Basic Principle of Earthquake-Resistant Design

Concept of design limit states

a)service limit state (operational) : building remains functioning

b)damage limit state (immediate occupancy): damages are limited

c)collapse limit state (life safety and collapse): building remains standing

Depending on the type and function of the building, any or all limit states could control.

Examples : hospital, nuclear power plant, office, house

For each Limit State, three questions must be answered :

1) How big an earthquake should a structure resist and still function ?
2) How should the buildings' response be calculated?
3) How should the building be designed in order to enhance its performance in this limit state?

Collapse Limit State

Design Earthquake

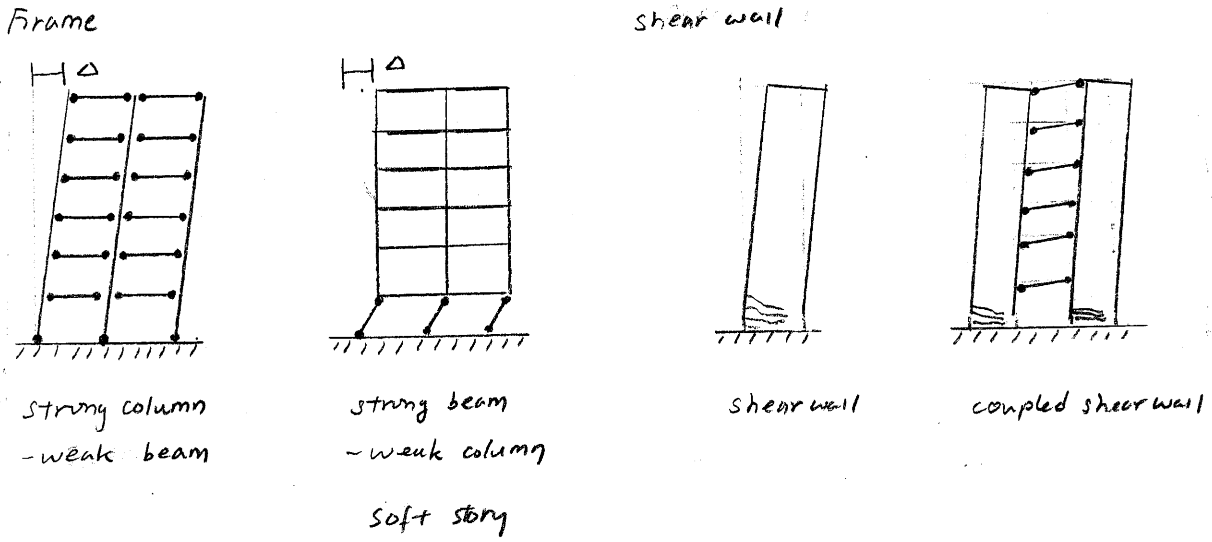
Earthquakes for this limit state will represent the strongest motions expected at a site, and can have ground accelerations near 0.4g at high seismic zone.

In Korea, the PGA = 0.143g

In some high seismic zone, large acceleration and velocity pulses may occur. Such pulses are thought to be caused by propagation of the instantaneous focus, along the length of the fault rupture. In design code, such pulse effect is considered by increasing the design EQ with the near source factor.

Response Calculation

In this limit state, we should expect serious structural damage. The structure will respond inelastic, with inelastic deformations concentrated in certain critical regions of the structure. The yielded structure will deflect as a mechanism.



Linear analyses are clearly insufficient. The following methods can be used.

1) Nonlinear time history analysis, step by step
2) Nonlinear static (push-over) analysis reflecting inelastic structural behavior and inelastic response spectrum reduced by overall displacement ductility
3) Equivalent linear static analysis using inelastic design response spectrum reduced for overall displacement ductility specified for structural types.
4) Equivalent linear dynamic analysis using modal superposition analysis and inelastic design response spectrum.

If the structure is expected to be affected by non-structural elements, the non-structural elements should be included in the structural analysis and design.

Available overall displacement ductility

μ_Δ = 5 frames with ductile detailing

μ_Δ = 4 flexural walls

μ_Δ = 1- 2 structure with little ductile detailing

no load factors are used.

Global displacement ductility of 4 imply local required curvature ductility of as high as 6 – 7 . If this local curvature ductility is not available, the structure must be re-analyzed for the higher forces consistent with that actual available displacement ductility.

General Design Process

Response will depend primarily on relation between frequency content of input, and characteristic frequencies of structure.

a) Design structure for vertical loads

b) Estimate the dynamic period of the structure T

If T is underestimated, the earthquake load can be underestimated.

Thus, the structural stiffness should not be excessively underestimated though the structure is expected to be severely damaged under strong earthquake.

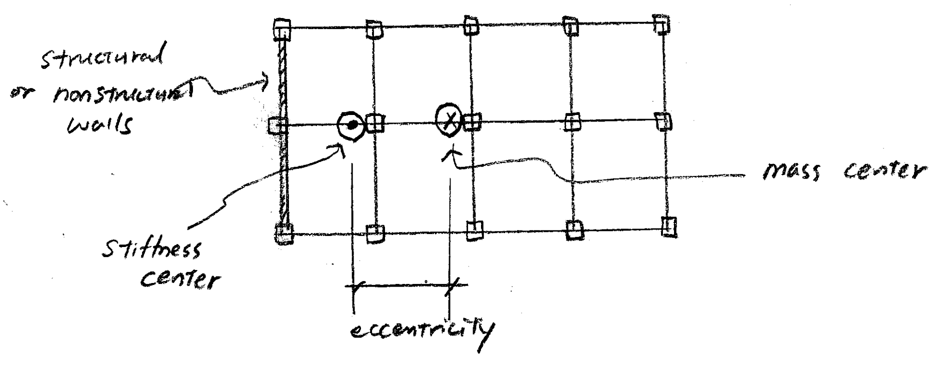
c) Compute response

$$\xi_1 = 5\ \%$$ for linear elastic response spectrum

If the structural stiffness is overestimated, the inelastic deformation can be underestimated. Thus, the structural stiffness should not be overestimated.

General Guidelines

1) It is generally impossible to change T by changing member sizes. It is usually necessary to change the structural system.
2) It is generally preferable to design structures with structural plans which reduce the distance between the center of mass and the center of rigidity at each floor level. The center of rigidity depend on non-structural stiffening elements as well as structural elements.



3) Very large member forces generally result from large concentrated masses or abrupt changes in stiffness between adjacent members. It is better to avoid such practices. One of the most common examples of an abrupt change in stiffness is the soft story created by discontinuing a wall at the first floor level.
4) It is generally impossible to design a member against high forces by increasing its size. The increased rigidity will simply attract more forces. It is usually necessary to revise the structural system.
5) The structural members must be proportional and detailed to develop the required local curvature ductility.
6) The structure should form a characteristic mechanism involving a large number of plastic hinges, preferably in the beams rather than the columns, so as not to reduce the gravity load resistance of the structure.
7) The structure should have more than one system for resisting lateral load.
8) Avoid abrupt changes in resistance within the structure.
9) Avoid unnecessary masses.
10) Deflections must be controlled to avoid problems with secondary moments (P-delta effects). Generally, story drifts in the collapse limit state should not exceed 2%. Buildings should be separated to avoid hammering.

Damage Limit State

Design Earthquake

The structure should be capable of withstanding earthquake without suffering severe or economically prohibitive damage.

Maximum ground acceleration will generally be in the 0.15 – 0.18 g range in high seismicity zone.

In low and moderate seismic zones, it is not necessary to consider the damage limit state because in these regions, the probability of low earthquakes is still low. However, very important facilities such as nuclear power plants should be designed for multiple limit states.

Response Calculation

Because no significant yielding is expected, the response should be calculated elastically, perhaps using a slightly lower percentage of critical damping (damping ratio = 5%)

Linear static or dynamic analysis can be used.

General Design Process

Generally this stage involves checking whether a structure is damaged or not. We are particularly interested in stresses in non-structural elements. For example, we want to know if stresses in infilled walls exceed cracking levels, or if deformations exceed the gaps between window frames and glass.

No load factor and strength reduction factor are used.

General Guidelines

It is important to avoid the use of elements whose rigidity is out of proportion to their strength. By reducing the periods of vibration of a structure, such elements increase the inertial forces acting on a structure. When such elements fail, they cause high repair or replacement costs. It is preferable to increase the strength of non-structural elements, or to reduce their mass and isolate them from the structure.

Interstory drift limitation = about 0.01

Service Limit State

Design Earthquake

The design earthquake should represent earthquakes with return periods of 5 years or so.

In high seismic zones, the maximum accelerations will usually be 0.06 – 0.10g.

Response Calculation

Because no damage is expected, the response should be calculated elastically.

Linear static or dynamic analysis can be used.

Compute response

ξ_1 = 2 % for steel frame

3 % for concrete frame

ξ_2 , ξ_3 = 5%

General Guidelines

Electrical and mechanical lines should be working.

The damage of a building should be none or minimal to a degree that does not affect the function of the building.

Interstory drift limitation = about 0.003

Architectural Considerations

While the provision of EQ resistance is accomplished through structural means, the architectural design plays a major role in determining the building's seismic performance. Configuration largely determines the ways in which seismic forces are distributed through out the building, and also influences the relative magnitude of those forces.

Structural defects are frequently induced by the irregular architectural configurations. The defects can not only reduce the seismic resistance of the corresponding member or elements but also increase the load to the other members and elements, and finally induce the failure of the entire structure.

Seismic ideal configuration

1) low height to base ratio
2) balanced resistance
3) symmetrical plan
4) uniform section and elevation
5) maximum torsional resistance
6) short spans
7) direct load paths
8) uniform floor heights

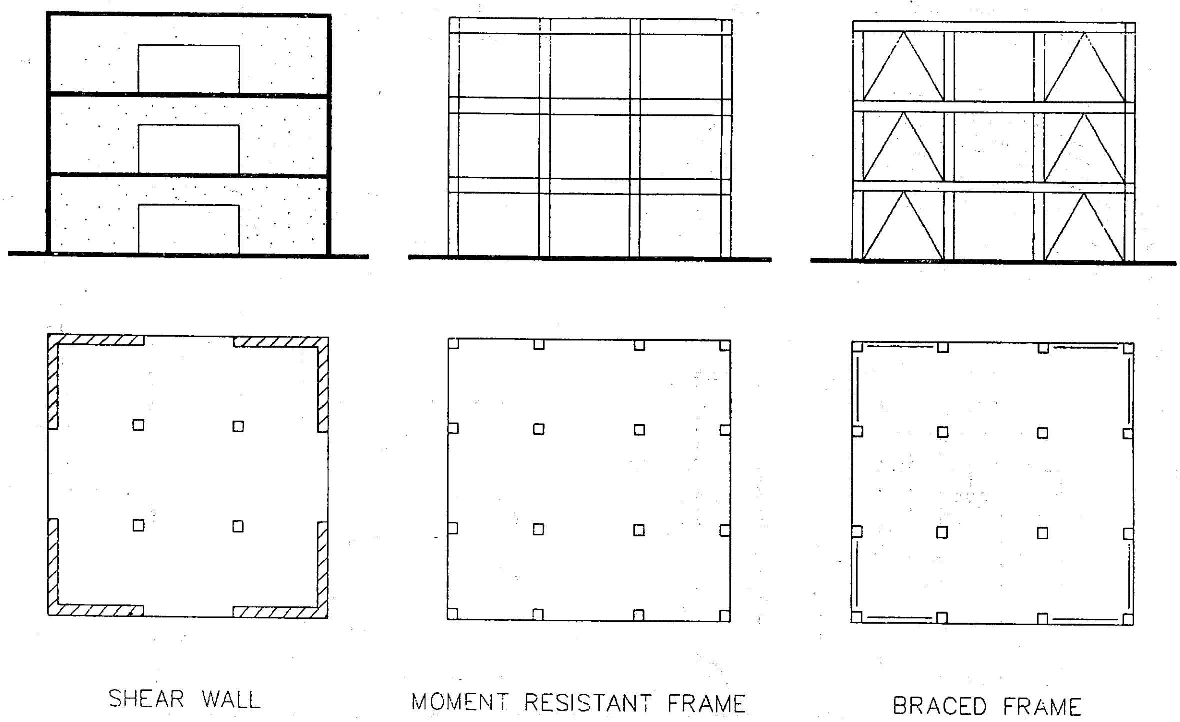


Figure 5-1 The optimal seismic configurations.

Irregular Configuration

SEAOC (Structural Engineers Association of California)

Irregular Structures or framing systems should involve extra analysis and dynamic consideration rather than use of the normal equivalent static-force method.

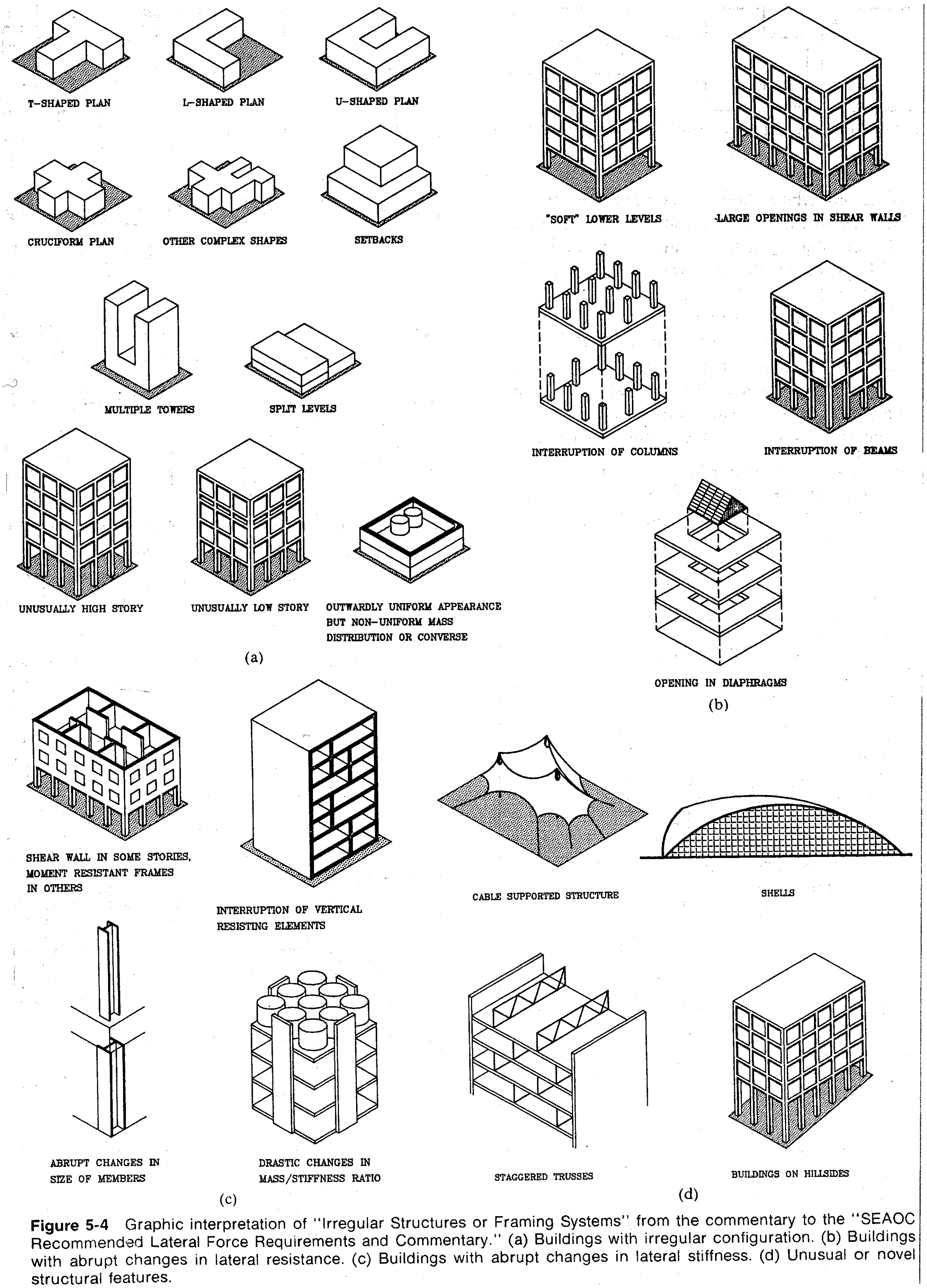


Figure 5-4 Graphic interpretation of "Irregular Structures or Framing Systems" from the commentary to the "SEAOC Recommended Lateral Force Requirements and Commentary." (a) Buildings with irregular configuration. (b) Buildings with abrupt changes in lateral resistance. (c) Buildings with abrupt changes in lateral stiffness. (d) Unusual or novel structural features.

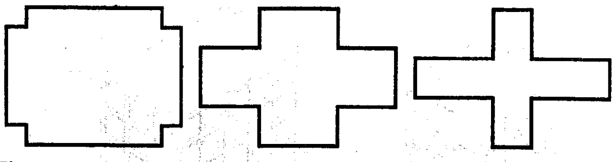


Figure 5-5 The reentrant corner plan: A range of significance.

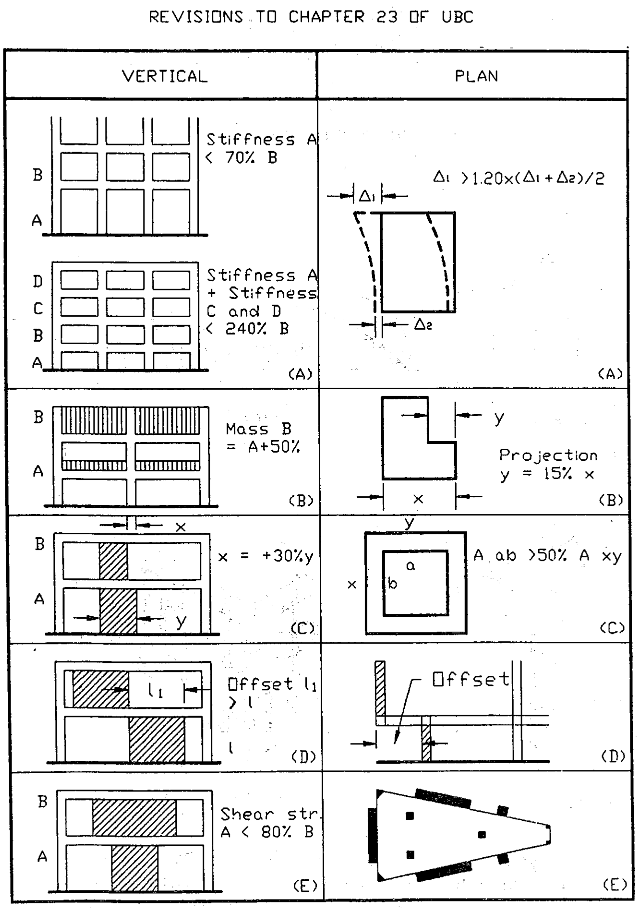


Figure 5-6 Problem configuration definitions interpreted from the 1988 Revisions to the Uniform Building Code.

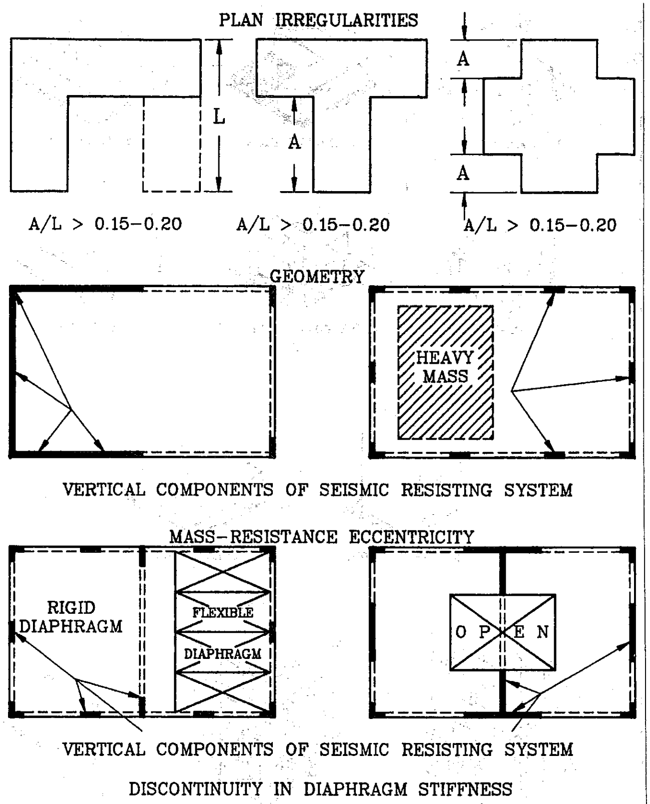


Figure 5-7 Plan irregularities, NEHRP Recommended Provisions (1985).

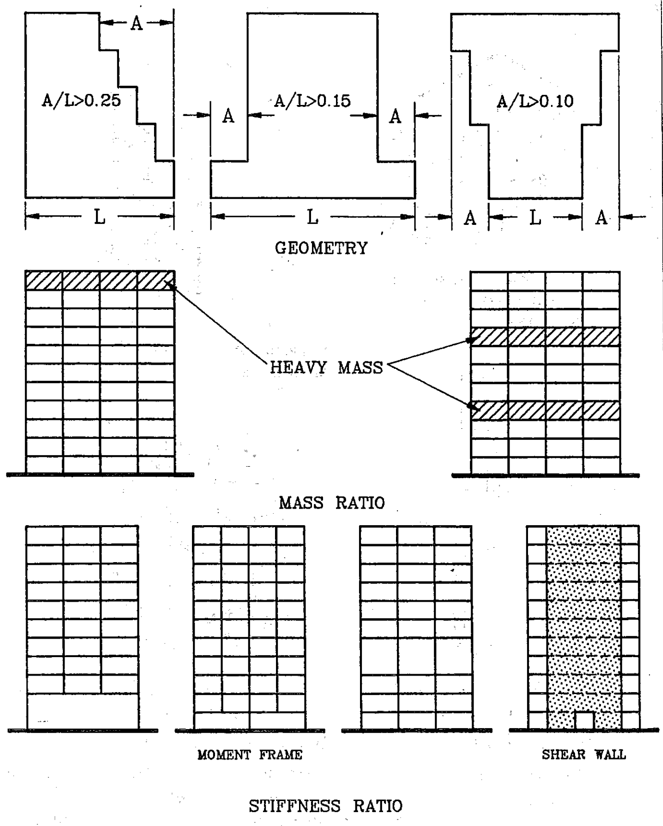
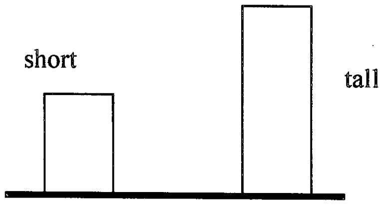


Figure 5-8 Vertical irregularities, NEHRP Recommended Provisions (1985).

Building Height

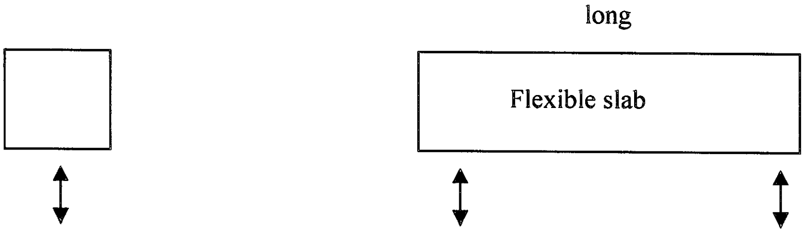
The effect of building periods must be considered in relation to the period of ground motion. **The doubling of building height from 5 to 10 stories may if amplification occurs, result in a four** to five fold increase in seismic forces.

Height limit : 100ft in Japan until 1964
150 ft 13 story limit in LA until 1957
100ft in San Francisco



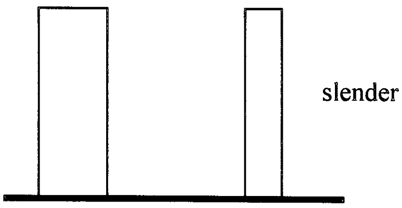
Plan Area

Large plan areas can be detrimental. When the plan becomes extremely large, even if it is symmetrical and of simple shape, the building can have trouble responding as one unit to the ground motion.



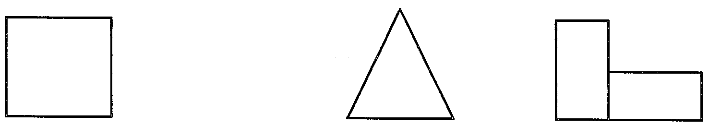
Proportion

The more slender a building the worse the overturning effects of an EQ and the greater the EQ stresses in the outer columns. Dowrick suggests to limit the height to depth = 3 to 4.



Symmetry

Experience in Mexico city shows that many buildings that were symmetrical and simple in overall plan suffered severely because of unsymmetrical location of service cores and escape staircase.



Symmetry asymmetry

Plan Density

The size and density of structural elements in the buildings of former centuries is strikingly, greater than in today's buildings.

Structural plan density = total area of all vertical structural elements divided by the gross floor area. The most striking characteristic of the modern framing building is the tremendous reduction of structural plan density compared to historic buildings.

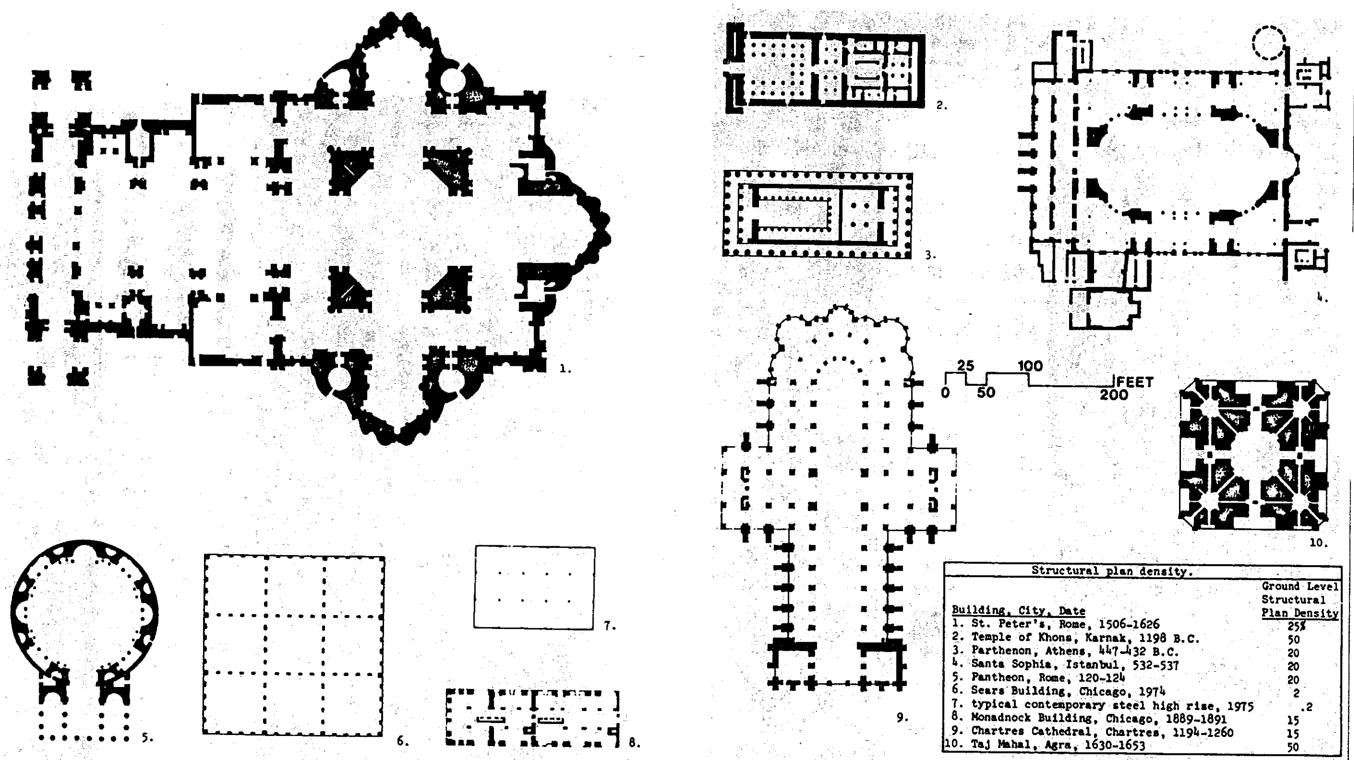
1% for moment-resisting-steel frame

2% for frame-shearwall buildings

50% for Taj Mahal in Agra, India

25% for St. Peter's in Rome

15% for 16-story Monadnock Building in Chicago.



Structural plan density.

Building, City, Date	Ground Level Structural Plan Density
1. St. Peter's, Rome, 1506-1626	25%
2. Temple of Khons, Karnak, 1198 B.C.	50
3. Parthenon, Athens, 447-432 B.C.	20
4. Santa Sophia, Istanbul, 532-537	20
5. Pantheon, Rome, 120-124	20
6. Sears Building, Chicago, 1974	2
7. typical contemporary steel high rise, 1975	.2
8. Monadnock Building, Chicago, 1889-1891	15
9. Chartres Cathedral, Chartres, 1194-1260	15
10. Taj Mahal, Agra, 1630-1653	50

Figure 5-11 Structural plan density.

Perimeter Resistance

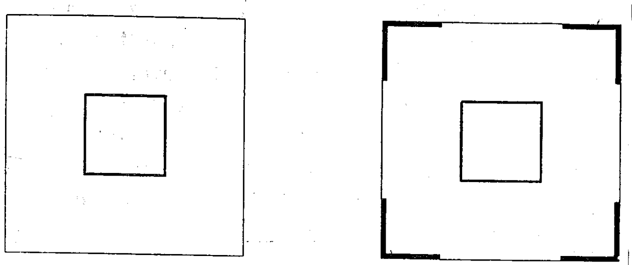
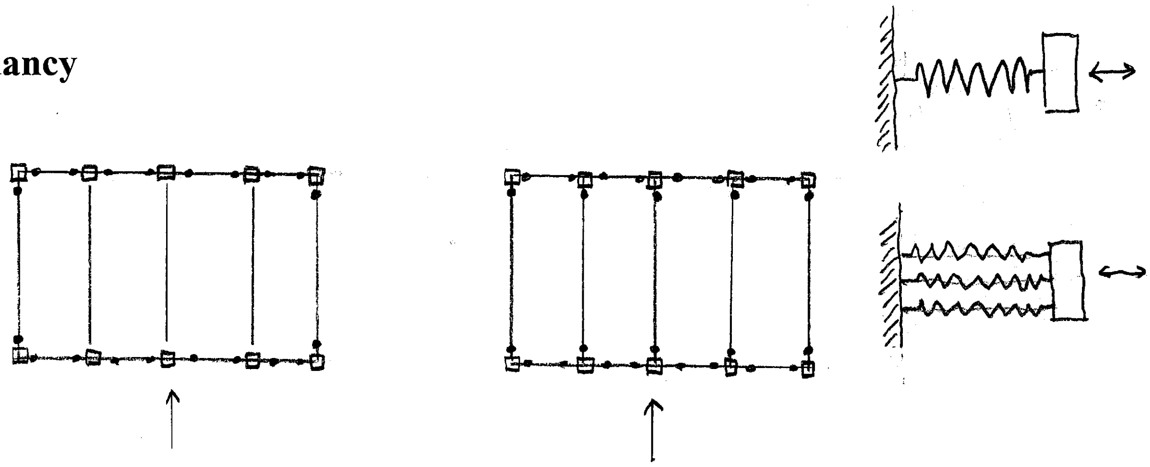


Figure 5-12 Location of lateral resistance systems.

Redundancy



Reentrant corners

The buildings with reentrant corners tend to produce variations of rigidity, and hence differential motions, between different parts of the building, resulting in a local stress concentration at the notch of the reentrant corner.

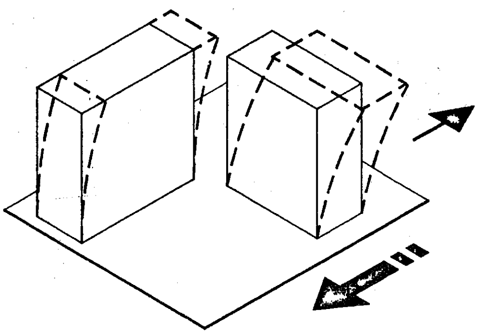


Figure 5-13 Separated buildings.

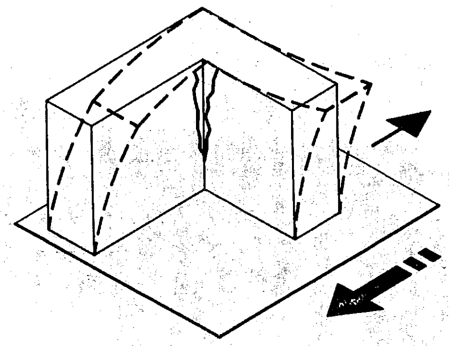


Figure 5-14 The L-shaped building.

Solutions

1) Separate the building structurally into simple shapes. This can create major problems of architectural detailing. Also, fire and smoke can propagate through the EQ joint. (MGM Grand Hotel in Las Vegas, 12 in . width)
2) Tie the building together strongly at lines of stress concentration and locate resistant elements to reduce torsion.

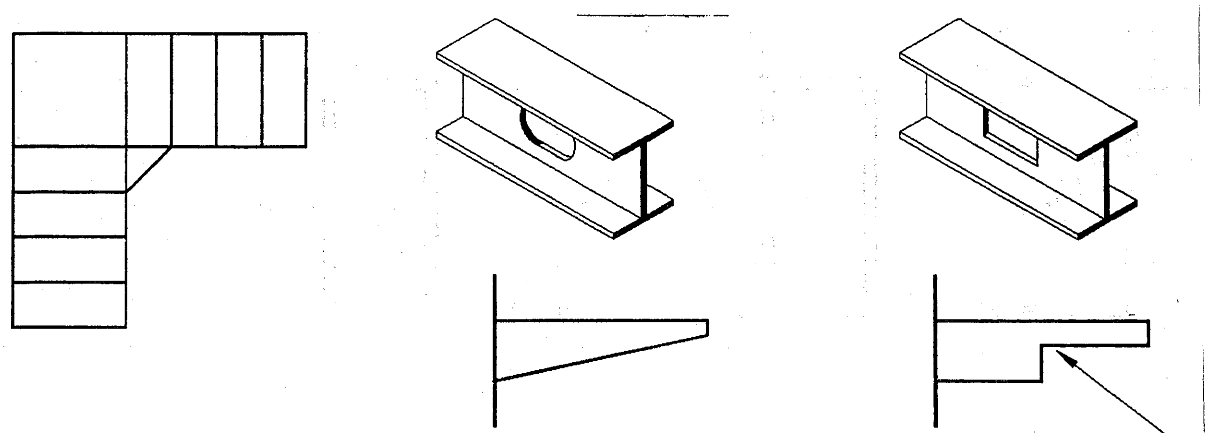


Figure 5-16 Splay in plan relieves reentrant corner stress.

Variations in Perimeter strength and stiffness

Typical in stores in streets, warehouse, and fire station.

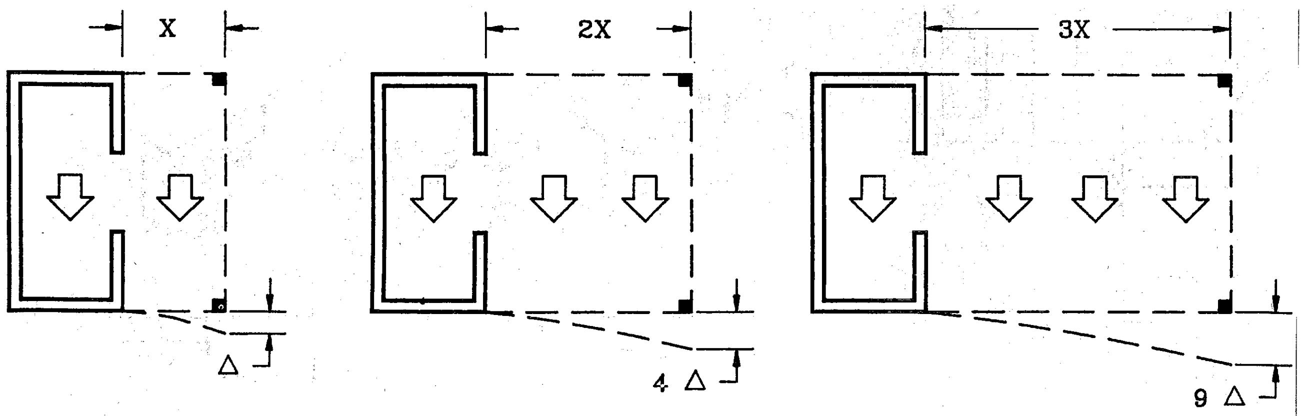


Figure 5-18 Open front design: Torsional deflection varies as the square of the length.

Increase in eccentricity of stiffness and mass (loading)

Solutions

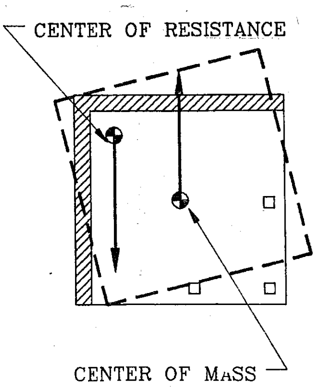


Figure 5-17 Torsional response.

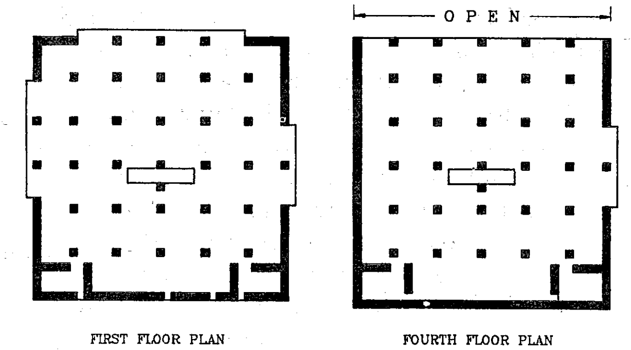


Figure 5-19 J.C. Penney Department Store, Anchorage, Alaska.

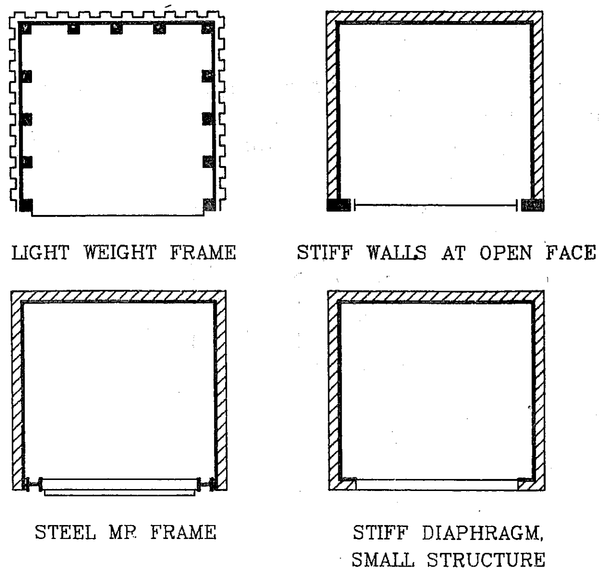


Figure 5-20 Solutions to open front design.

Non-parallel Systems

The vertical load-resisting elements are not parallel to or symmetric about the major orthogonal axes of the lateral-force-resisting systems. This condition results in a high probability of torsional forces under ground motion.

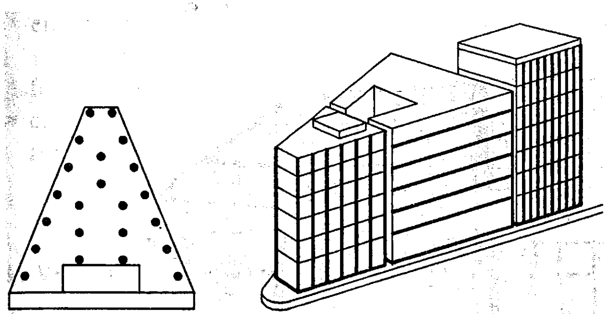


Figure 5-21 Wedge-shaped plan: invitation to torsion.

Soft Stories

A soft story is one that shows a significant decrease in lateral stiffness or strength from that immediately below. The term is also sometimes restricted to a decrease in stiffness, and “weak story” used to indicate a decrease in strength.

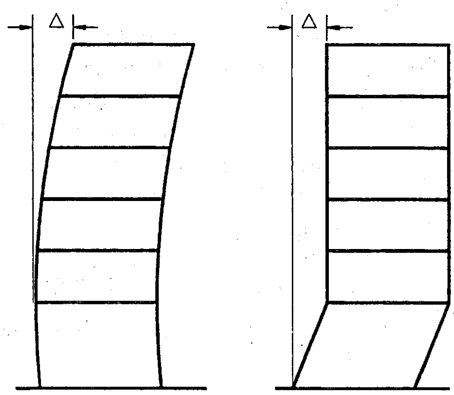
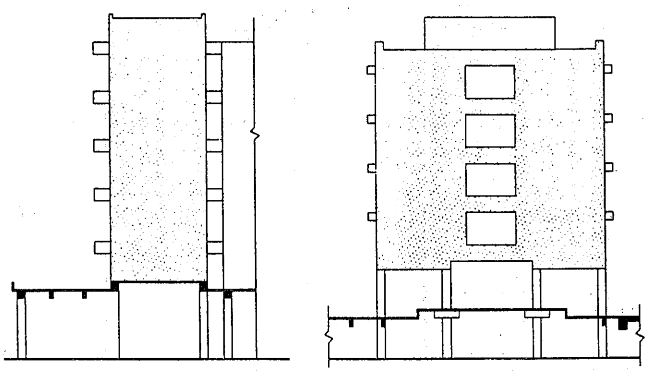
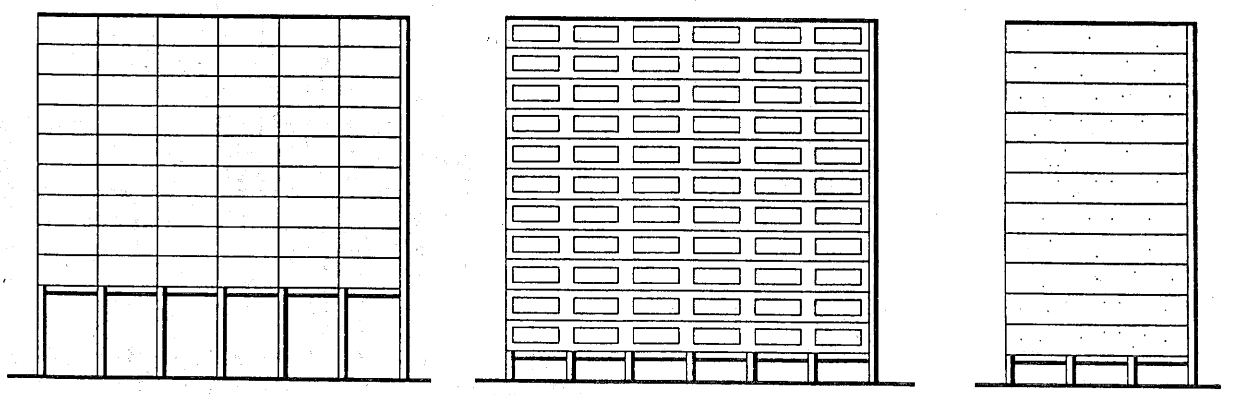


Figure 5-24 The soft story effect.



(a) (b)

Figure 5-26 Olive View Hospital, San Fernando Valley, California. (a) Elevation of staircase towers. (b) Section through main building.



FLEXIBLE FIRST FLOOR

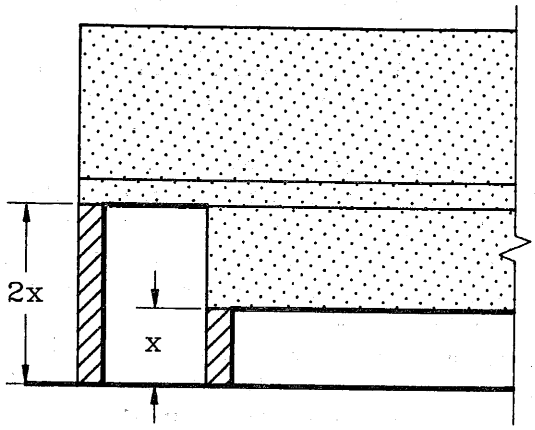
CHANGE OF STIFFNESS ABOVE FIRST FLOOR

DISCONTINUOUS SHEAR WALL

Figure 5-25 Types of soft story.

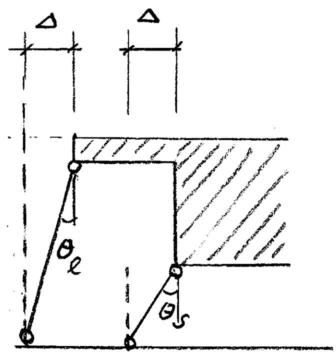
Short Columns

Seismic loads are distributed in proportion to the stiffness of the resisting members. Hence, if the stiffness of the supporting columns varies, those that are stiffest will attract the most forces.



SHORT COLUMN TAKES 8 TIMES THE LATERAL LOAD OF THE LONG COLUMN

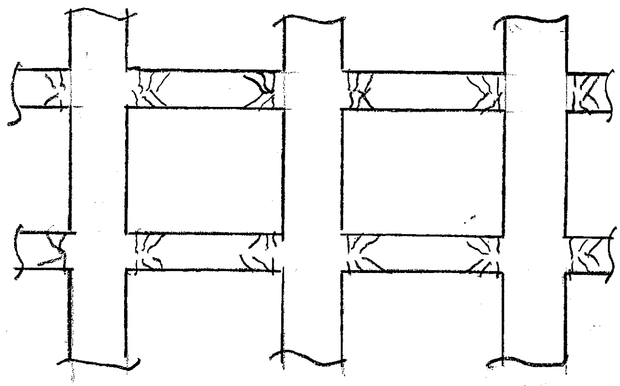
Figure 5-29 Variation of stiffness.

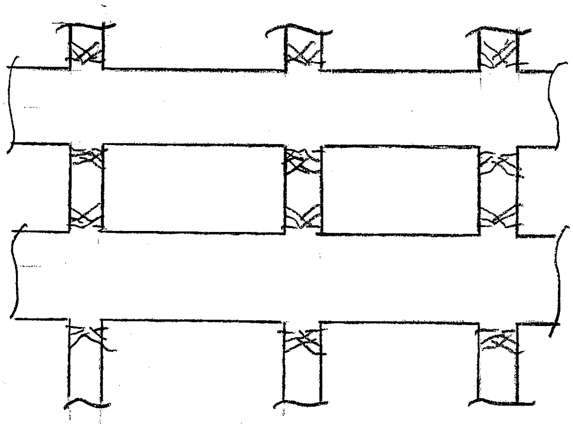


$\theta_s > \theta_\ell$

Short columns { attract more force, are subject to large rotation. more shear force

Weak Column – Strong Beam





Strong column-weak beam

Damages on beams usually induces ductile behavior.

Weak column-strong beam

Damages on column could leads to Collapse of the building.