University of Engineering and Technology Peshawar, Pakistan

CE-409: Introduction to Structural Dynamics and Earthquake Engineering

MODULE 2:

FUNDAMENTAL PRINCIPLES OF EARTHQUAKE RESISTANT DESIGN PLANNING & CONSTRUCTION

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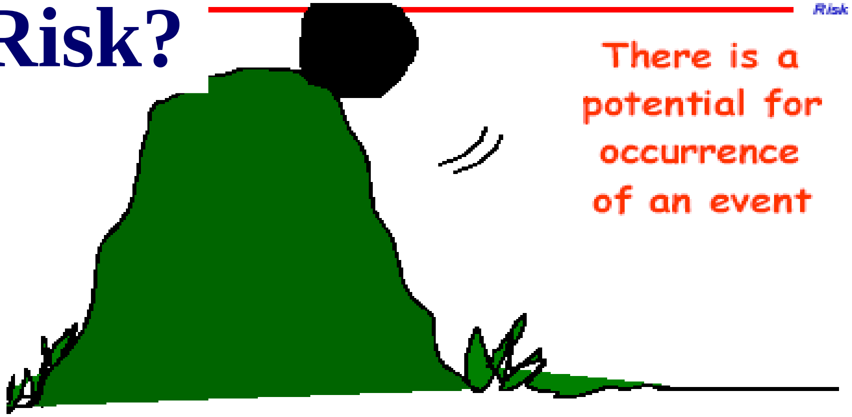
What is Risk ?

Risk?



HAZARD is any substance, phenomenon or situation, which has the potential to cause disruption or damage to people,their property, thei services and their environment

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Vulnerability is a concept which describes **factors or constraints** of an economic, social, physical or geographic nature, which **reduce the ability to prepare for and cope with the impact of hazards.**

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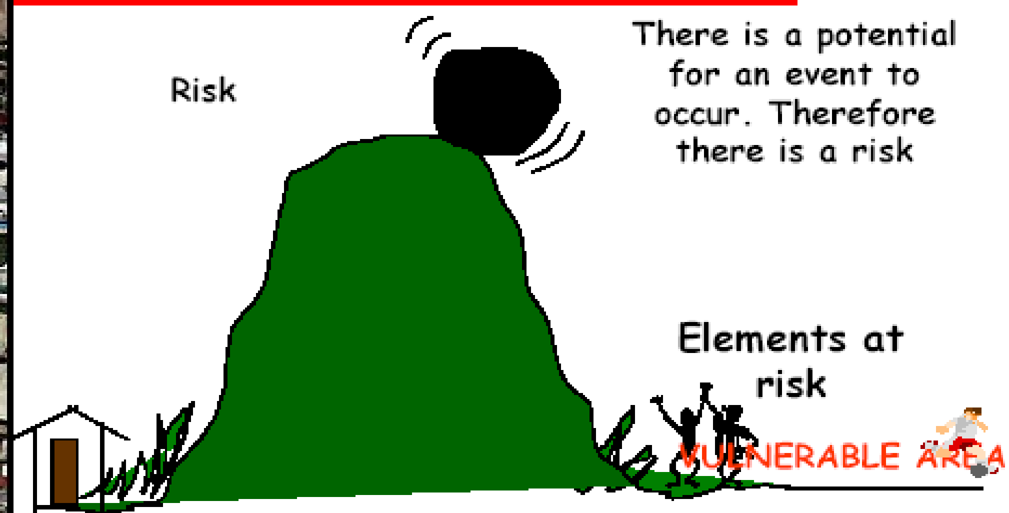
Asian Disaster Preparedness Center

An event causing widespread human or material losses which exceeds the ability of the affected community to cope using its own resources



RISK is the probability that negative consequences may arise when hazards interact with vulnerable areas, people, property, environment.
RISK is a concept which describes a potential set of consequences that may arise from a given set of circumstances.

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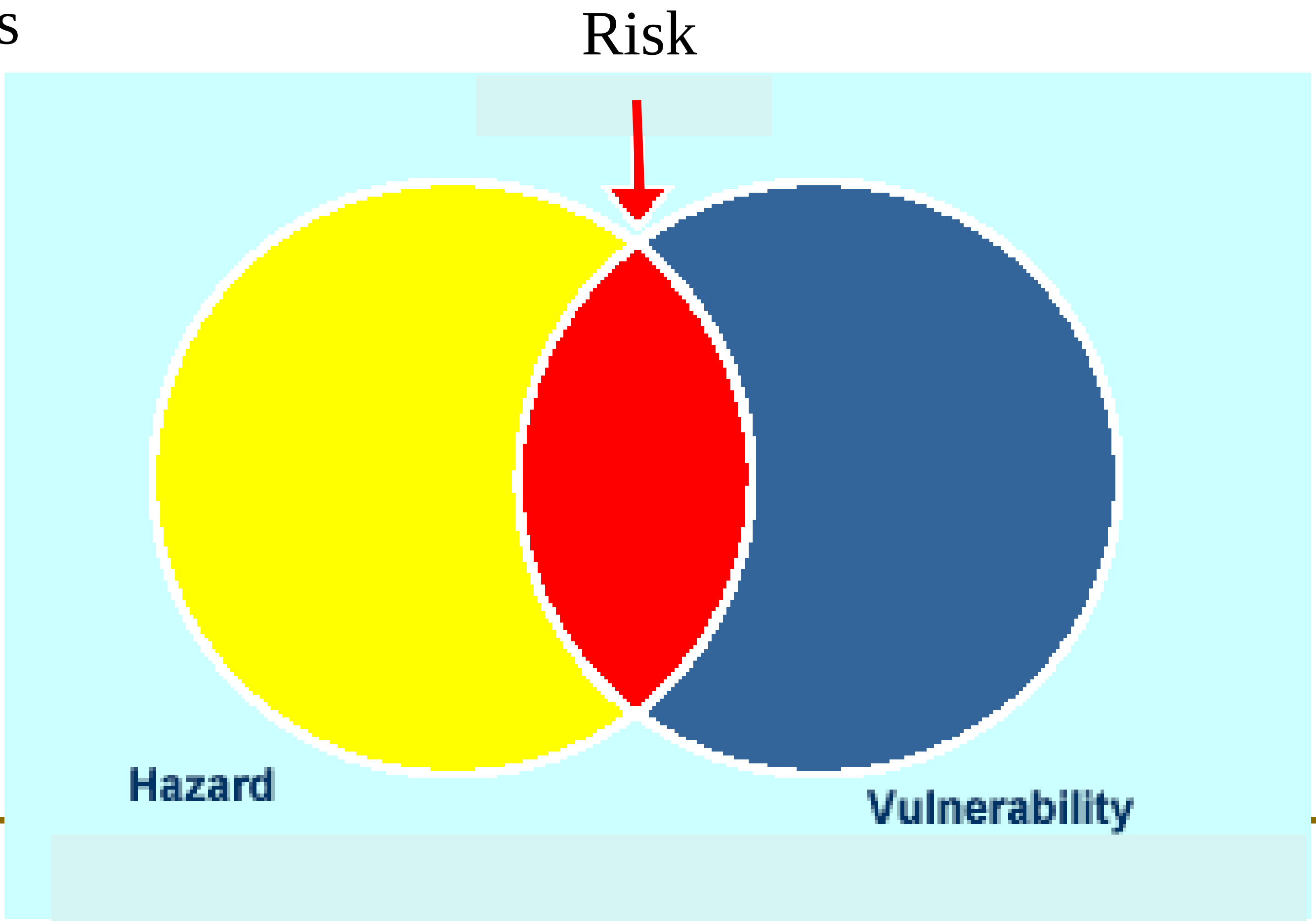
Seismic Risk

- Seismic risk directly depends upon Seismic Hazard, Seismic Vulnerability, and Exposure of elements at risk.

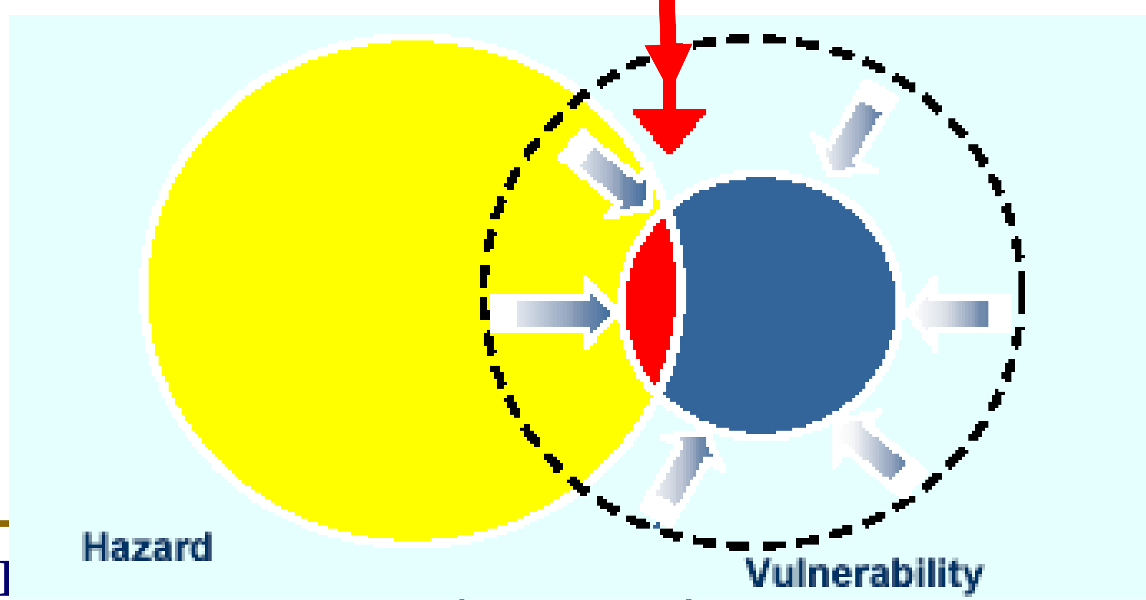
- For the purpose of simplicity we will discuss only first two parameters



Seismic Risk

- **Seismic hazard** depend on the geology of site and, therefore, cannot be controlled.
- **Seismic vulnerability** belong to structures and can ,therefore, be reduced by appropriate design and construction

Seismic Risk can be minimized by reducing seismic vulnerability of structures



The seismic risk keeps increasing

- The current building stock is constantly enlarged by the addition of new buildings, many with significant, or even excessive, earthquake vulnerability. This is above all due to the fact that for new buildings, the basic principles of earthquake resistant design and also the earthquake specifications of the building codes, are often not followed.
- **The reason is either unawareness, convenience or intentional ignorance**
- As a result, the earthquake risk continues to increase unnecessarily.

Urgent Actions Needed

- The preceding remarks clearly illustrate that there is a large deficit in the structural measures for seismic protection in many parts of the world.
- New buildings must be designed to be reasonably earthquake resistant to prevent the constant addition of new vulnerable structures to a building stock that is already seriously threatened.
- Your course " Introduction to Structural dynamics and earthquake Engineering" aims at conveying the fundamental knowledge to the Civil Engineers regarding seismic resistant design and construction of structures

Some of the basic considerations for seismic design

Effect of relative stiffness on lateral forces distribution

- The lateral force is distributed (at a particular story level) in proportion to the relative stiffness of the resisting members.
- The applied forces are "attracted to" and concentrated at the stiffer elements of the building.
- Thus the engineer must calculate the stiffness of the resisting elements to ascertain the forces that they must accommodate.
- If two elements (two frames, walls, braces, or any combination) are forced to deflect the same amount, and if one is stiffer, that one will take more of the load.

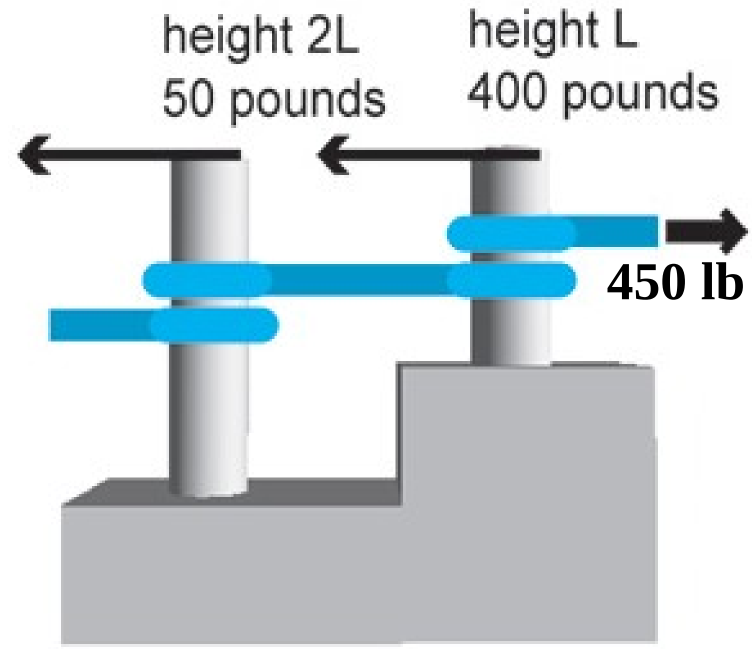
Effect of relative stiffness on forces distribution

- The evaluation of relative rigidities is a necessary part of most seismic analysis problems in order to determine the relative distribution of the total horizontal force to the various resisting elements.
- An important aspect of this concept in relation to column lateral stiffness is illustrated in figure .

Effect of relative stiffness on forces distribution

- In the figure the columns have the same cross-section, but the short column is half the length of the long one.

- Mathematically, the stiffness of a column varies approximately as the cube of its length. Therefore, the short column will be eight times stiffer (2^3) instead of twice as stiff and will be subject to eight times the horizontal load of the long column. Stress is concentrated in the short column, while the long column is subject to nominal forces.



H.Assignment 1 (Module 2). HA1M2

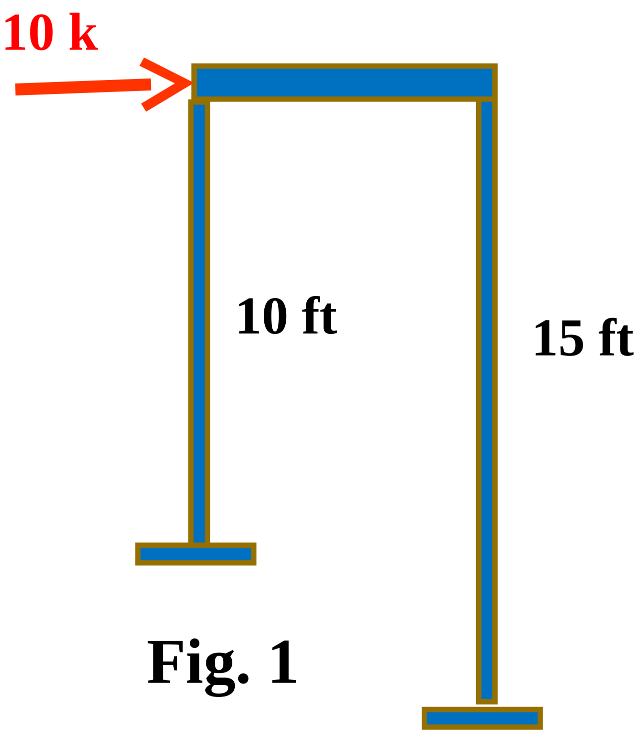


Fig. 1

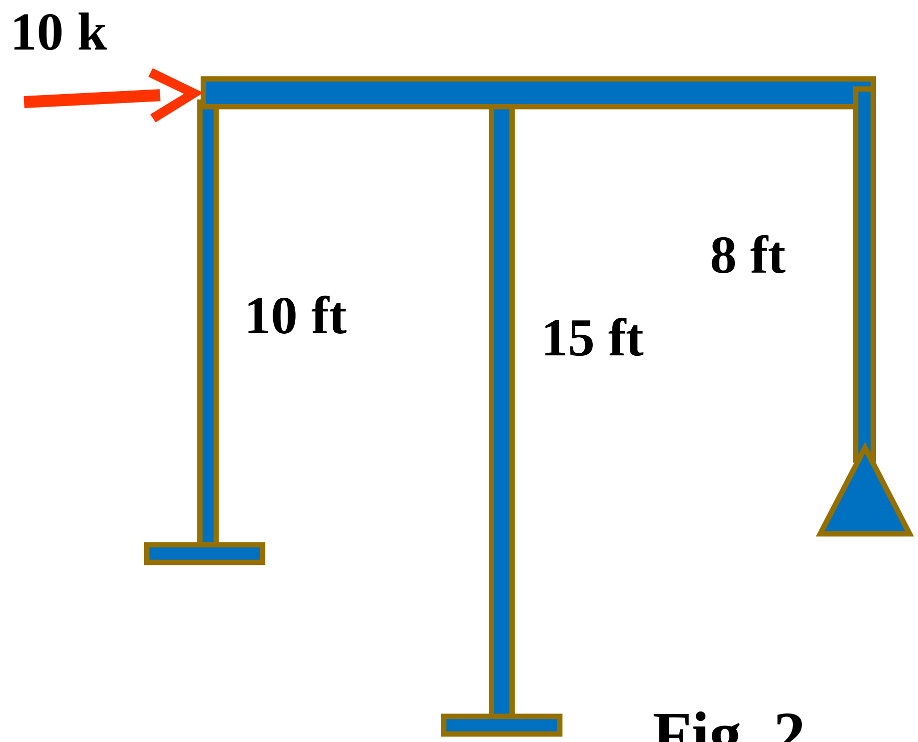


Fig. 2

Draw S.F.D and B.M.D of given frames. Assume:

1. EI= Constant in all cases
2. Beams are infinitely stiff in flexure. i.e. beam-column joints act as fixed supports

H.Assignment 1 (Module 2). HA1M2

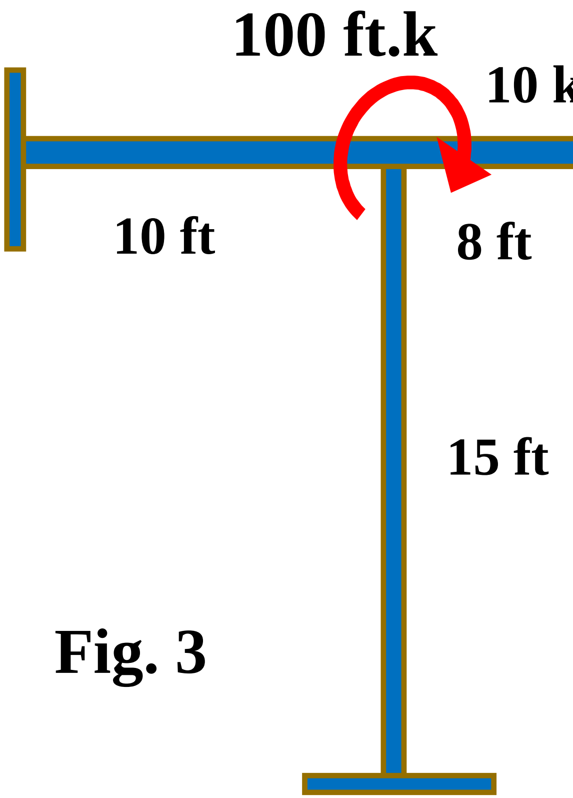


Fig. 3

Calculate Bending Moment at all the supports of given frame.
Assume $\mathbf{(EI)_{column} = (EI)_{beam} / 2}$. where EI for both beams are same

Torsional Forces

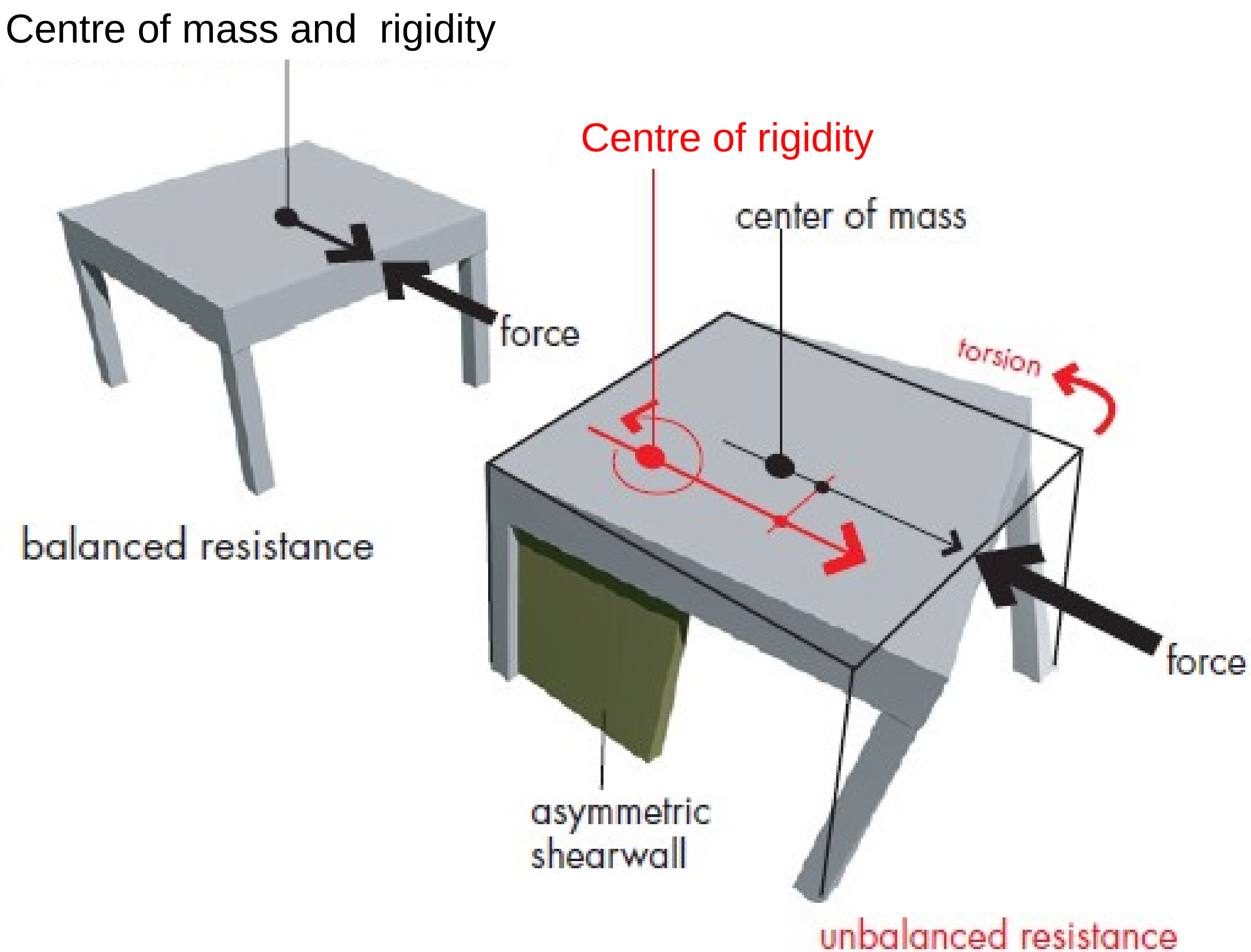
- The **center of mass, or center of gravity**, of an object is the point at which it could be exactly balanced without any rotation resulting.

- If the mass (or weight) of a building is uniformly distributed (in plan), the result is that the plan's **geometric center (centroid)** will coincide with the center of mass.

- In a building, the main lateral force is contributed by the weight of the floors, walls, and roof, and this force is exerted through the **center of mass**, usually the geometric center of the floor (in plan).

- If the mass within a floor is uniformly distributed, then the resultant force of the horizontal acceleration of all its particles is exerted through the floor's geometric center

Torsional Forces



Torsional forces.

Torsional Forces

- Torsional forces are created in a building by a lack of balance between

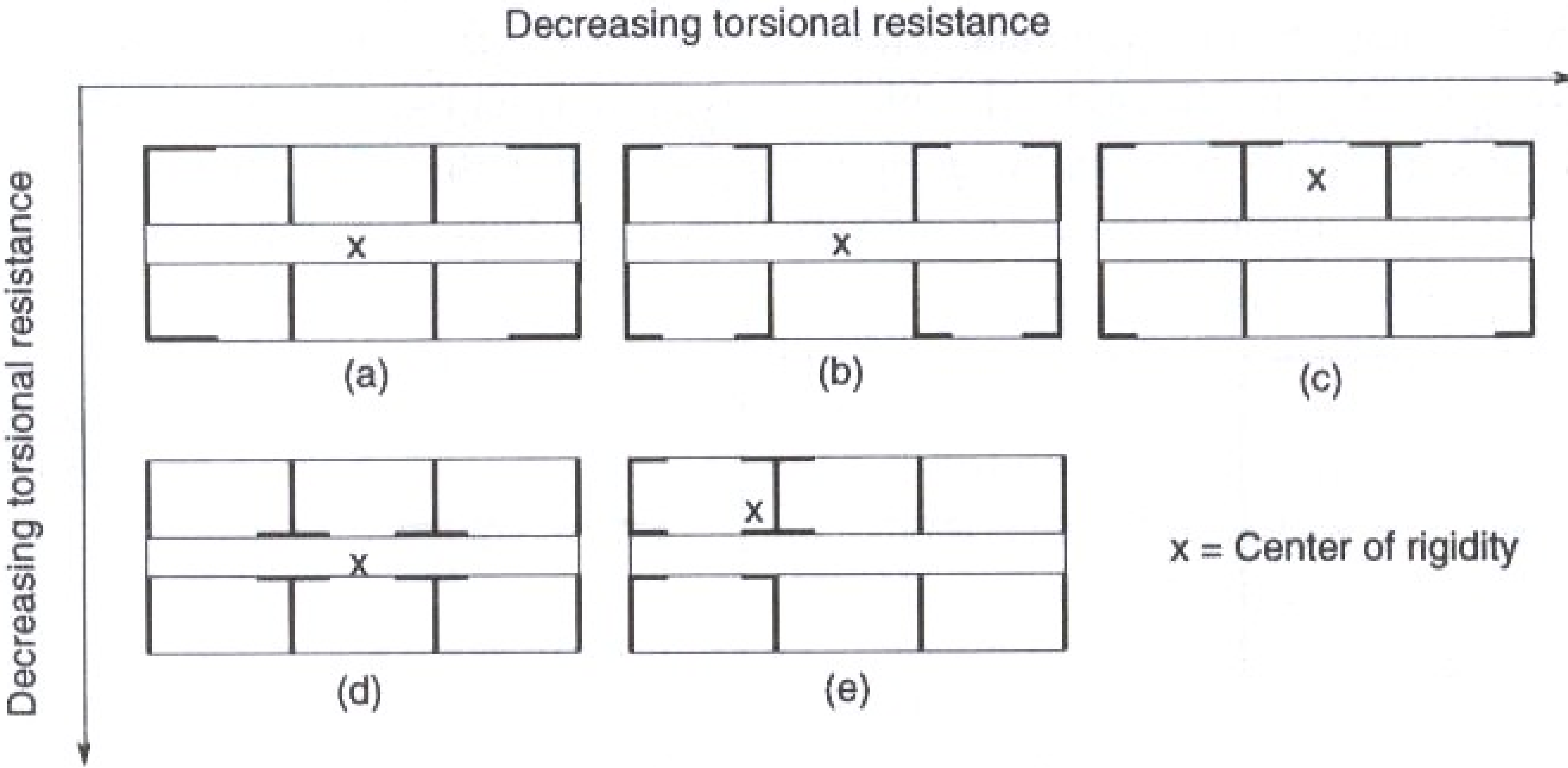
- Engineers refer to this as **eccentricity between the center of mass and the center of rigidity, C.R. (or centre of stiffness),** which makes a building subjected to ground motion rotate around its center of rigidity, creating torsion - a twisting action in plan, which results in undesirable and possibly dangerous concentrations of stress

Torsional Forces

- In a building in which the mass is approximately evenly distributed in plan (typical of a symmetrical building with uniform floor, wall and column masses) the ideal arrangement is that the earthquake resistant elements should be symmetrically placed, in all directions

- In practice, some degree of torsion is always present, and the building code makes provision for this.

Effect of shear walls arrangement on the torsional resistance of buildings



Effect of shear walls arrangement on torsional resistance (*the same total length of longitudinal wall is distributed in a different way for each layout.*

Effect of shear walls arrangement on the torsional resistance of buildings

- Greatest torsional resistance is obtained by concentrating the longitudinal walls at the comers of the building, as in Fig. **a**. The center of rigidity is at the center of the plan (from symmetry) and the longitudinal walls, being placed as distant as possible from this center, produce the greatest torsional resistance.

- Although the position of the centre of rigidity of the symmetrical arrangement in Fig. **b** remains at the center of the plan, the longitudinal walls are not entirely placed at the extremities thus resulting in a reduced torsional resistance

Effect of shear walls arrangement on the torsional resistance of buildings

- Because of lack of symmetry about one axis in Fig. **c**, the center of rigidity will move slightly off centroidal axis and lateral forces will have an increased torsional effect due to this offset of the center of rigidity. Also the distances from the center of rigidity of the flanged sections created with longitudinal walls have been reduced, thus reducing the torsional resistance.

- Although the arrangement of walls in Fig. **d** is symmetrical, the longitudinal walls have been moved close to the center of rigidity and the sections produced have a greatly reduced influence on the torsional resistance of the total arrangement.

Effect of shear walls arrangement on the torsional resistance of buildings

- A very poor arrangement of longitudinal walls is shown in Fig. **e**. Here they are clustered toward one comer, displacing the center of rigidity a large distance from the center of the plan and greatly increasing the torsional effects of the lateral loads. In addition, the longitudinal walls are at a short distance from the center of rigidity and therefore contribute less to the overall torsional resistance.

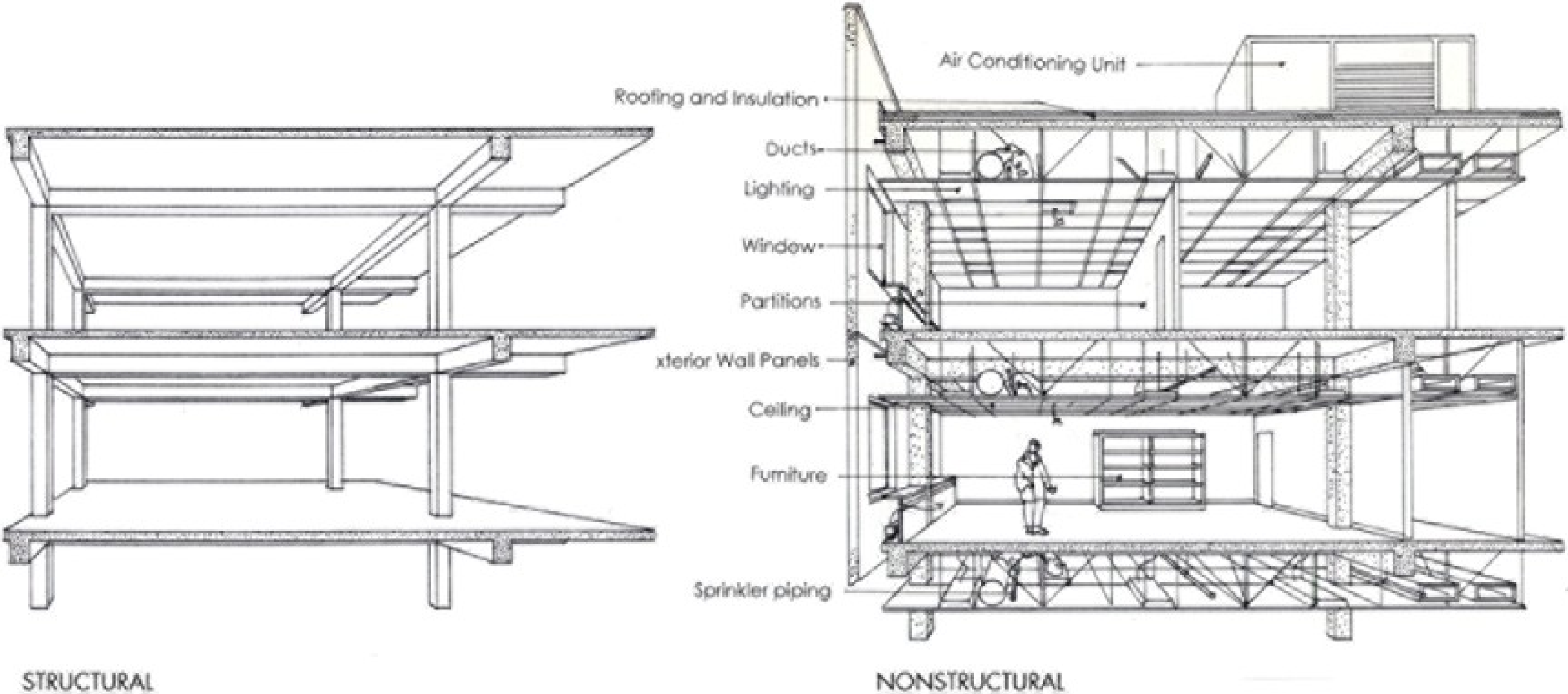
Non structural components

- For many decades, seismic building codes focused exclusively on the structure of the building—that is, the system of columns, beams, walls, and diaphragms that provides resistance against earthquake forces.

- Although this focus remains dominant for obvious reasons, experience in more recent earthquakes has shown that damage to nonstructural components is also of great concern.

- In most modern buildings, the nonstructural components account for 60 to 80 percent of the value of the building (figure on next slide). Most nonstructural components are fragile (compared to the building structure), easily damaged, and costly to repair or replace

Non structural components



Structure (left), nonstructural components and systems (right).

Non structural components

- The nonstructural elements (such as parapet walls, furniture video 1 start at 4:00 , video 2) if not properly anchored can impose serious threat to human lives.

- Collapse of boundary walls and parapet walls were the cause of a significant number of fatalities during 2005 Kashmir earthquake.

- The nonstructural components or systems may modify the structural response in ways detrimental to the safety of the building.

- Examples are the placing of heavy nonstructural partitions in locations that result in severe torsion and stress concentration, or the placement of nonstructural partitions between columns in such a way as to produce a short column condition (video start at 1:00). This can lead to column failure, distortion, and further nonstructural damage.

- Failure of the fire protection system, because of damage to the sprinkler system, may leave the building vulnerable to post-earthquake fires caused by electrical or gas system damage.

Some common mistakes resulting in reduced seismic resistance of structures

Four serious configurations conditions

Four serious configurations conditions

Four configuration conditions (two vertical and two in plan) that originate in the architectural design and that have the potential to seriously impact seismic performance are:

1. Soft and weak stories

2. Discontinuous shear walls

3. Variations in perimeter strength and stiffness

4. Re-entrant corners

Soft and Weak Stories

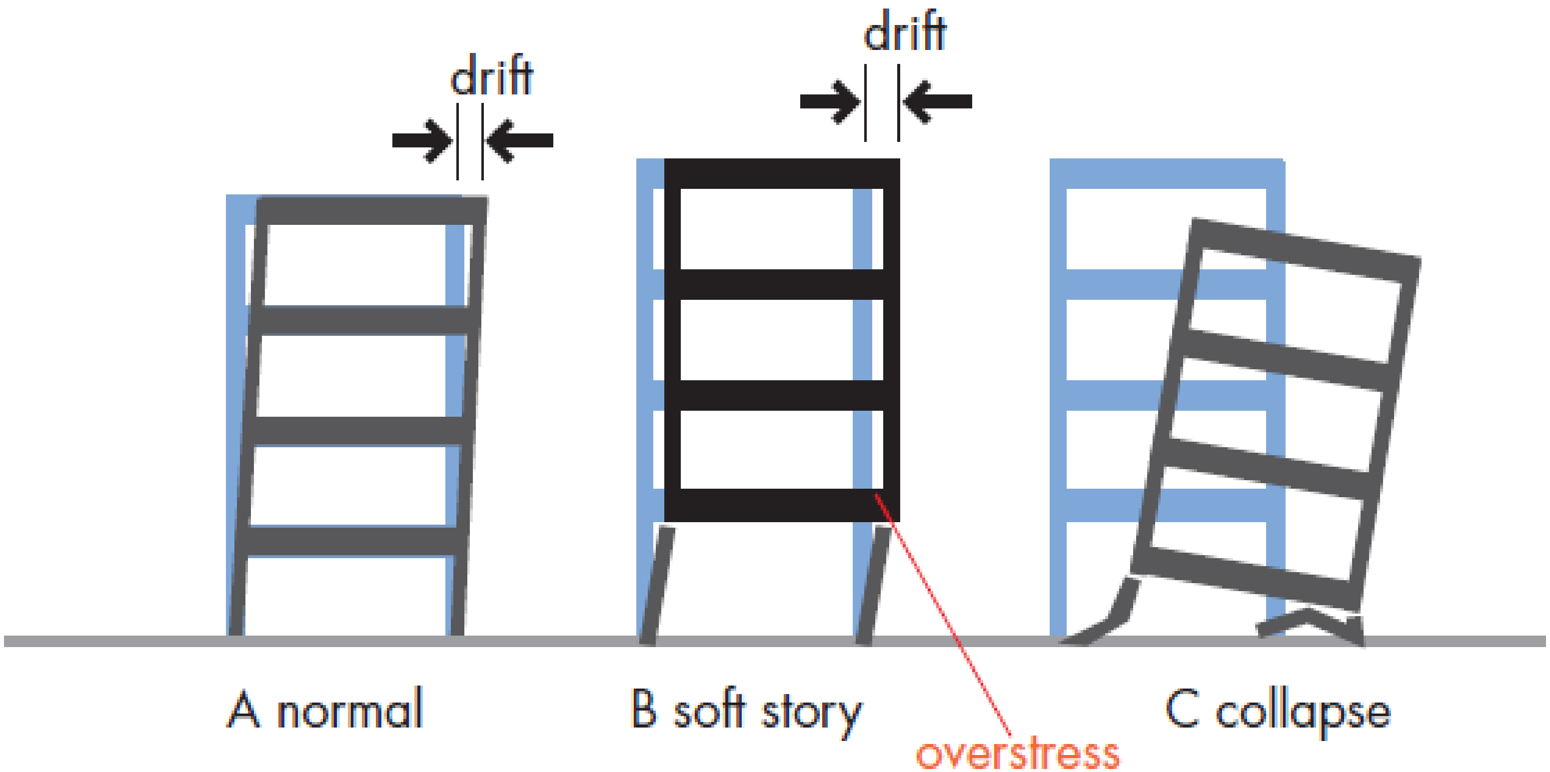
- The most prominent of the problems caused by severe stress concentration is that of the “soft” story. The term has commonly been applied to buildings whose ground-level story is less stiff than those above.

- The building code distinguishes between “soft” and “weak” stories. Soft stories are less stiff, or more flexible, than the story above; weak stories have less strength.

- A soft or weak story at any height creates a problem, but since the cumulative loads are greatest towards the base of the building, a discontinuity between the first and second floor tends to result in the most serious condition .

Soft-storey effect

- The most prominent of the problems caused by severe stress concentration is that of the “soft” story.



The soft first story failure mechanism.

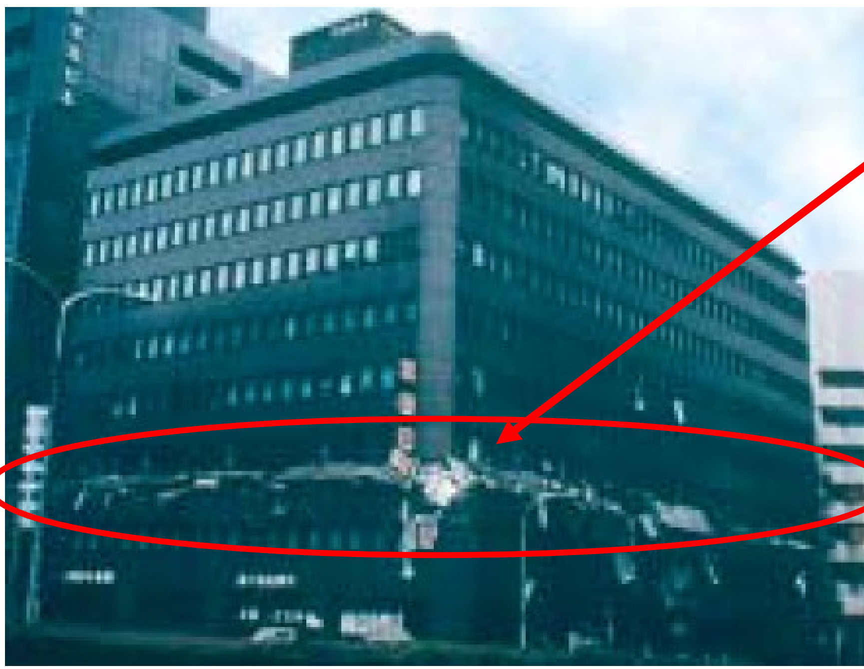
Avoid soft-storey ground floors!

Lower story columns were collapsed in a hotel at Balakot, 2005 Kashmir earthquake

Permanent plastic deformation in the ground floor of a building under construction. Soft story effect almost provoked a collapse (Friaul, Italy 1976).

Avoid soft-storey Upper floors!

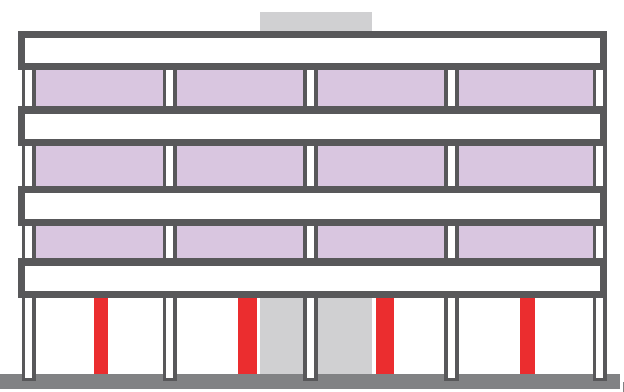
Intermediate story columns are completely collapsed



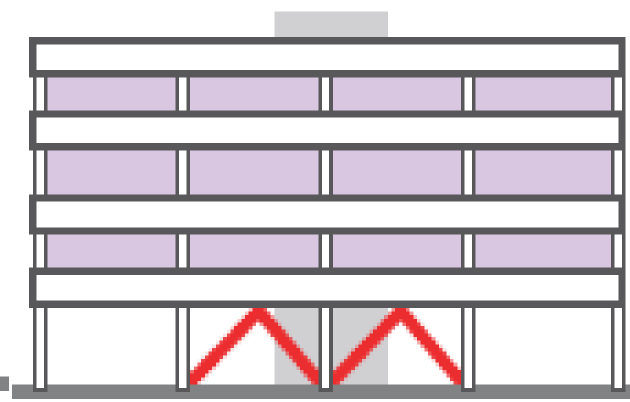
Kobe, Japan 1995.

Bagh, 2005 Kashmir earthquake

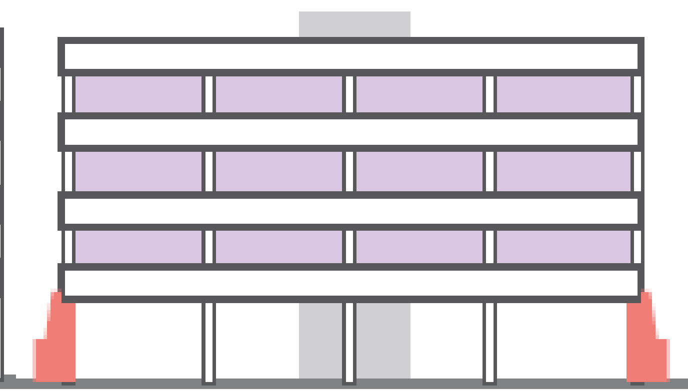
Solutions



Add columns



Add bracing



Add external buttresses

Solutions

Fig A

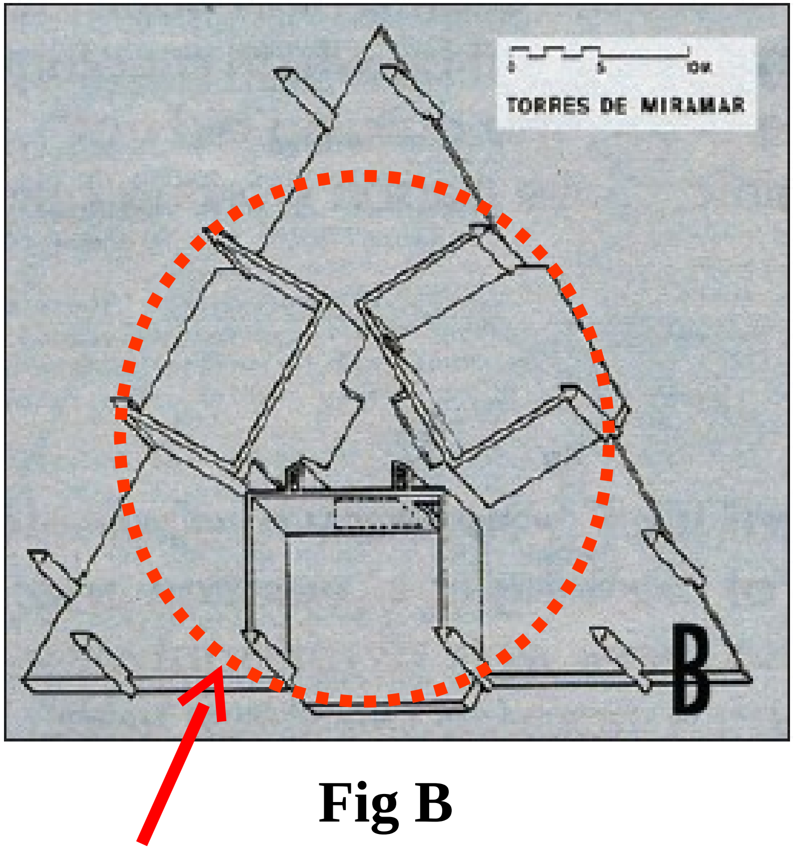


Fig B

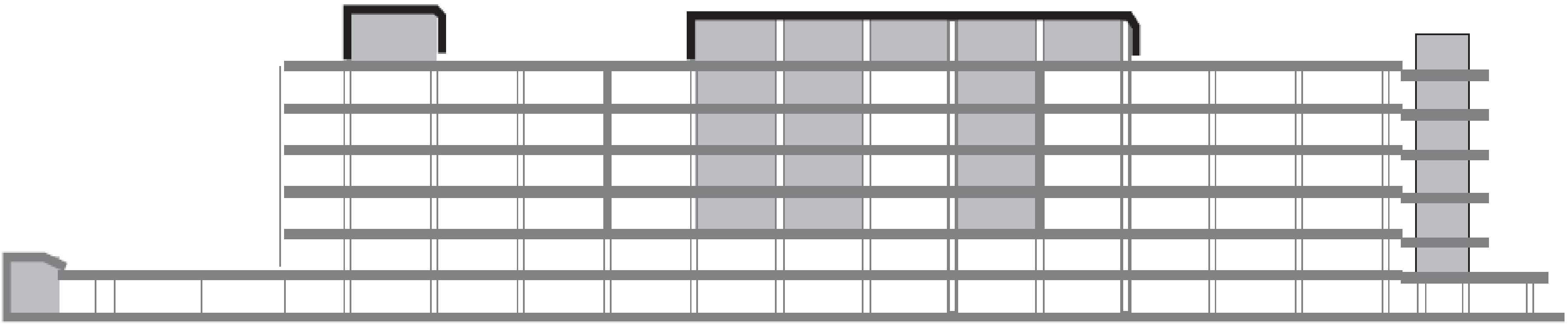
This apartment house appears to have a soft first story (Figure A), but the lateral force-resisting system is a strong internal shear wall box, in which the shear walls act as party walls between the dwelling units (Figure B).

Avoid discontinuous Shear Walls

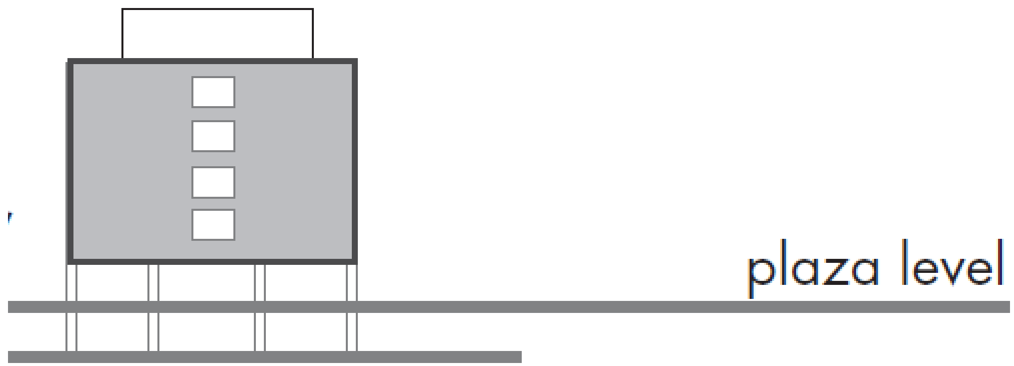
- When shear walls form the main lateral resistant elements of a structure, and there is not a continuous load path through the walls from roof to foundation, the result can be serious overstressing at the points of discontinuity. This discontinuous shear wall condition represents a special, but common, case of the "soft" first-story problem.

- The discontinuous shear wall is a fundamental design contradiction: the purpose of a shear wall is to collect diaphragm loads at each floor and transmit them as directly and efficiently as possible to the foundation. To interrupt this load path is undesirable.

Avoid discontinuous Shear Walls



Long section, Olive View Hospital. Note that the shear walls stop at the third floor.



Cross section, Olive View hospital, showing the second-floor plaza and the discontinuous shear wall.

Avoid discontinuous Shear Walls

Olive View hospital, San Fernando earthquake, 1971, showing the extreme deformation of the columns above the plaza level.

Solutions

- The solution to the problem of the discontinuous shear wall is to eliminate the shear walls.
- If the decision is made to use shear walls, then their presence must be recognized from the beginning of schematic design, and their size and location made the subject of careful architectural and engineering coordination early.

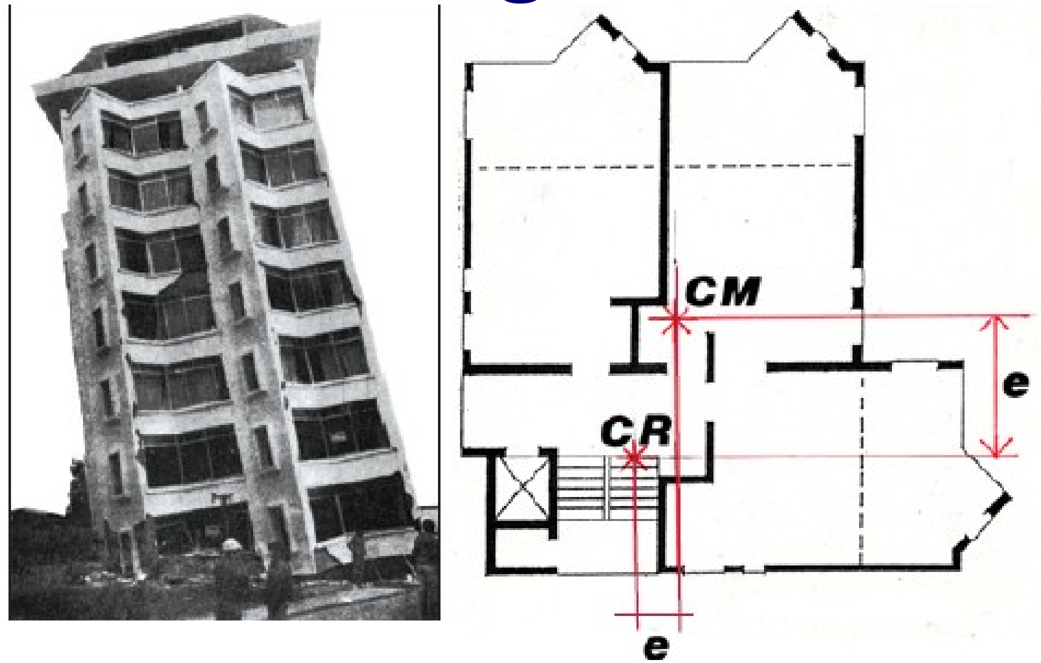
Variations in Perimeter Strength & Stiffness

- This problem may occur in buildings whose configuration is geometrically regular and symmetrical, but nonetheless irregular for seismic design purposes.

- A building's seismic behavior is strongly influenced by the nature of the perimeter design. If there is wide variation in strength and stiffness around the perimeter, the center of mass will not coincide with the center of resistance, and torsional forces will tend to cause the building to rotate around the center of resistance.

Variations in Perimeter Strength & Stiffness

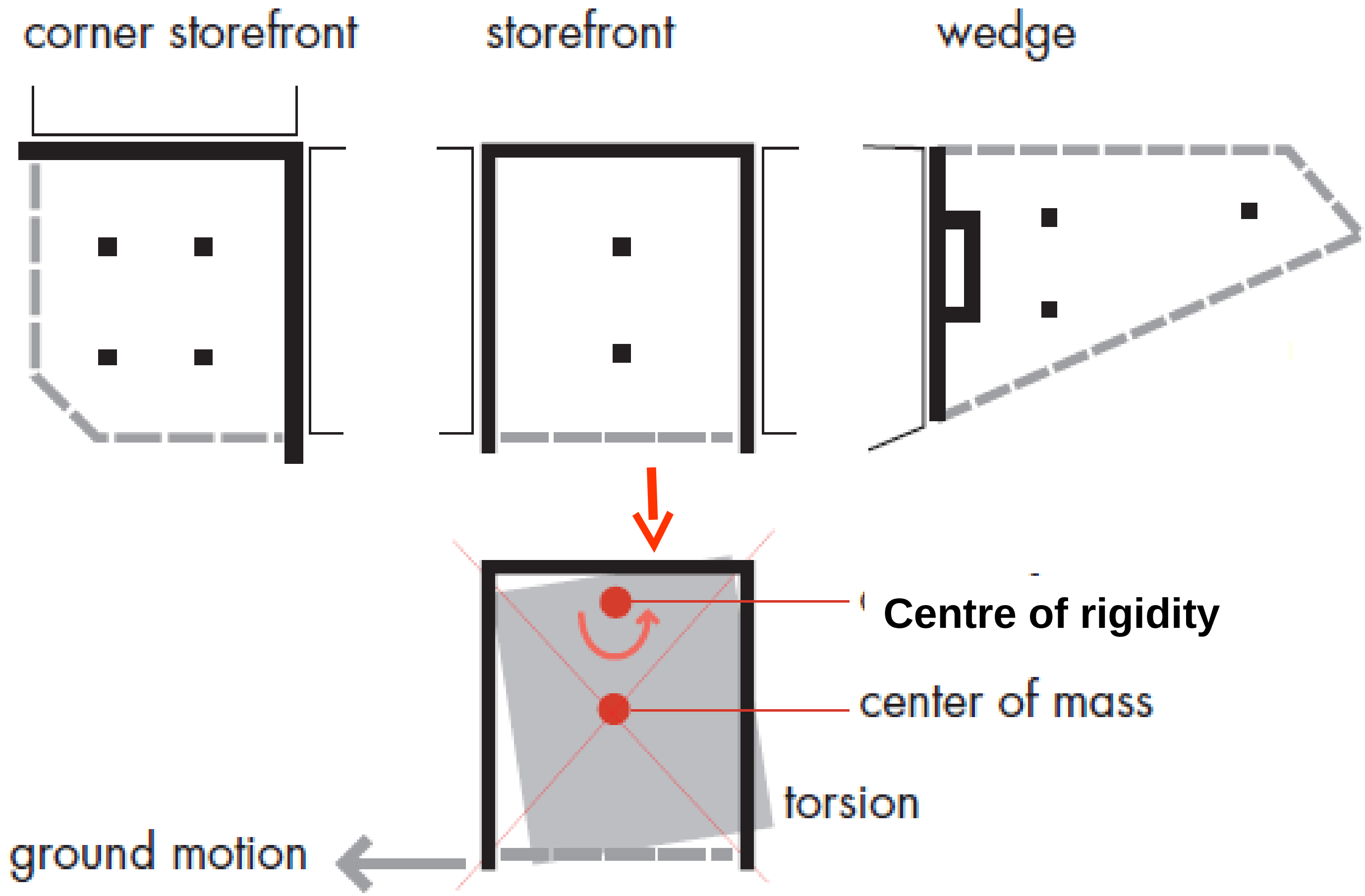
Left, the building after the earthquake. Right, typical floor plan showing the Center of Mass (CM), Center of Resistance (CR), and Eccentricity (e) along the two axes.



The figure shows an apartment house in Viña del Mar, Chile, following the earthquake of 1985. The apartment, designed with open frontage, had only three apartments per floor, with the service areas and elevator concentrated to the rear and surrounded by reinforced concrete walls that provided the seismic resistance. The lack of balance in resistance was such that the building rotated around its center of resistance, tilted sharply, and nearly collapsed. The building was subsequently demolished.

Variations in Perimeter Strength & Stiffness

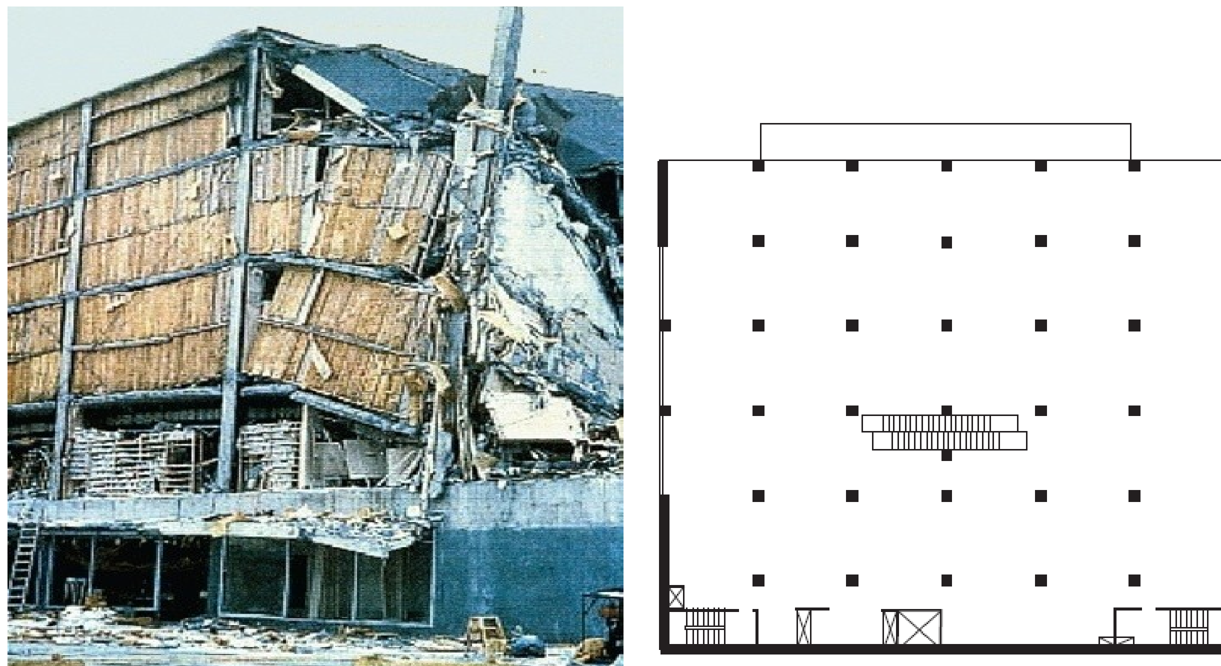
- A common instance of an unbalanced perimeter is that of open-front design in buildings, such as fire stations and motor maintenance shops in which it is necessary to provide large doors for the passage of vehicles.



C Unbalanced perimeter resistance: storefronts and "wedges."

Variations in Perimeter Strength and

- Stores, individually or as a group in a shopping mall, are often designed as boxes with three solid sides and an open glazed front .
- The large imbalance in perimeter strength and stiffness results in large torsional forces. Large buildings, such as department stores, that have unbalanced resistance on a number of floors to provide large window areas for display are also common.



Penney's store, Anchorage, Alaska, earthquake, 1964. Left: Damage to the store: Right: Second-floor plan, showing unbalanced perimeter resistance

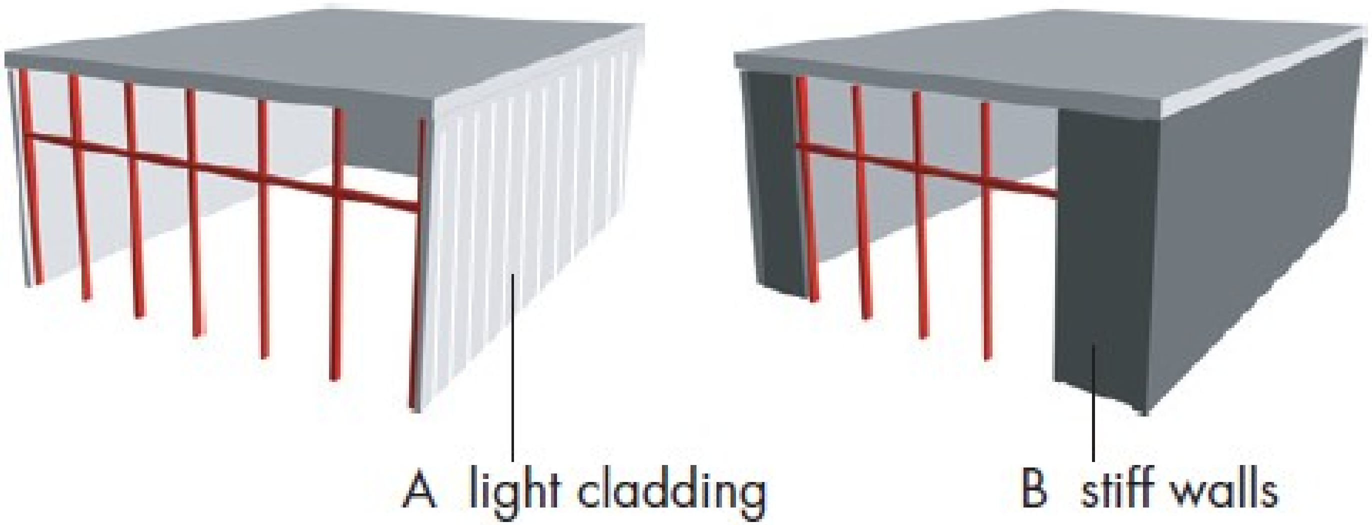
Solutions

- The solution to this problem is to reduce the possibility of torsion by endeavoring to balance the resistance around the perimeter.

- The first strategy is to design a frame structure of approximately equal strength and stiffness for the entire perimeter

- The opaque portion of the perimeter can be constructed of nonstructural cladding, designed so that it does not affect the seismic performance of the frame. This can be done either by using lightweight cladding or by ensuring that heavy materials, such as concrete or masonry, are isolated from the frame **(Figure A)**

Solutions

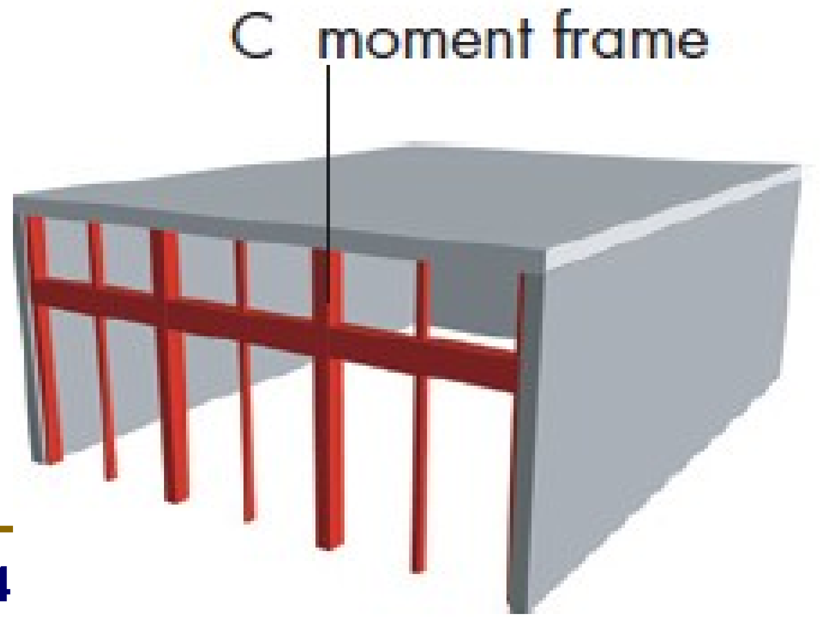


- A second approach is to increase the stiffness of the open facades by adding sufficient shear walls, at or near the open face, designed to approach the resistance provided by the other walls **(Figure B).**
- A third solution is to use a strong moment resisting or braced frame at the open front, which approaches the solid wall in stiffness.

Solutions

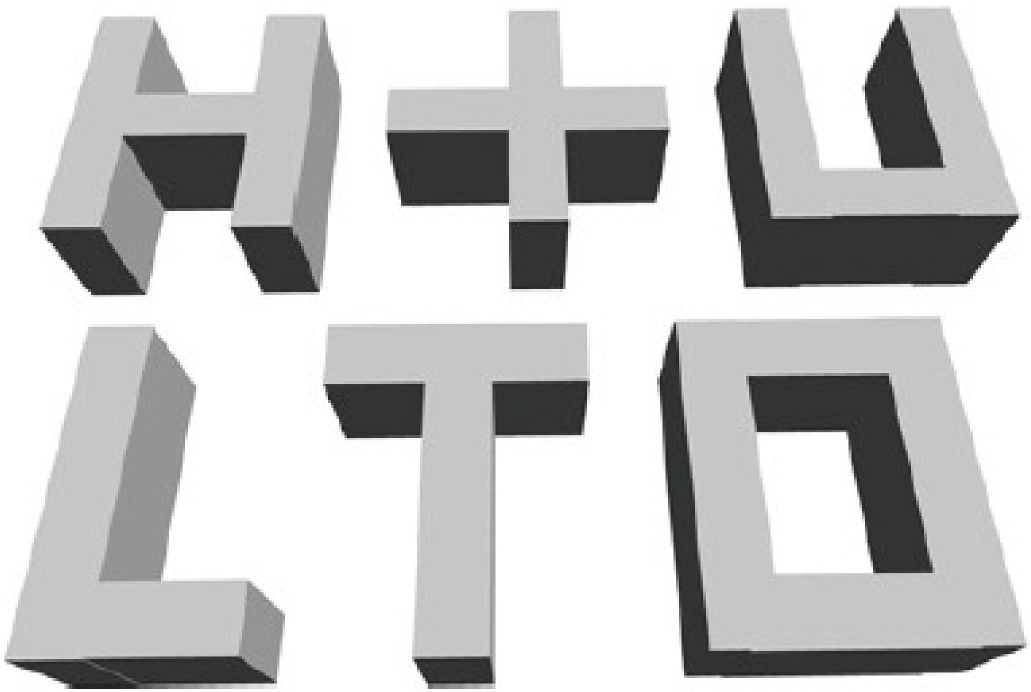
- The ability to do this will depend on the size of the facades; a long steel frame can never approach a long concrete wall in stiffness.

- This is, however, a good solution for wood frame structures, such as small apartment buildings, or motels with ground floor garage areas, or small store fronts, because even a comparatively long steel frame can be made as stiff as plywood shear walls **(Figure C).**



Re-entrant Corners

The re-entrant corner is the common characteristic of building forms that, in plan, assume the shape of an L, T, H, etc., or a combination of these shapes



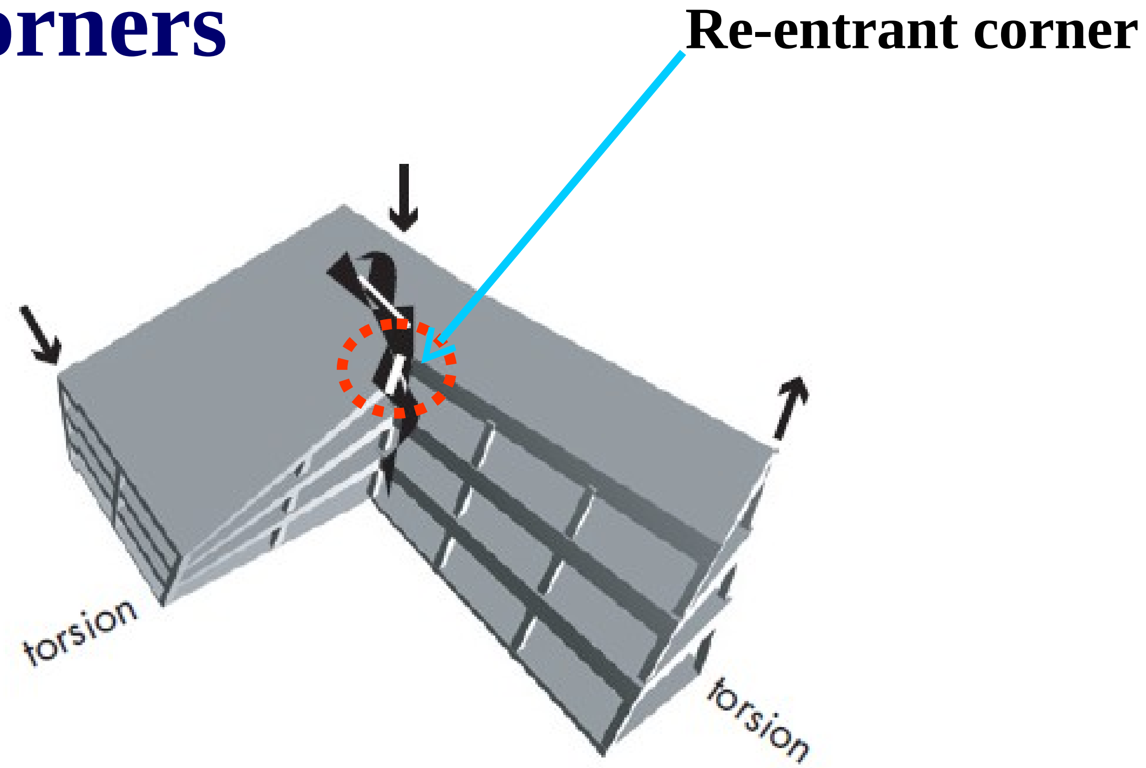
Re-entrant corner plan forms.

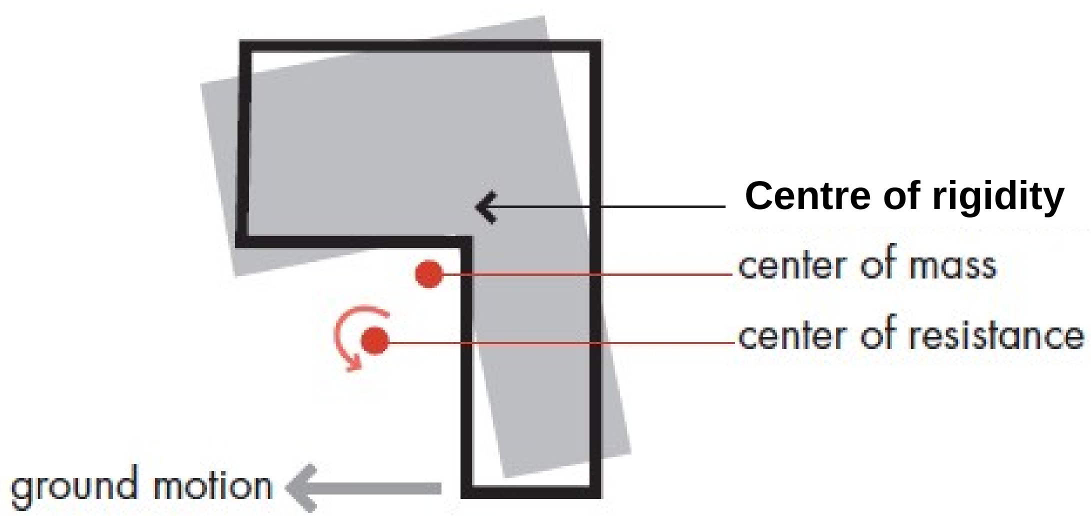
Re-entrant Corners

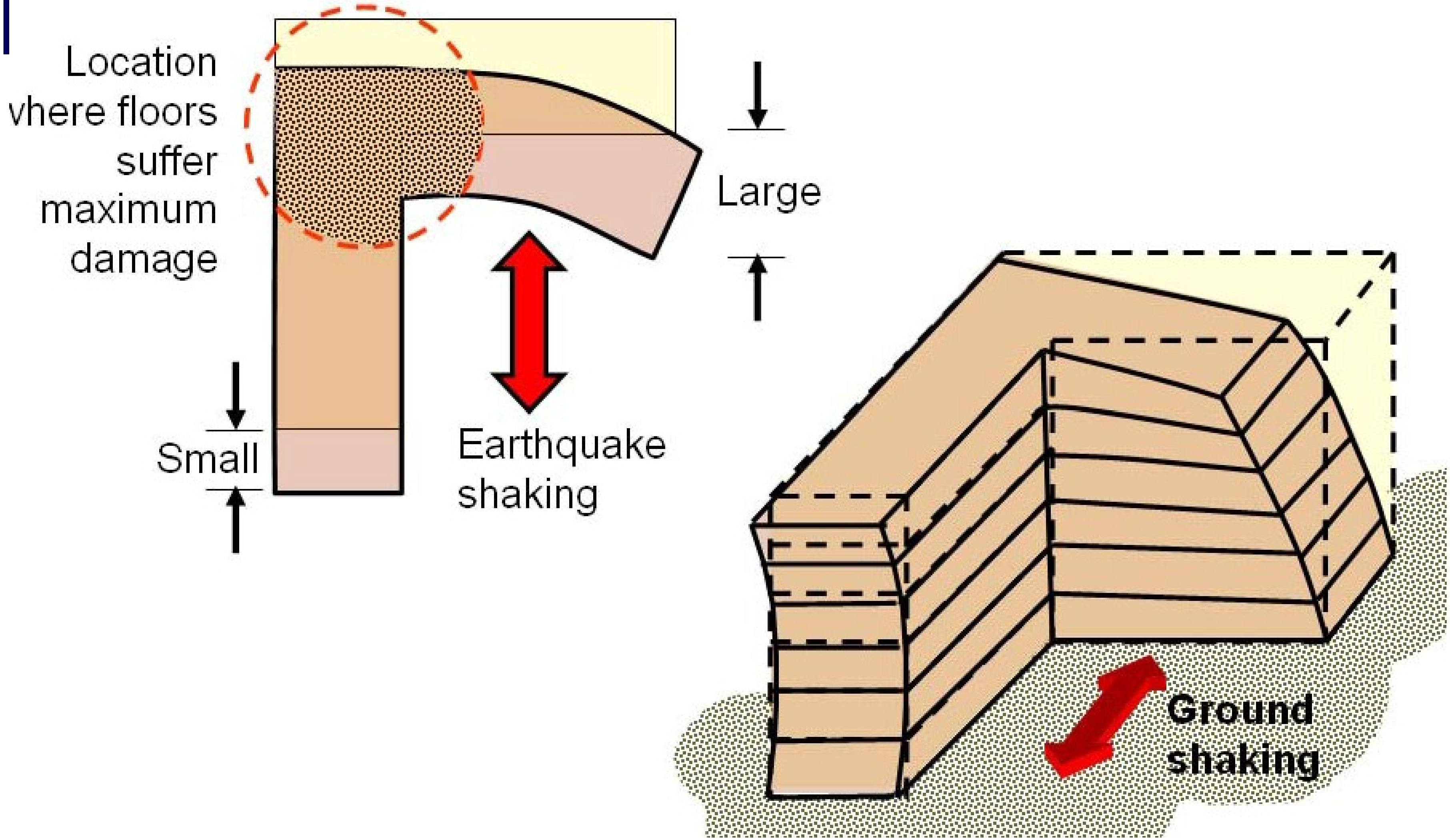
- There are two problems created by these shapes. The first is that they tend to produce differential motions between different wings of the building that, because of stiff elements that tend to be located in this region, result in local stress concentrations at the re-entrant corner.

- The second problem of this form is torsion. Which is caused because the center of mass and the center of rigidity in this form cannot geometrically coincide for all possible earthquake directions. The result is rotation. The resulting forces are very difficult to analyze and predict.

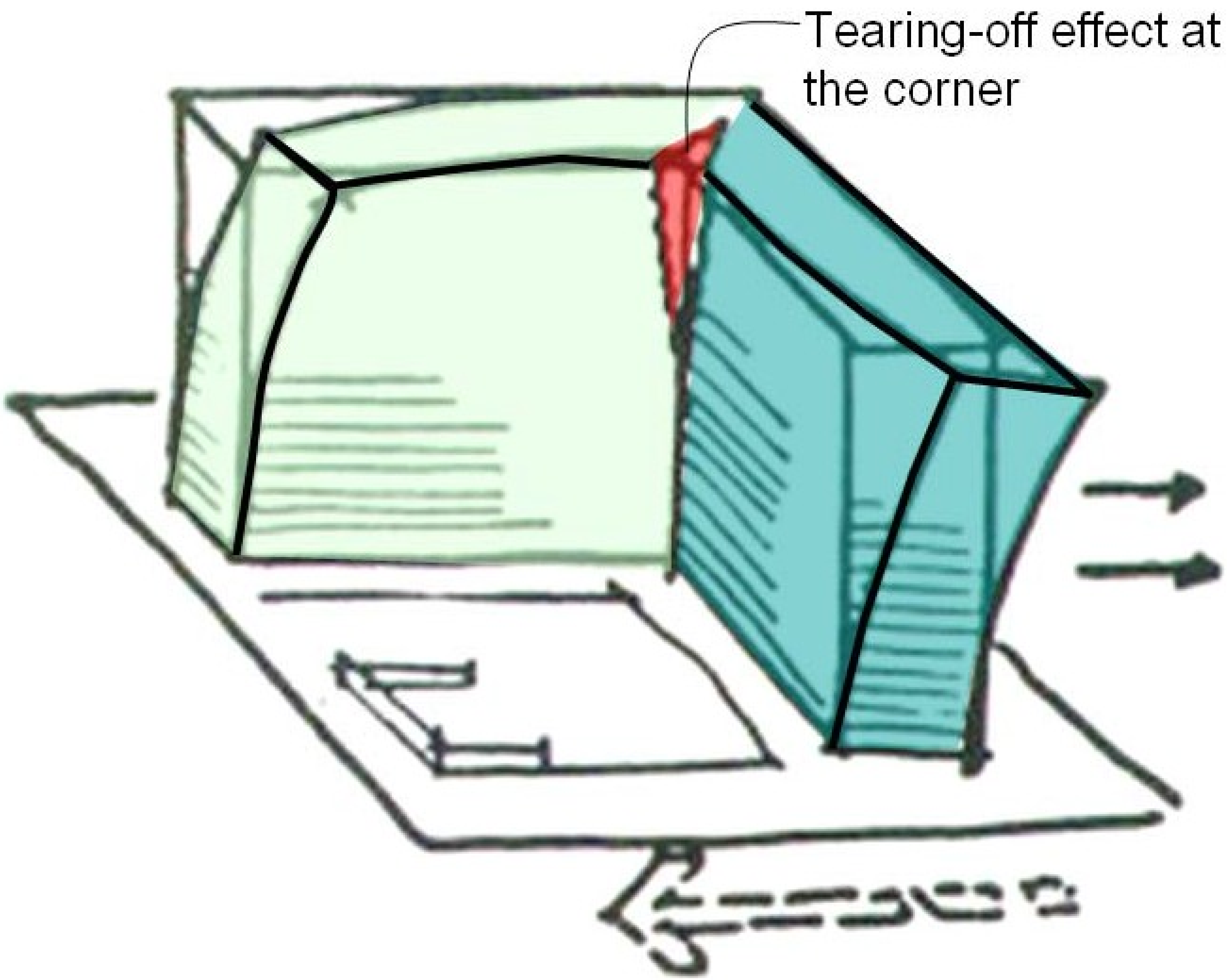
Re-entrant Corners





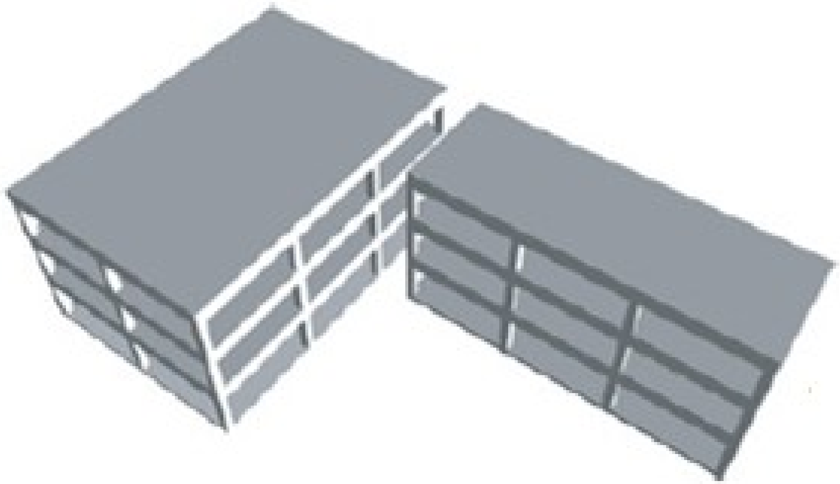


Differential deformation at the junction of two wings

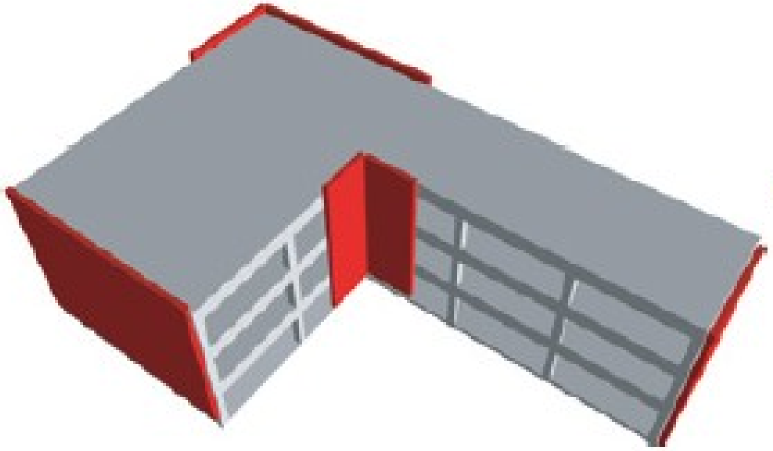

Tearing-off effect at
the corner

Solutions

There are two basic alternative approaches to the problem of re-entrant-corner forms: structurally to separate the building into simpler shapes, or to tie the building together more strongly with elements positioned to provide a more balanced resistance (see figure). The latter solution applies only to smaller buildings



Seperation

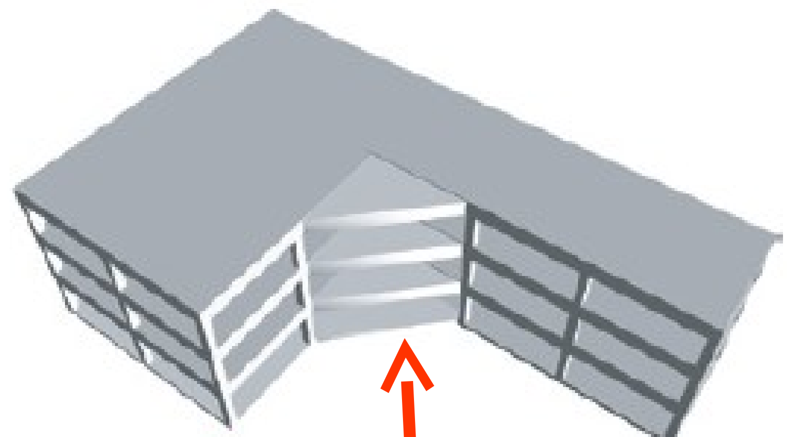


Stiff resistant elements

In case of separation building must be sufficiently away to ensure they do not pound together and damage each other in an earthquake

Solutions

The use of splayed rather than right angle re-entrant corners lessens the stress concentration



Splayed re-entrant corners

This is analogous to the way a tapered beam is structurally more desirable than an abruptly notched one.

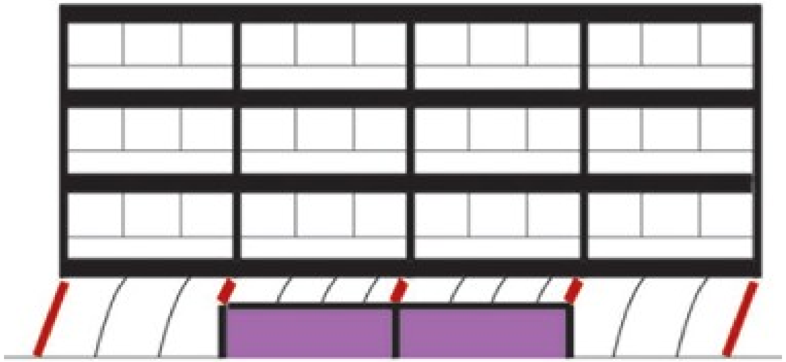
Additional features (to be taken care of) to minimize structural damages during an earthquake

Avoid short columns!

- The space between columns is sometimes filled in by a rigid wall, leaving a short space for a clerestory window (a high windows above eye level to bring outside light, fresh air, or both into the inner space).

- Such a simple act of remodeling may not seem to require engineering analysis, and a contractor may be hired to do the work: often such work is not subject to building department reviews and inspection. Serious damage has occurred to buildings in earthquakes because of this oversight.

Avoid short columns!



Partial floor- height panel infill Start time 1:00 **Failure pattern**

inserting parapet walls into a frame led to a short column phenomenon. Owing to the good confinement of the transverse reinforcement, no actual shear failure occurred, but an equally dangerous sway mechanism developed (Friaul, Italy 1976).

Avoid short columns!

The diagonal cracks and shear failures in the short columns of a multi-storey car park almost caused collapse (Northridge, California 1994).

Provide Redundancy

- Redundancy in the structural system permits redistribution of internal forces in the event of failure of key elements.

- After experience in many earthquakes and much study and discussion, the engineering profession has generally concluded that more than a single system is the ideal solution for successful seismic resistance.

- If carefully selected, multiple systems can each serve a purpose; one to add damping and to limit deflection or drift, the other to provide strength.

- Multiple systems also serve to protect the entire structure by allowing failure of some elements without endangering the total building.

Provide Redundancy

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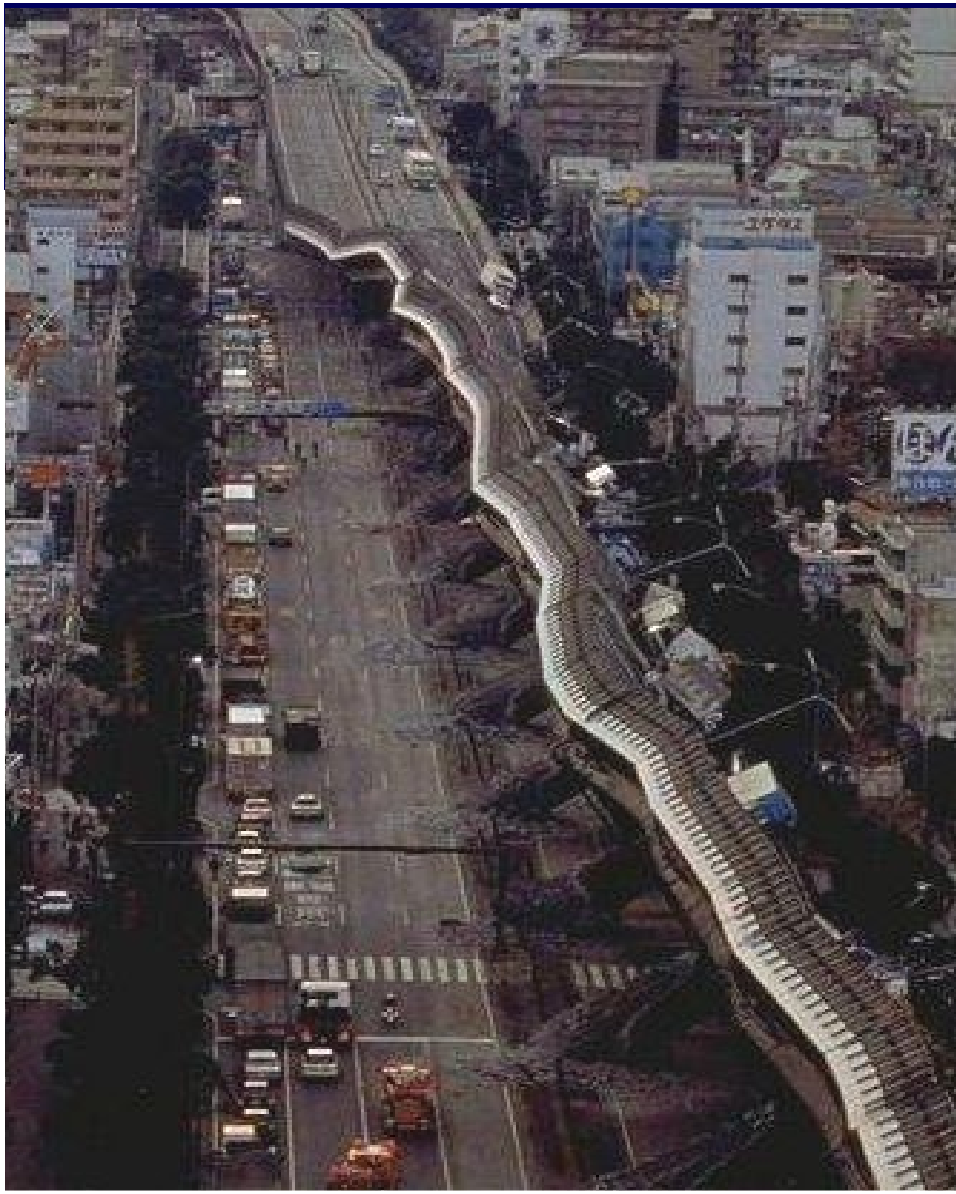
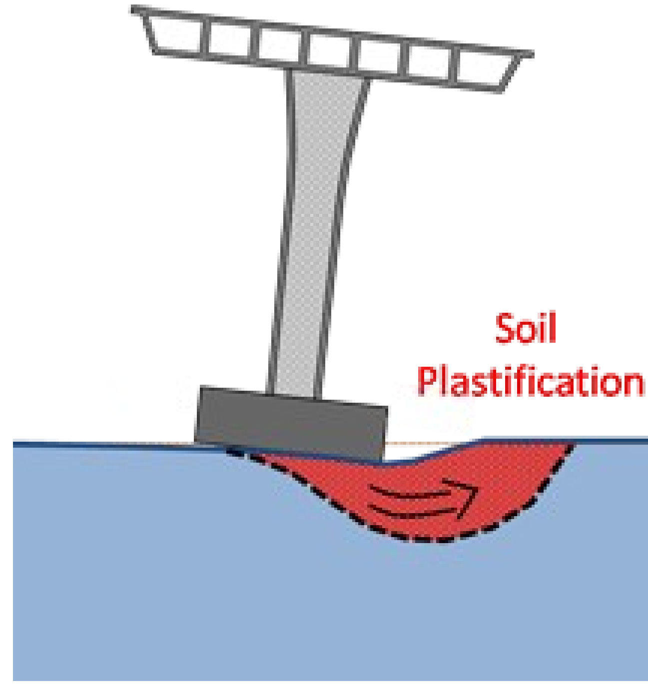
- After experience in many earthquakes and much study and discussion, the engineering profession has generally concluded that more than a single system is the ideal solution for successful seismic resistance.

Provide Redundancy





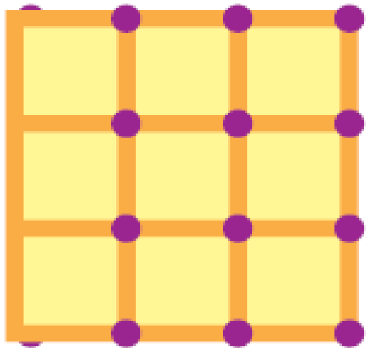
The Hanshin Expressway after the 1995, Kobe Earthquake , Japan. Columns in the partially collapsed portion failed due to inadequate shear reinforcement. Existing soil conditions and lack of redundancy aggravated the situation

Provide Redundancy

- If carefully selected, multiple systems can each serve a purpose; one to add damping and to limit deflection or drift, the other to provide strength.
- Multiple systems also serve to protect the entire structure by allowing failure of some elements without endangering the total building.
- An informative sketch of a classic redundant-framing concept, with frames on each grid line, versus a contemporary multiple system with two types of framing, one for strength, the other for damping, is shown in figure on next slide.
- The current dual systems now being developed and utilized are a significant improvement over the historic single seismic resisting systems.

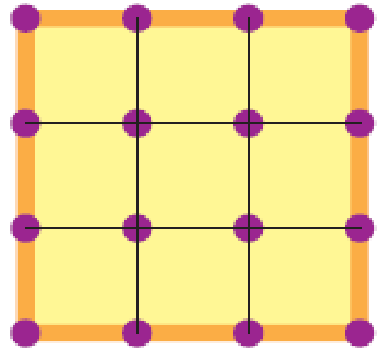
Moment-Frame Seismic Systems

Complete 2-Way MF 1960 - 1970



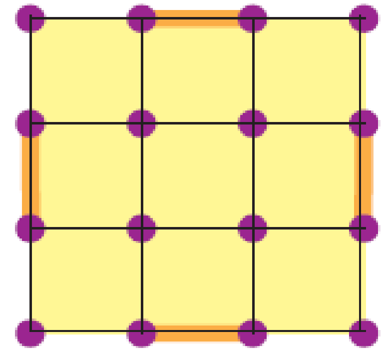
32 MF Joints

Perimeter MF 1970 - 1980



16 MF Joints

Limited MF 1980 –

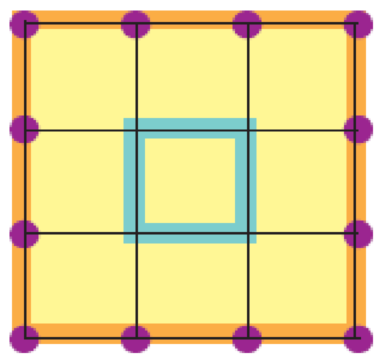


8 MF Joints

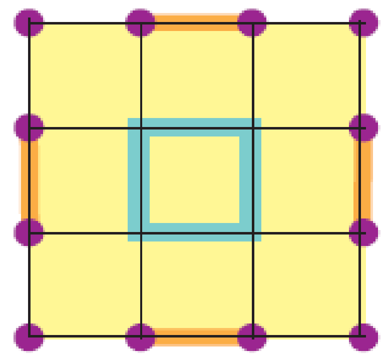
Dual Core Systems

- Dampers
- Eccentric-Braced Frames
- Shear Walls

16 MF Joints



8 MF Joints



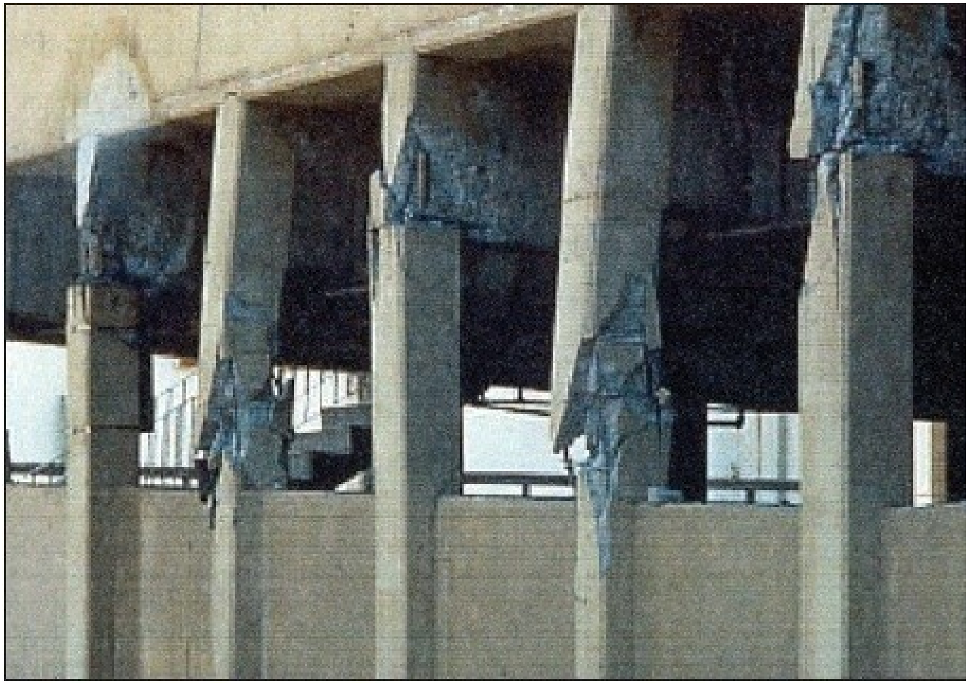
Dual Systems with Moment-Frame Seismic Systems

- **Single and multiple system concepts.**

Avoid strong beam- weak column

Strong beam-weak column joint simulates fixed support, resulting in larger moments at joint

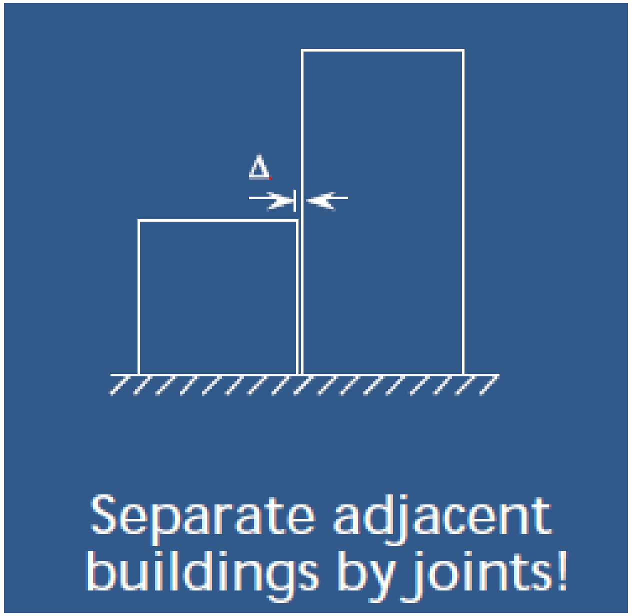
Ground floor of an under construction commercial plaza (Muzzafarabad, 2005)



Provide Adequate Anchorage

Inadequate lap of longitudinal bars in a collapsed column.
Left (Abbotabad,2005), Right (Muzzafarabad,2005)

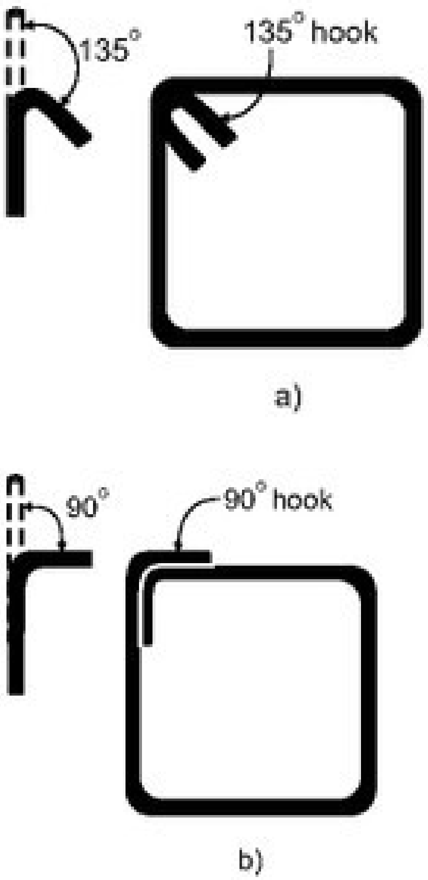
Separate adjacent buildings by joints!

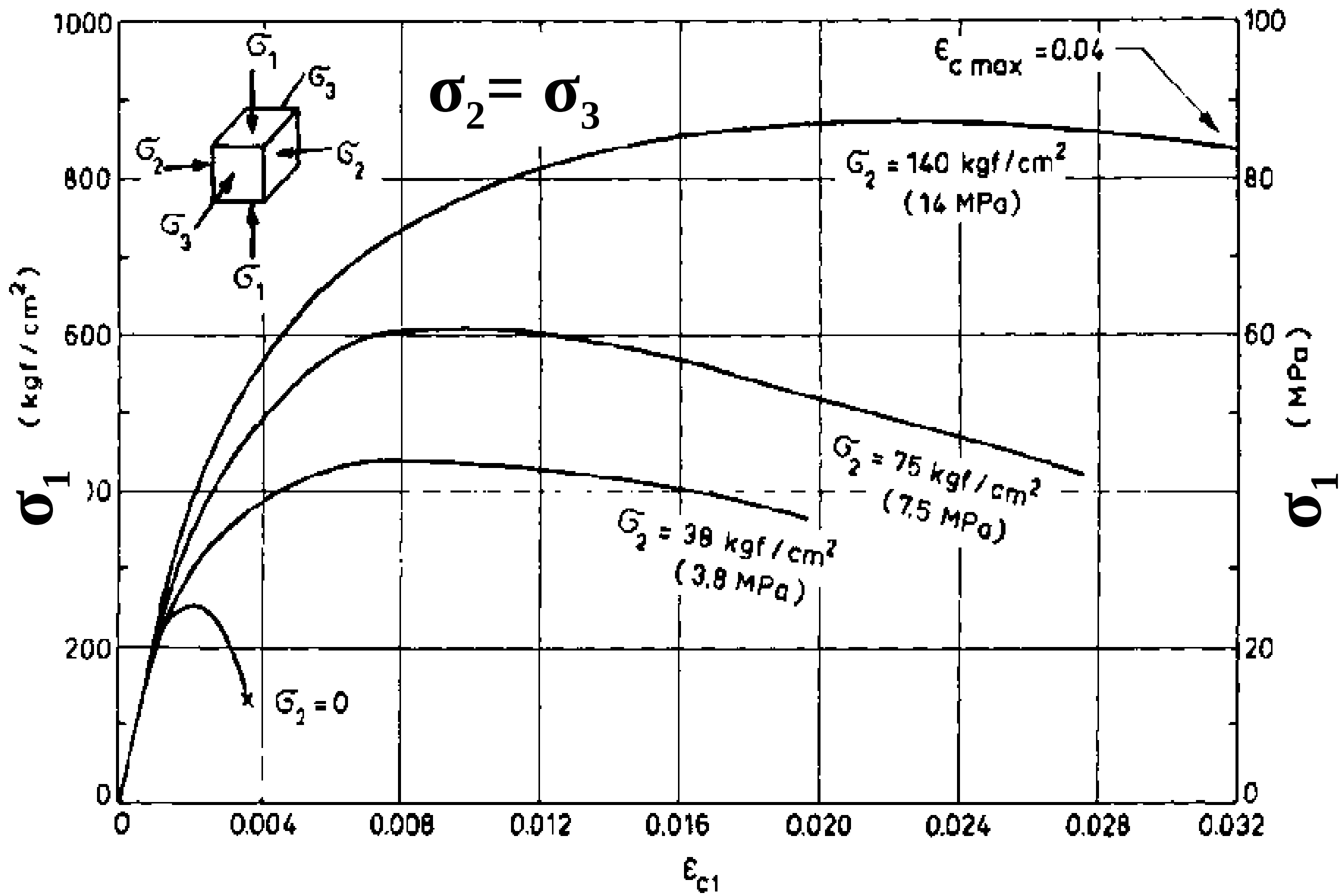


Building must have sufficient separation to ensure they do not pound together and damage each other in an earthquake. Generally if framed buildings are separated by at least 0.01 H, pounding will not be a problem. (e.g. two 6-metre tall buildings should be separated by 60mm.)

Separate adjacent buildings by joints!

Use closely spaced transverse reinforcement with 135° hooks in structural walls and columns!





90° hooks open up at relatively smaller force as compared to 135° hooks

Effect of confinement on the compressive strength of plain concrete

Use closely spaced transverse reinforcement with 135° hooks in structural walls and columns!

Largely spaced rings resulted in failure of column (due to spalling of concrete from rings) in a building at Abbotabad during 2005 Kashmir earthquake

Use closely spaced transverse reinforcement with 135° hooks in structural walls and columns!

Closely spaced rings avoided collapse of column.

Left (Muzaffarabad secretariat,2005. Right (Taiwan, 1999)

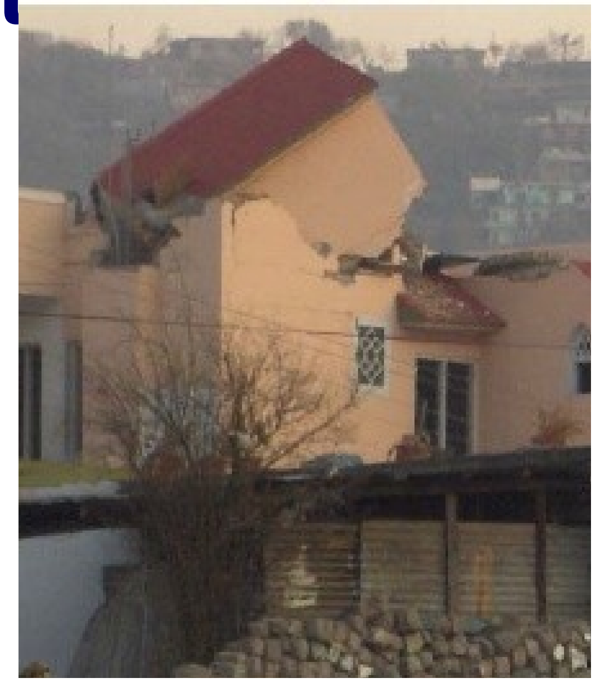
Anchor free standing parapets walls & other elements attached to the structure!

Out-of-plane overturning of freely standing masonry infills in reinforced concrete frames in Muzaffarabad during 2005 Kashmir earthquake

Anchor free standing parapets walls & other elements attached to the structure!

Typical failure of boundary walls (left, Abbotabad) and overturning of a slender parapet prevented by proper bracing across the length (right, Garhi Habibullah). 2005 Kashmir earthquake.

Anchor free standing parapets walls & other elements attached to the structure!

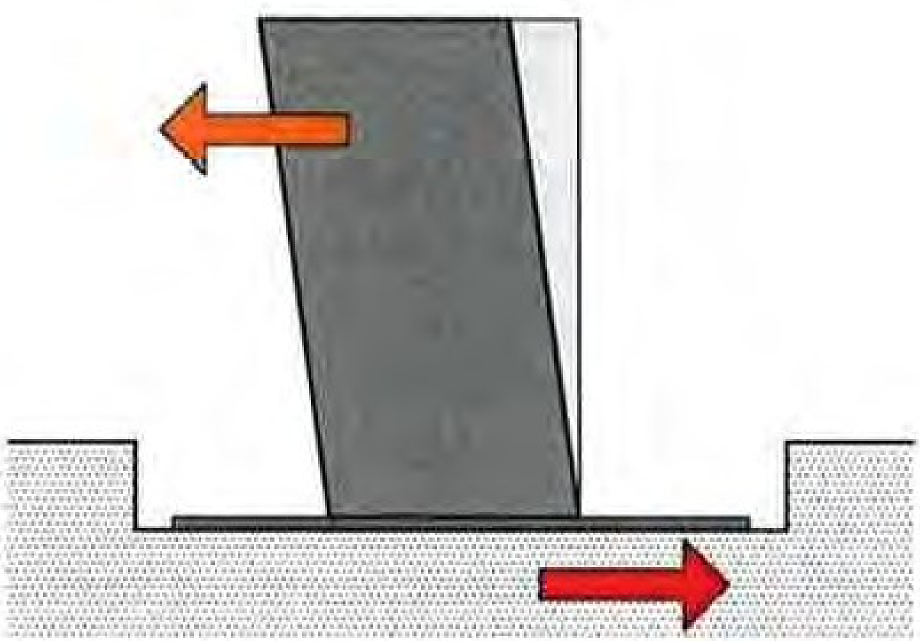


Water tanks fallen from supporting masonry piers due to their tensile failure Abbotabad & Mansehra during 2005 Kashmir earthquake. Tanks, properly anchored to R.C. Columns through steel reinforcement could have avoided this situation

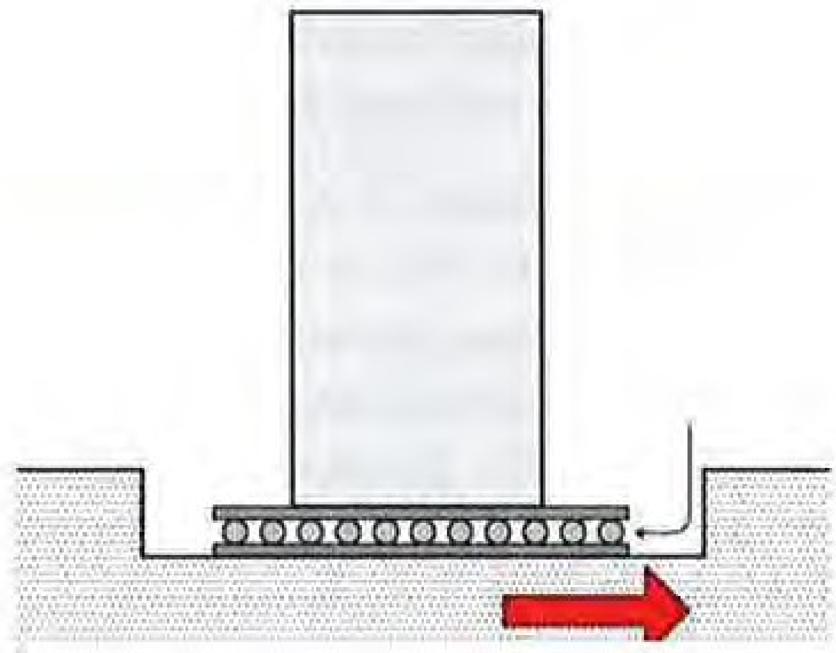
Various mechanisms to dissipate energy imparted to a structure by an earthquake

Base Isolation

- Response of a building with no base isolation is shown in Figure **a**. Where, response of the building with base isolation can be simulated by Figure **b,** where the rollers move during ground shaking but the building above does not move and no force is transferred to the building due to shaking.



(a)



(b)

Base Isolation

- Base isolation is carried out, mostly, by using

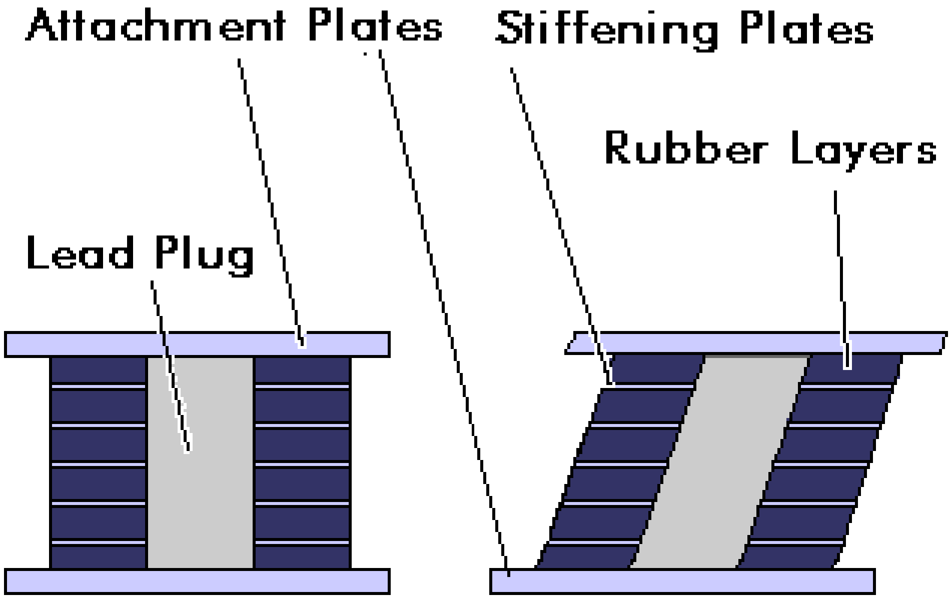
i. Laminated rubber bearing (LRB)

ii. Spherical Sliding Isolation Systems

- **Lead-rubber bearings** (LRB) are among the frequently-used types of base isolation bearings. (See figure on next slide)
- An LRB is made from layers of rubber sandwiched together with layers of steel. In the middle of the bearing is a solid lead "plug." On top and bottom, the bearing is fitted with steel plates which are used to attach the bearing to the building and foundation. The bearing is very stiff and strong in the vertical direction, but flexible in the horizontal direction.

Base Isolation

a) Laminated rubber bearing (LRB).



Lead-Rubber Bearing

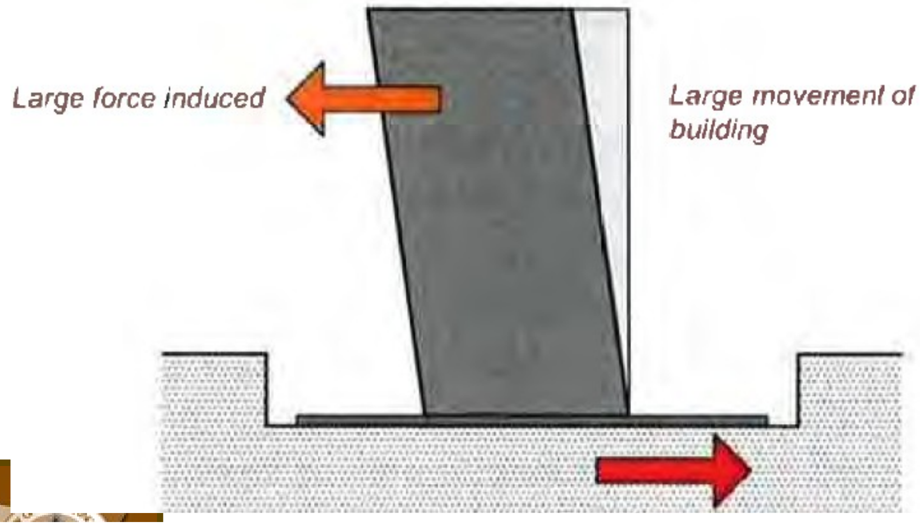
- The bearing is very stiff and strong in the vertical direction, but flexible in the horizontal direction.

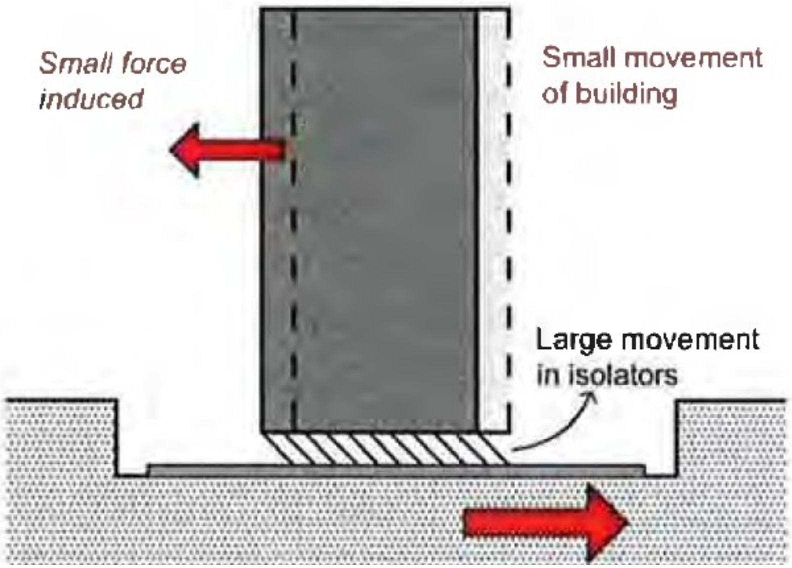
- Lead plug in the middle of bearing experiences the same deformation as the rubber. However, it also generates heat as it does so. In other words, the lead plug reduces, or **dissipates,** the energy of motion--i.e., **kinetic energy**--by converting that energy into heat

Base Isolation

a) Laminated rubber bearing (LRB).

- Experiments and observations of base-isolated buildings in earthquakes have been shown to reduce building accelerations video1, video 2 to as little as 1/4 of the acceleration of comparable fixed-base buildings, Increase or decrease in acceleration proportionally increases or decreases inertial force as inertial forces are directly related to acceleration ($F_I = ma$).





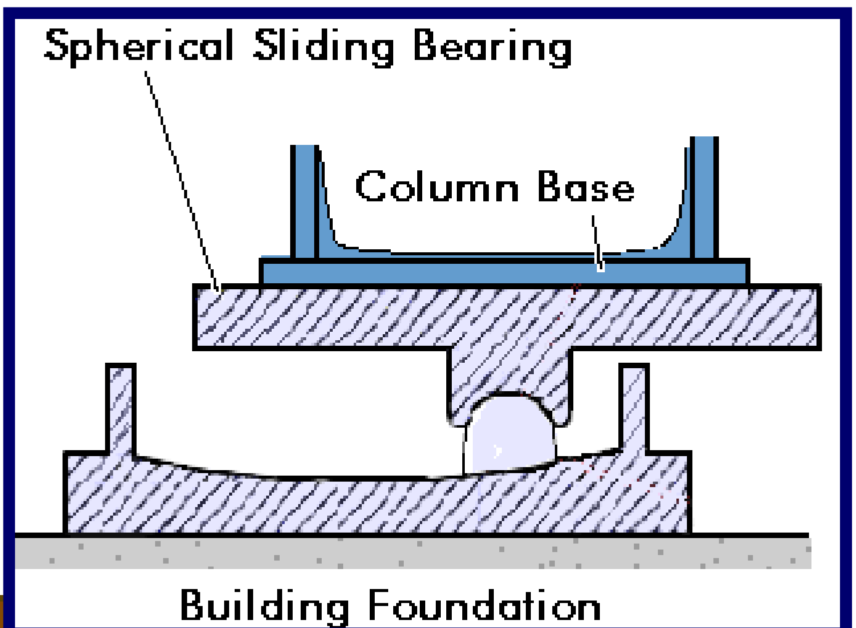
Building resting directly on ground (large displacements and acc. In building)

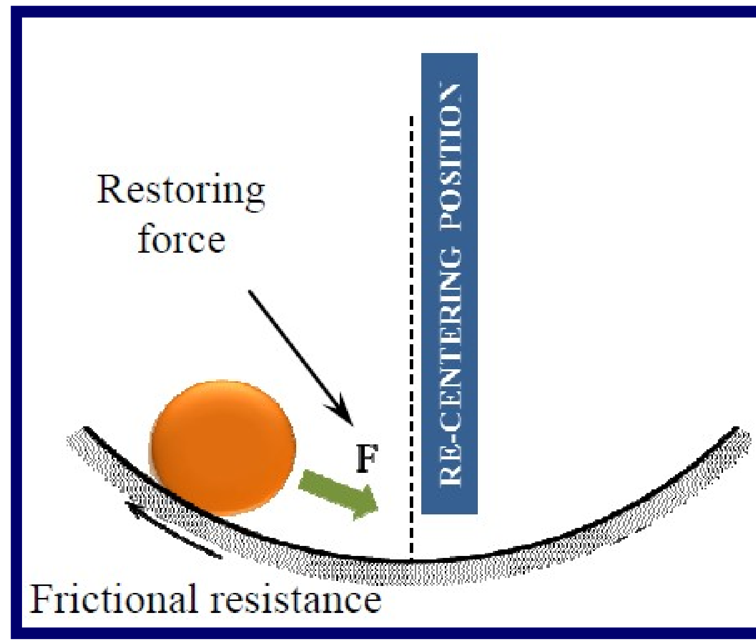
Building base isolated with LRB (lower displacement and acc. in building)

Base Isolation

b) Spherical Sliding Isolation Systems .

- Lead-rubber bearings are just one of a number of different types of base isolation bearings which have now been developed. **Spherical Sliding Isolation Systems** are another type of base isolation. The building is supported by bearing pads that have a curved surface and low friction.





Base Isolation

b) Spherical Sliding Isolation Systems .

- The force needed to move the building upwards limits the horizontal or lateral forces (Transformation of K.E into P.E & vice versa) which would otherwise cause building deformations.
- It should be noted that base isolation is not suitable for tall high rise buildings or buildings located on soft soil.
- Base isolation is most effective for short to medium rise buildings located on hard soil.

Tuned Mass Damper (TMD)

- Under a simple harmonic load, one can show that the main mass can be kept completely stationary when the natural time period (of the
attached absorber is chosen to be (or tuned to) the time period of excitati
.

- During an earthquake or wind , TMD will move against the direction of main structural vibration and an inertia force will be acted on the structure to reduce the response of the structure .

- TMD are effective in controlling wind induced excessive vibration in high rise buildings due to one specific value of time period of tuned mass. However, multiple tuned mass dampers have also been devised to control vibration during earthquake

H.Assignment 2 (Module 2). HA2M2

1. Can we reduce the seismic risk of an existing building stock? Support your answer with argument(s)
2. What will be your strategy as a design engineer to avoid soft story effect at a floor (other than ground floor) without providing any wall?
3. How you will cope, as a design engineer, where you cannot avoid short columns?
4. How you will handle a situation as a design engineer where you cannot change the x-sectional dimensions of a very stiff beam connected to a flexible column?
5. Suggest at least two methods of bracing the boundary walls.