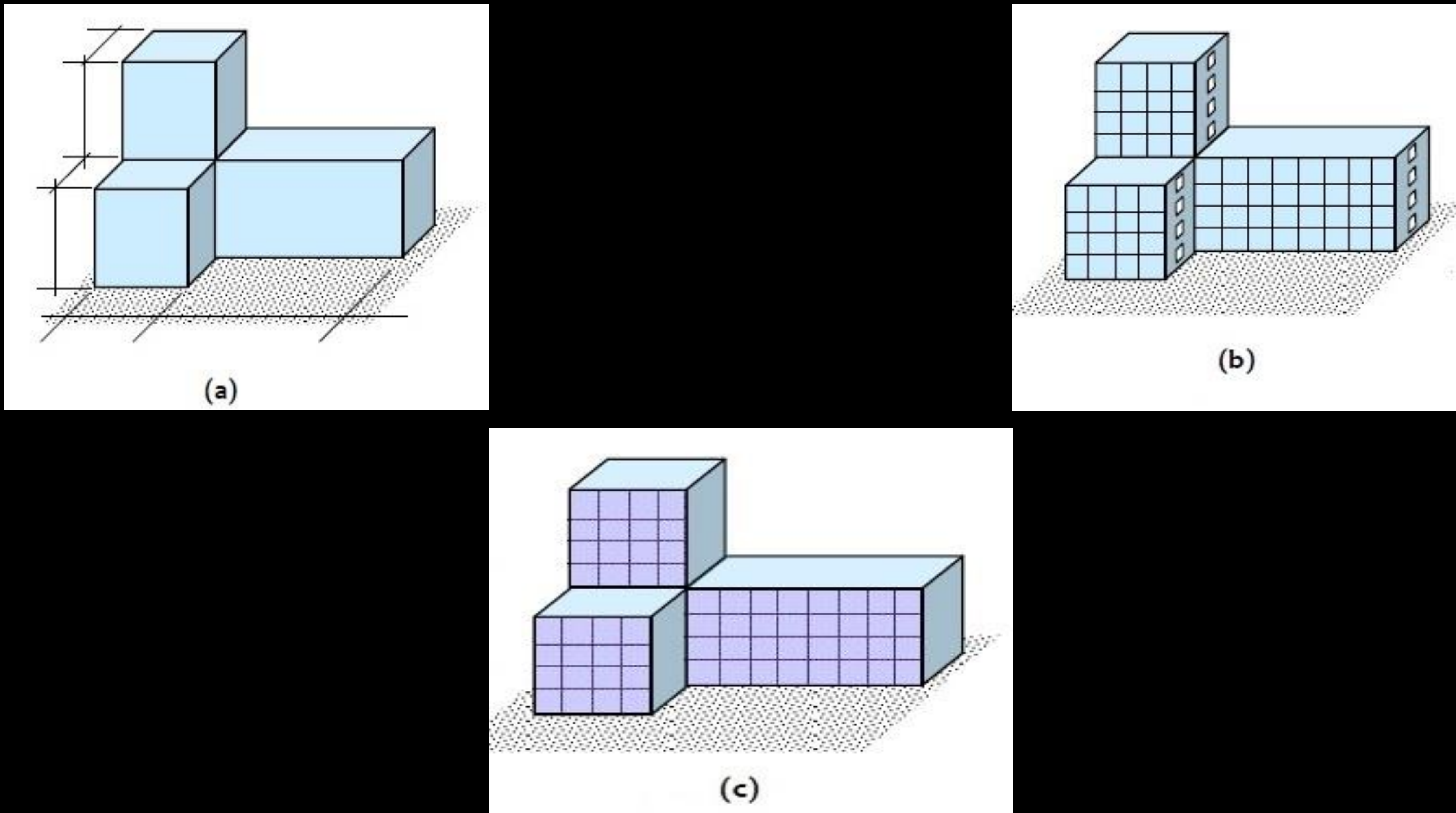
- Influence of the geometry of a building on its earthquake performance is best understood from the **basic geometries of *convex* and *concave* lenses from school-day physics class**.

- The line joining any two points within area of the convex lens, lies completely within the lens.

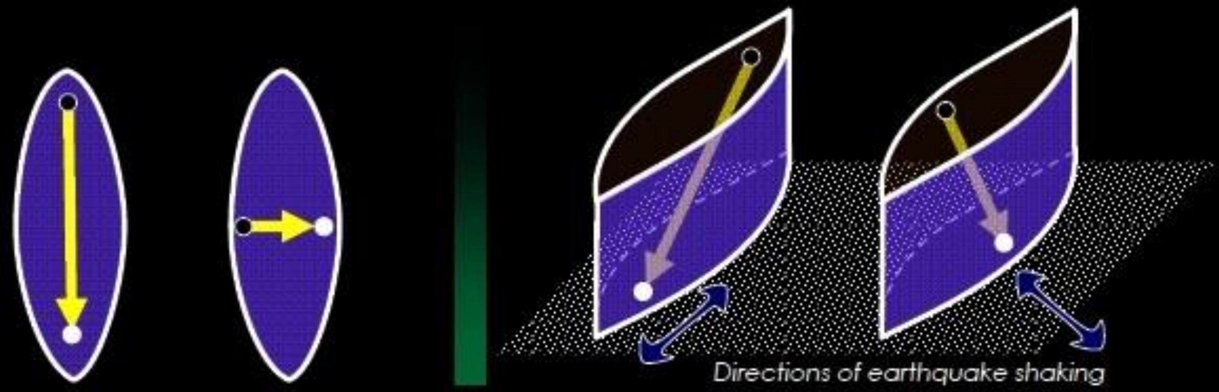
- But, the same is **not true for the concave lens**; a part of the line may lie outside the area of the concave lens.

- **Structures with *convex* geometries are preferred to those with concave geometries**, as the former demonstrate superior earthquake performance.

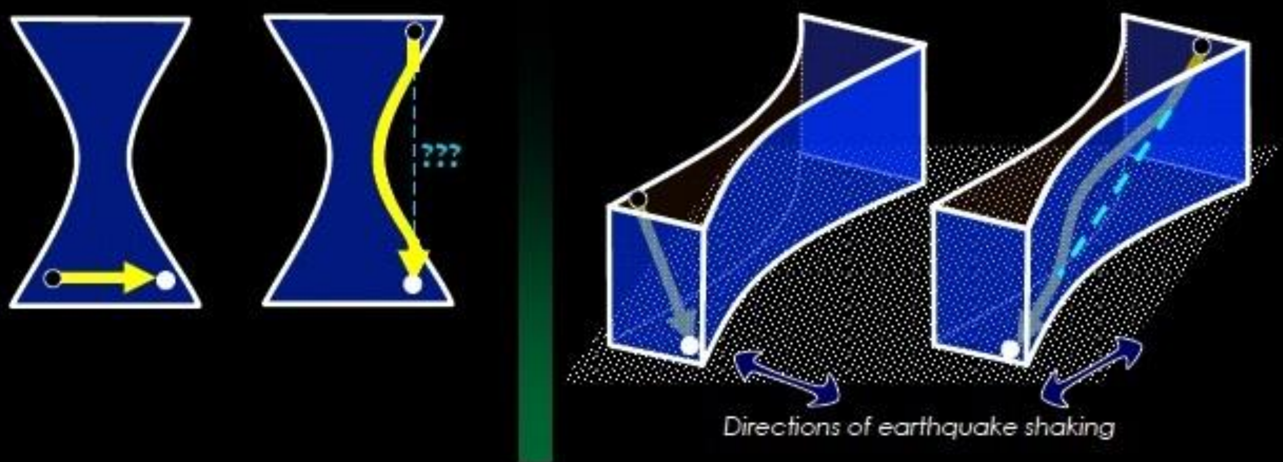
- In the context of buildings, convex shaped buildings have direct load paths for transferring earthquake shaking induced inertia forces to their bases for any direction of ground shaking, while **concave buildings necessitate bending of load paths for shaking of the ground along certain directions that result in stress concentrations at all points where the load paths bend.**



Components of seismic structural configuration:
(a) overall geometry, (b) structural elements (*e.g.*, moment resisting frames and structural walls), and (c) significant non-structural elements (*e.g.*, façade glass)



(a)



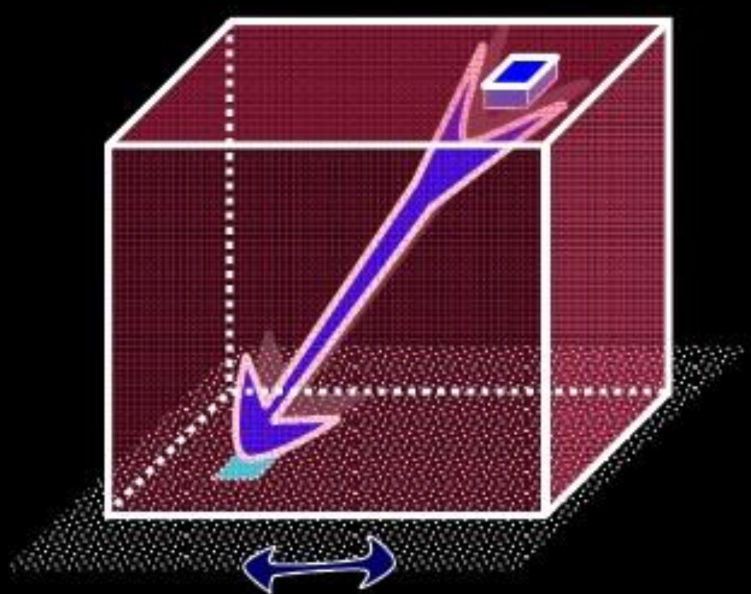
(b)

***Basic forms of seismic structural configuration*: Two geometries of architectural forms (a)convex and (b) concave**

- Based on the above discussion, normally built buildings can be placed in two categories, namely ***simple and complex***.

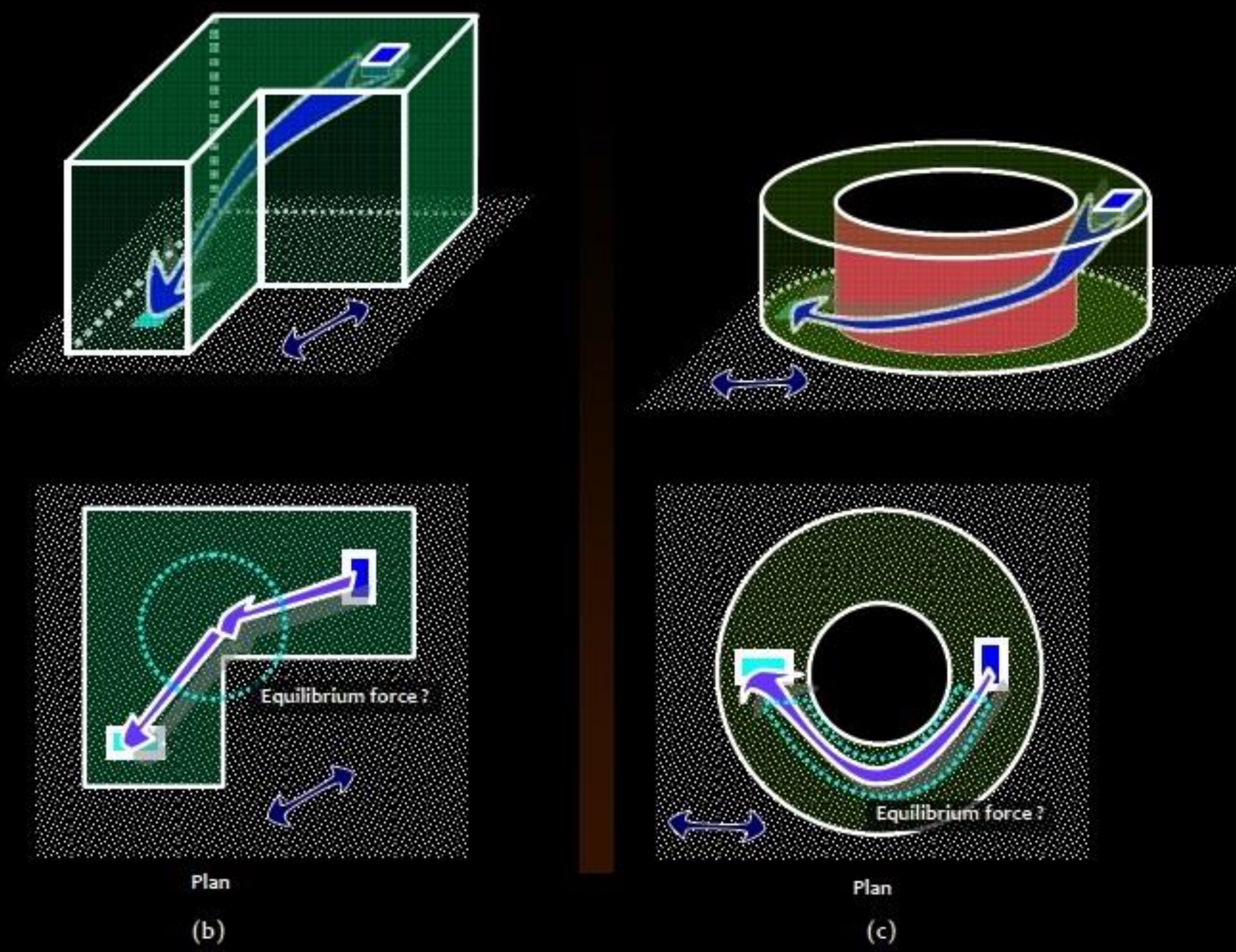
- Buildings with rectangular plans and straight elevation stand the best chance of doing well during an earthquake, **because inertia forces are transferred without having to bend due to the geometry of the building.**

- But, **buildings with setbacks and central openings** offer geometric constraint to the flow of inertia forces; these **inertia force paths have to bend before reaching the ground.**



(a)

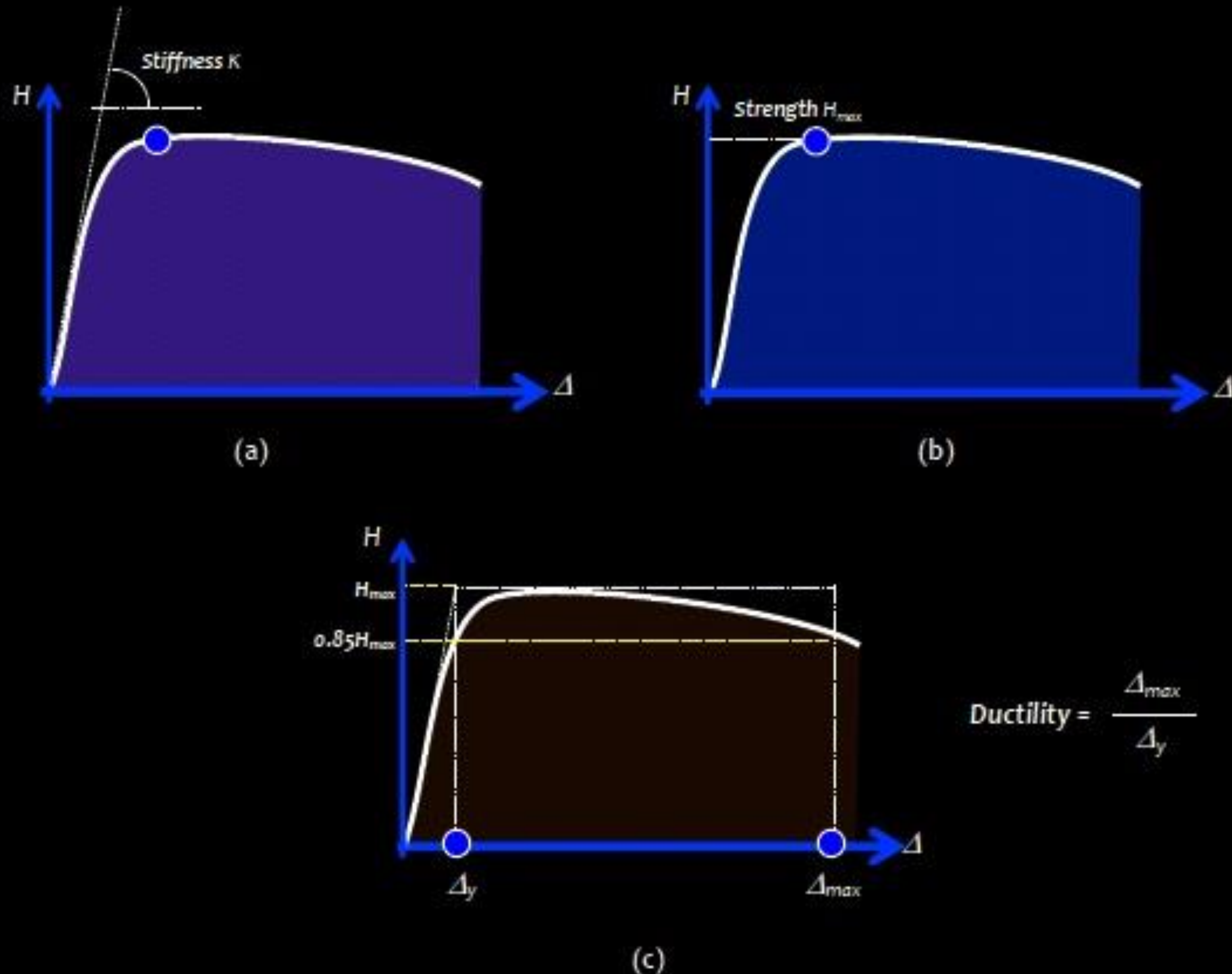
Simple Building



(b) And (c) Complex Buildings

Structural Stiffness, Strength and Ductility

- The next three overall properties of a building, namely *lateral stiffness*, *lateral strength* and *ductility*, are illustrated using ***lateral load – lateral deformation* curve of the building.**
- ***Lateral stiffness*** refers to the ***initial* stiffness of the building**, even though stiffness of the building reduces with increasing damage.
- ***Lateral strength*** refers to the **maximum resistance** that the building offers during its entire history of resistance to relative deformation.
- ***Ductility*** towards lateral deformation refers the **ratio of the maximum deformation and the idealised yield deformation.**
- **The maximum deformation** corresponds to the **maximum deformation sustained by it, if the load-deformation curve does not drop** and **to 85% of the ultimate load on the dropping side of the load-deformation response curve after the peak strength or the lateral strength is reached, if the load-deformation curve does drop after reaching peak strength.**



Structural Characteristics: Overall load deformation curves of a building, indicating (a) lateral stiffness, (b) lateral strength, and (c) ductility towards lateral deformation

What are the Four Virtues?

- All buildings are vertical cantilevers projecting out from the earth's surface. Hence, when the *earth shakes*, these cantilevers experience whiplash effects, especially when the shaking is violent.
- Hence, special care is required to protect them from this jerky movement. Buildings intended to be earthquake-resistant have competing demands.
- Firstly, **buildings become expensive, if designed not to sustain any damage during strong earthquake shaking.**
- Secondly, **they should be strong enough to not sustain any damage during weak earthquake shaking.**
- Thirdly, **they should be stiff enough to not swing too much, even during weak earthquakes.**
- And fourthly, **they should not collapse during the expected strong earthquake shaking to be sustained by them even with significant structural damage.**

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These competing demands are accommodated in buildings intended to be *earthquake resistant* by incorporating four *desirable* characteristics in them. These characteristics, called the *four virtues of earthquake-resistant buildings*, are:

1. **Good *seismic configuration***, with no choices of architectural form of the building that is detrimental to good earthquake performance and that does not introduce newer complexities in the building behaviour than what the earthquake is already imposing;

2. **At least a minimum *lateral stiffness*** in each of its plan directions (uniformly distributed in both plan directions of the building), so that there is no discomfort to occupants of the building and no damage to contents of the building;

3. **At least a minimum *lateral strength*** in each of its plan directions (uniformly distributed in both plan directions of the building), to resist low intensity ground shaking with no damage, and not too strong to keep the cost of construction in check, along with a minimum *vertical strength* to be able to continue to support the gravity load and thereby prevent collapse under strong earthquake shaking; and

4. **Good overall *ductility*** in it to accommodate the imposed lateral deformation between the base and the roof of the building, along with the desired mechanism of behaviour at ultimate stage. Behaviour of buildings during earthquakes depend critically on these four virtues. Even if any one of these is not ensured, the performance of the building is expected to be poor.

Who Controls the Four Virtues?

- Henry Degenkolb, a noted earthquake engineer of USA, aptly summarized the immense importance of seismic configuration in his words: ***"If we have a poor configuration to start with, all the engineer can do is to provide a band-aid - improve a basically poor solution as best as he can. Conversely, if we start-off with a good configuration and reasonable framing system, even a poor engineer can't harm its ultimate performance too much."***

- Likewise, Nathan M. Newmark and Emilo Rosenbleuth, eminent Professors of Earthquake Engineering in USA and Mexico, respectively, batted for the concepts of earthquake-resistant design in their foreword to their book: ***"If a civil engineer is to acquire fruitful experience in a brief span of time, expose him to the concepts of earthquake engineering, no matter if he is later not to work in earthquake country."***

- In many countries, like India, in the design of a *new building*, **the *architect* is the team leader, and the engineer a team member.**

- **And, in the design of *retrofit of an existing building*, the *engineer* is the team leader, and the architect a team member.**

- **What is actually needed is that both the architect and the engineer work *together* to create the best design with good interaction at all stages of the process of the design of the building.**

- Here, the architect brings in perspectives related to *form*, *functionality*, *aesthetics* and *contents*, while the engineer brings the perspectives of *safety* and *desired earthquake performance* during an expected earthquake.

- **There is a two way influence of the said parameters handled both by the architect and by the engineer; their work has to be in unison.**

How to Achieve the Four Virtues?

- The four virtues are achieved by inputs provided at all stages of the development of the building, namely in its ***planning***, ***design***, ***construction*** **and** ***maintenance*****.**
- **Each building to be built is only one of the kind ever, and no research and testing is performed on that building, unlike factory made products like aircrafts, ships and cars.**
- The owner of the building *trusts* the professionals (*i.e.*, architect and engineer) **to have done due diligence to design and construct the building.**
- Thus, **professional experience** is essential to be able to conduct a safe design of the building, because it affects the safety of persons and property.
- Traditionally, in countries that have advanced earthquake safety initiatives, **governments have played critical role through the enforcement of techno-legal regime, wherein the municipal authorities arrange to examine, if all requisite technical inputs have been met with to ensure safety in the building, before allowing the building to be built, the construction to be continued at different stages, or the users to occupy the building.**
- **These stages are: (1) conceptual design stage, (2) design development stage through peer review of the structural design, (3) construction stage through quality control and quality assurance procedures put in place.**