ESSENTIAL OF STRUCTURAL SYSTEM FOR SEISMIC RESISTANCE

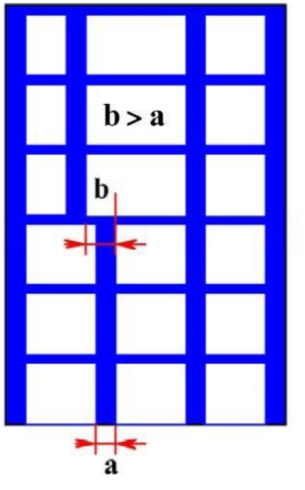
- All structural systems are not created equal when response to earthquake-induced forces is of concern.
- Aspects of structural configuration, symmetry, mass distribution, and vertical regularity must be considered, and the importance of strength, stiffness, and ductility in relation to acceptable response appreciated.
- The first task of the designer will be to select a structural system most conducive to satisfactory seismic performance within the constraints dictated by architectural requirements.

ESSENTIAL OF STRUCTURAL SYSTEM FOR SEISMIC RESISTANCE

- Where possible, architect and structural engineer should discuss alternative structural configurations at the earliest stage of concept development to ensure that undesirable geometry is not locked-in to the system before structural design begins.
- Irregularities, often unavoidable, contribute to the complexity of structural behavior. When not recognized, they may result in unexpected damage and even collapse.
- There are many sources of structural irregularities.

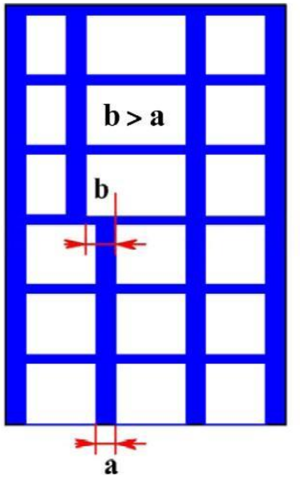
ESSENTIAL OF STRUCTURAL SYSTEM FOR SEISMIC RESISTANCE

- Drastic changes in geometry, interruptions in load paths, discontinuities in both strength and stiffness, disruptions in critical regions by openings, unusual proportions of members, reentrant corners, lack of redundancy, and interference with intended or assumed structural deformations are only a few of the possibilities.



ESSENTIAL OF STRUCTURAL SYSTEM FOR SEISMIC RESISTANCE

- The recognition of many of these irregularities and of conceptions for remedial measures for the avoidance or mitigation of their undesired effects rely on sound understanding of structural behavior.

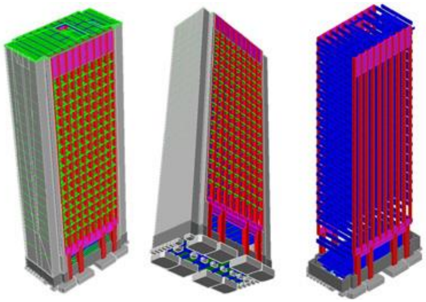


ESSENTIAL OF STRUCTURAL SYSTEM FOR SEISMIC RESISTANCE

- Awareness to search for undesired structural features and design experience are invaluable attributes.
- The relative importance of some irregularities may be quantified.
- In this respect some codes provide limited guidance.
- Examples for estimating the criticality of vertical and horizontal irregularities in framed buildings are given in next section.

STRUCTURAL SYSTEM FOR SEISMIC FORCES

- The primary purpose of all structures used for building is to support gravity loads.
- However, buildings may also be subjected to lateral forces due to wind or earthquakes.
- The taller a building, the more significant the effects of lateral forces will be.
- It is assumed here that seismic criteria rather than wind or blast forces govern the design for lateral resistance of buildings.
- Three types of structures, most commonly used for buildings.



STRUCTURAL SYSTEM FOR SEISMIC FORCES

- **Structural Frame Systems** Structures of multistory reinforced concrete buildings often consist of frames.
- Beams, supporting floors, and columns are continuous and meet at nodes, often called “rigid” joints.
- Such frames can readily carry gravity loads while providing adequate resistance to horizontal forces, acting in any direction.

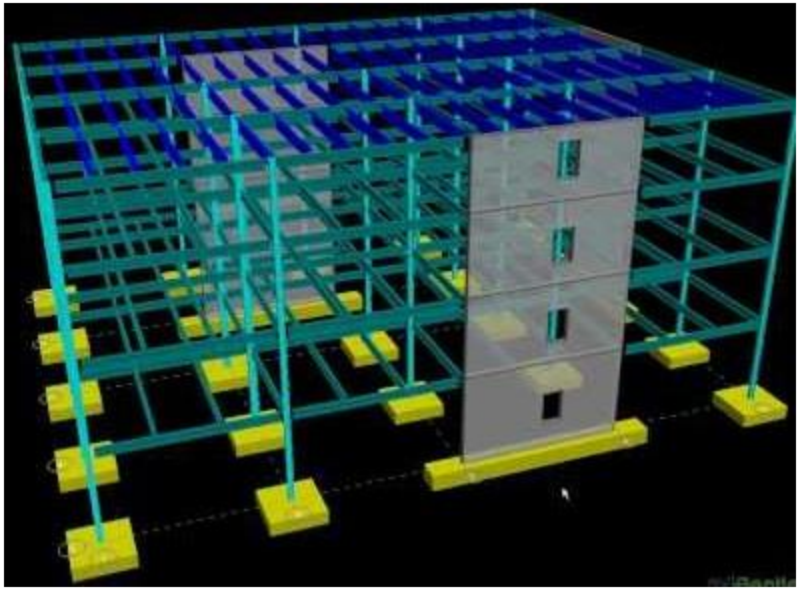
STRUCTURAL SYSTEM FOR SEISMIC FORCES

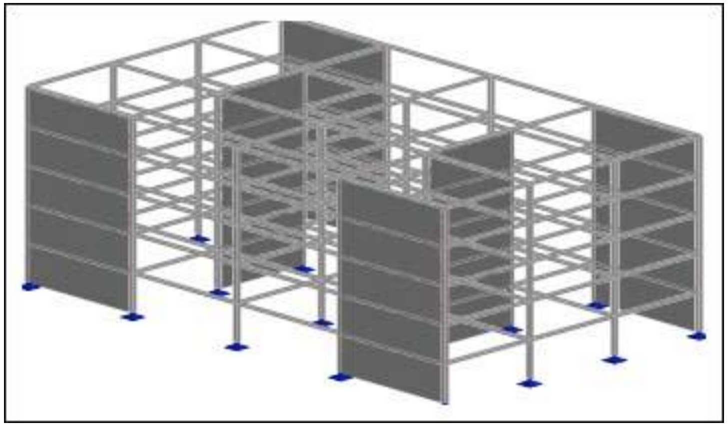
- **Structural Wall System** When functional requirements permit it, resistance to lateral forces may be assigned entirely to structural walls, using reinforced concrete or masonry.
- Gravity load effects on such walls are seldom significant and they do not control the design.
- Usually, there are also other elements within such a building, which are assigned to carry only gravity loads.

- **Structural Wall System**
- Their contribution to lateral force resistance, if any, is often neglected.
- The special features of reinforced masonry, particularly suited for the construction of walls that resist both gravity loads and lateral forces.

STRUCTURAL SYSTEM FOR SEISMIC FORCES

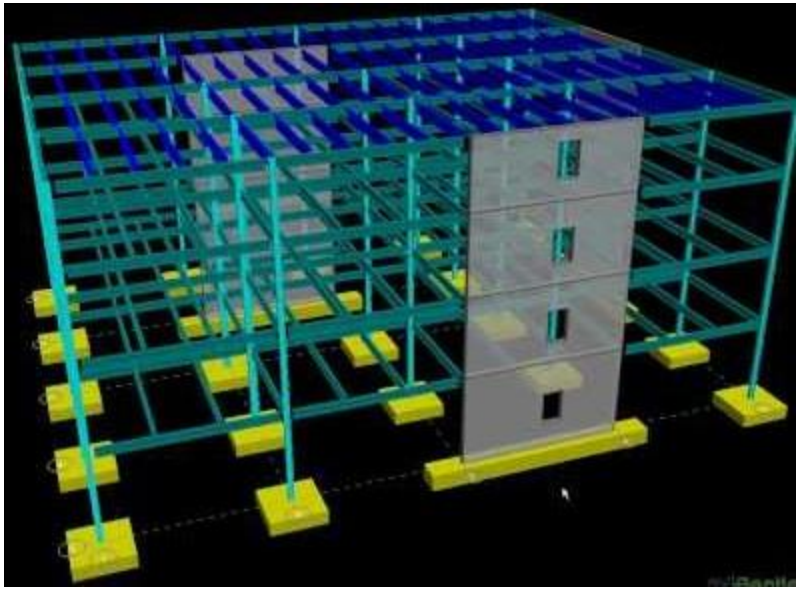
- **Dual Systems** In these, reinforced concrete frames interacting with reinforced concrete or masonry walls together provide the necessary resistance to lateral forces, while each system carries its appropriate share of the gravity load. These types of structures are variously known as dual, hybrid, or wall-frame structures.

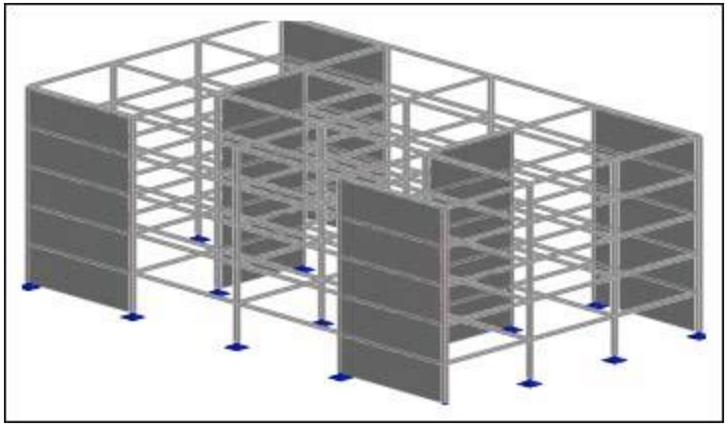




STRUCTURAL SYSTEM FOR SEISMIC FORCES

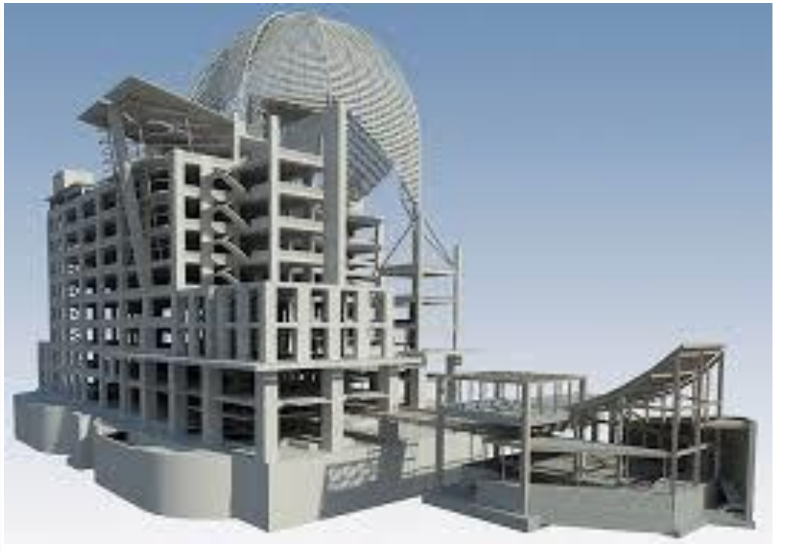
- **Dual Systems**
- The selection of structural systems for buildings is influenced primarily by the intended function, architectural considerations, internal traffic flow, height and aspect ratio, and to a lesser extent, the intensity of loading.

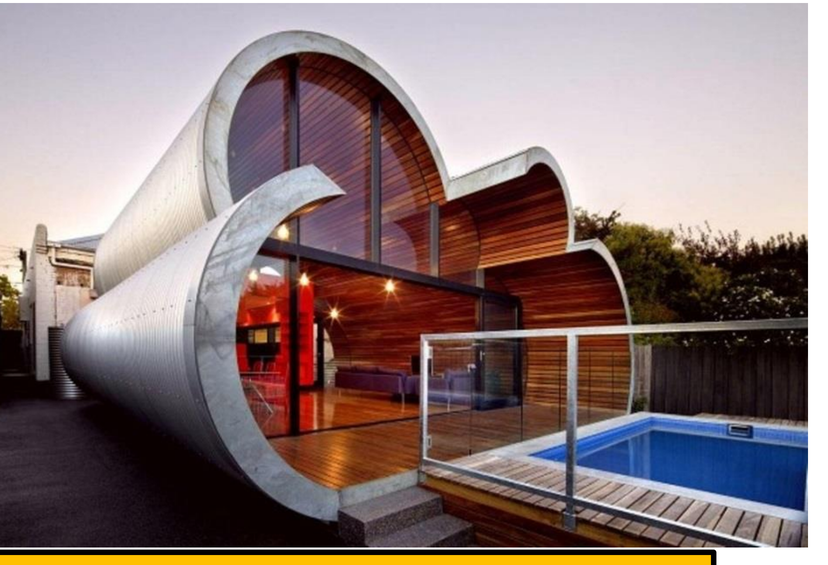




STRUCTURAL SYSTEM FOR SEISMIC FORCES

- The selection of a building's configuration, one of the most important aspects of the overall design, may impose severe limitations on the structure in its role to provide seismic protection.
- Because the intent is to present design concepts and principles, rather than a set of solutions, various alternatives within each of these three groups of distinct structural systems, listed above, will not be considered.
- Some structural forms are, however, deliberately omitted.



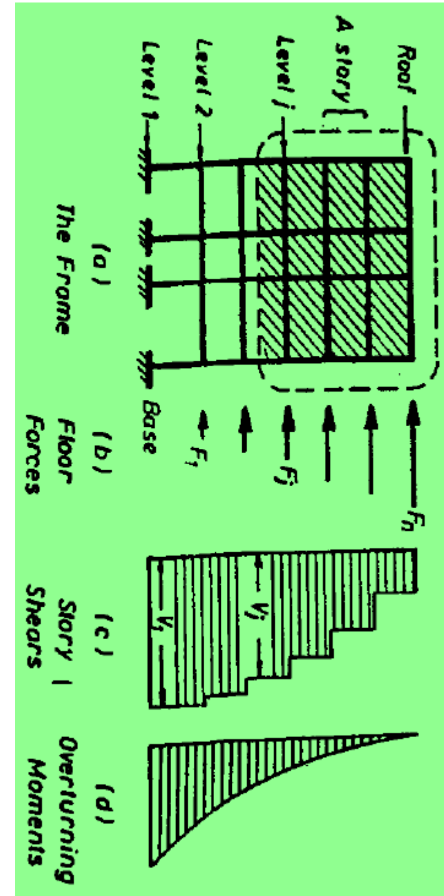


STRUCTURAL SYSTEM FOR SEISMIC FORCES

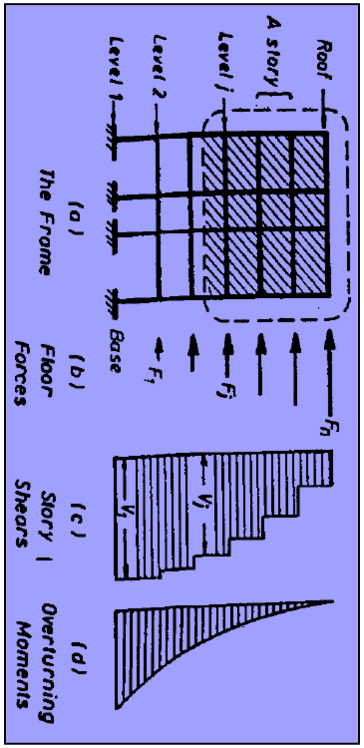
- For example, construction consisting of flat slabs supported by columns is considered to be unsuitable on its own to provide satisfactory performance under seismic actions because of excessive lateral displacements and the difficulty to providing the adequate and dependable shear transfer between columns and slabs, necessary to sustain lateral forces, in addition to gravity loads.

GROSS SEISMIC RESPONSE-RESPONSE IN ELEVATION

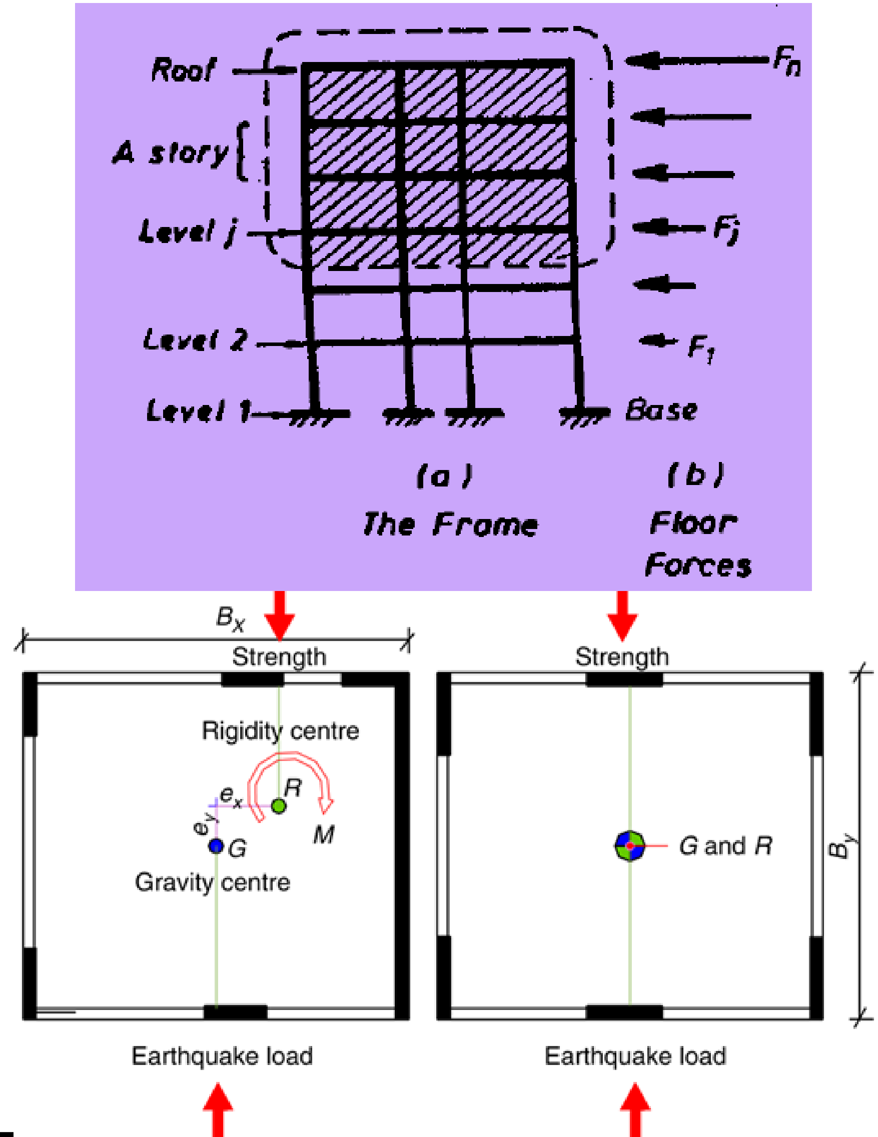
- The Building When subjected to lateral forces only, a building will act as a vertical cantilever.
- The resulting total horizontal force and the overturning moment will be transmitted at the level of the foundations.
- Once the lateral forces, such as may act at each level of the building, are known, the **story shear forces**, as well as the magnitude of overturning moments at any level, shown in figure, can readily be derived from usual equilibrium relationships.



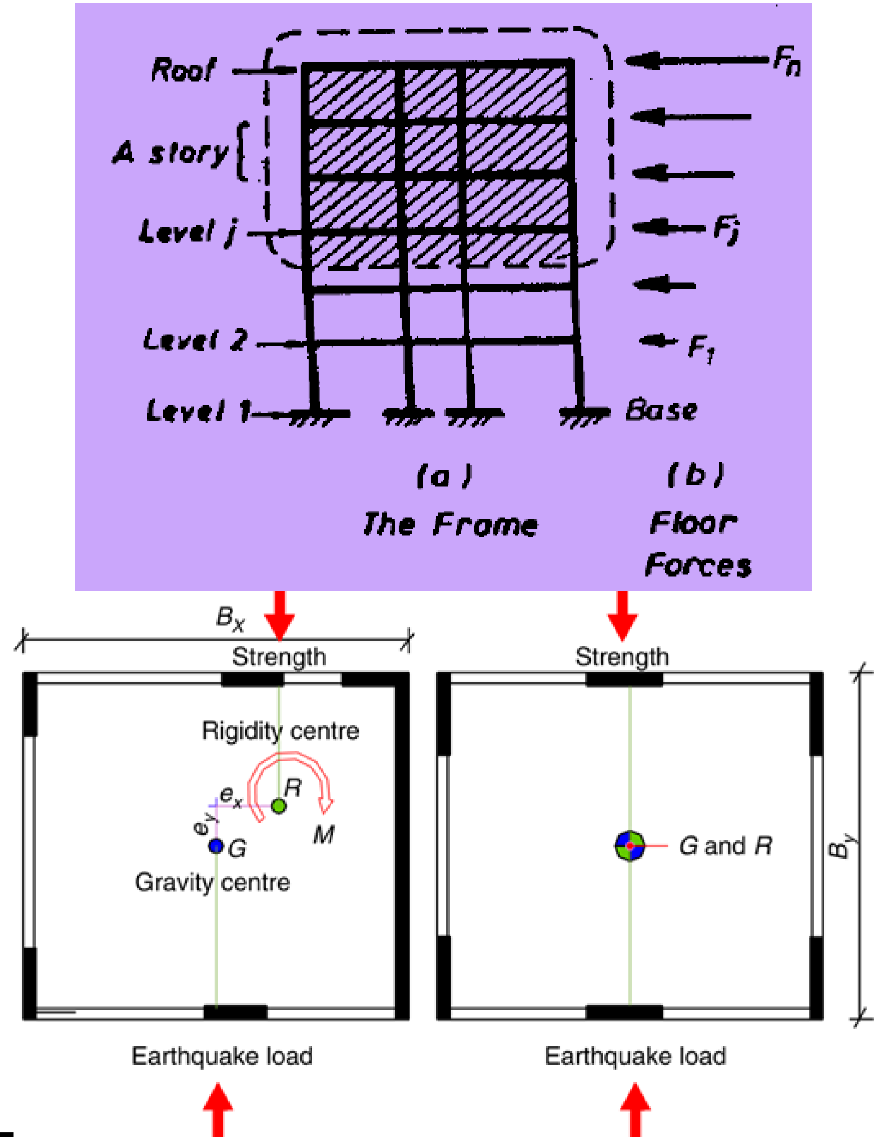
- For example, in figure ,the sum of shear of all floor forces acting on the shaded portion of the building must be resisted by shear and axial forces and bending moments in the vertical elements in the third story.
- The following terminology is used.
- All structures are assumed to be founded at the base or level 1. The position of a floor will be identified by its level above the base.
- Roof level is identical with the top level.
- The space or vertical distance between adjacent levels is defined as a story. Thus the first story is between levels 1 and 2, and the top story is that below roof level.



- **Centers of Mass and Rigidity** The structural system may consist of a number of frames, as shown in figure (a) or walls, or a combination of these.
- The position of the resultant force V_j in the horizontal plane will depend on the plan distribution of vertical elements, and it must also be considered.

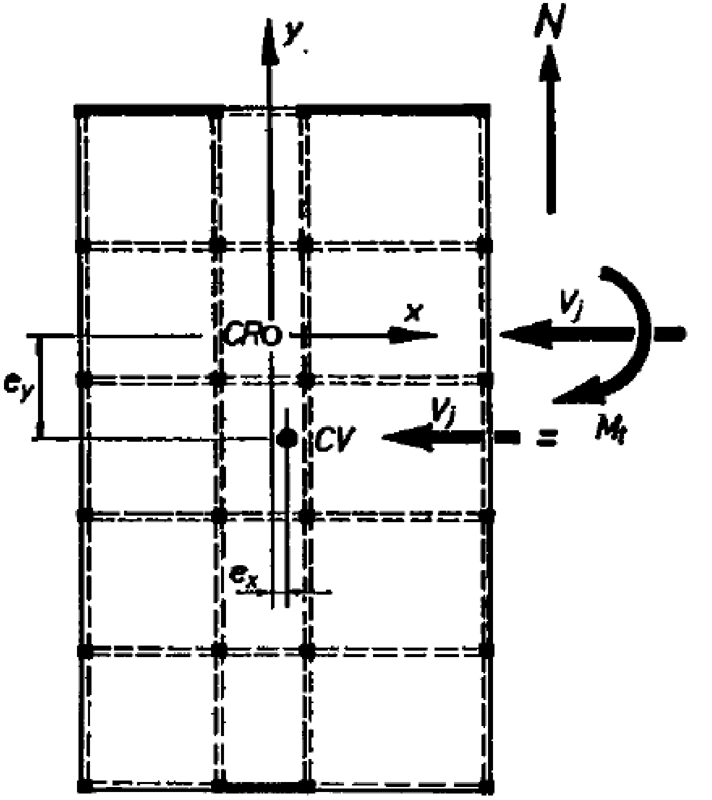


- **Centers of Mass and Rigidity**
- As a consequence, two important concepts must be defined. These will enable the effects of building configurations on the response of structural systems to lateral forces to be better appreciated.



GROSS SEISMIC RESPONSE-RESPONSE IN PLAN

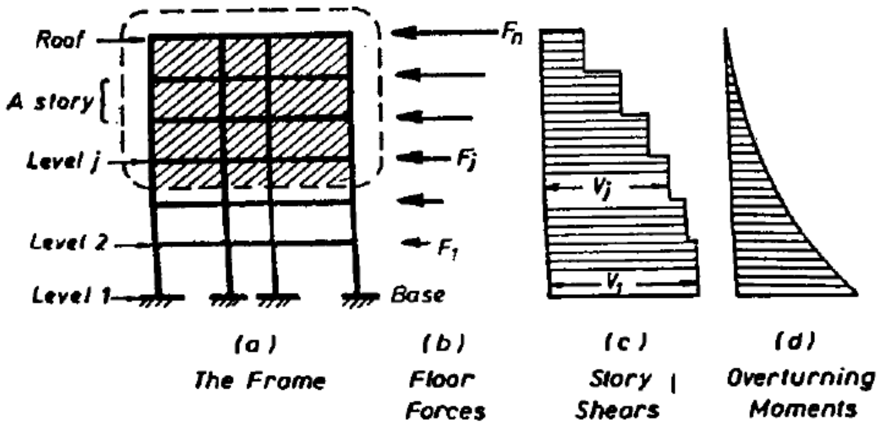
- **Center of Mass:** During an earthquake, acceleration-induced inertia forces will be generated at each floor level, where the mass of an entire story may be assumed to be concentrated.
- Hence the location of a force at a particular level will be determined by the center of the accelerated mass at that level.
- In regular buildings, such as shown in figure (d), the positions of the centers of floor masses will differ very little from level to level.

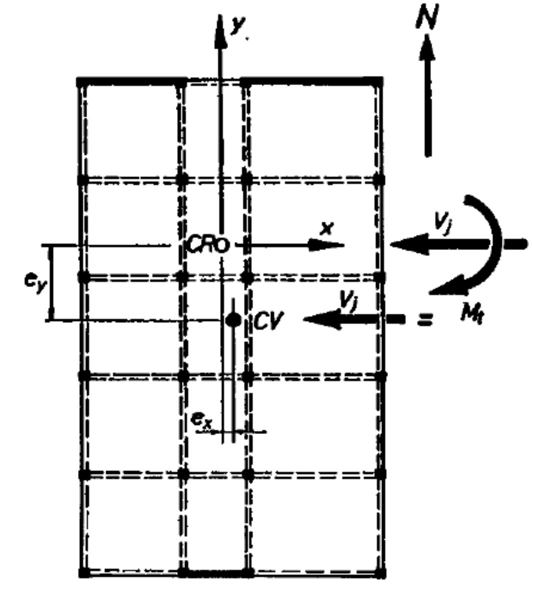


(d) Eccentricities

GROSS SEISMIC RESPONSE-RESPONSE IN PLAN

- However, irregular mass distribution over the height of a building may result in variations in centers of masses, which will need to be evaluated.
- The summation of all the floor forces, in figure (a), above a given story, with due allowance for the in-plane position of each, will then locate the position of the resultant force ***Vj*** within that story.

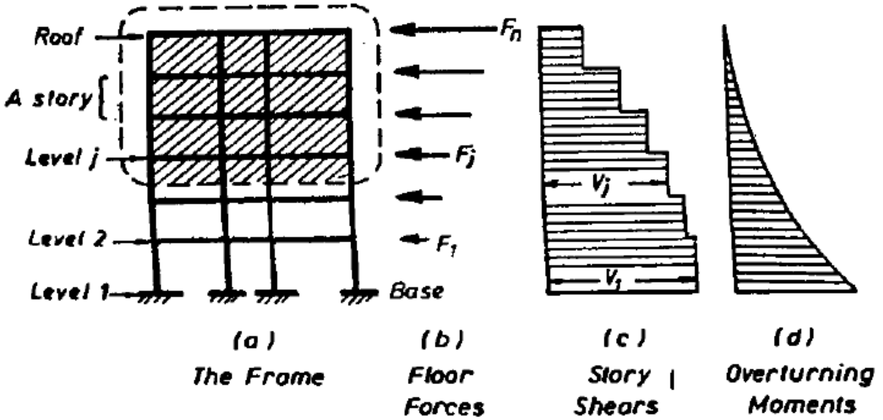


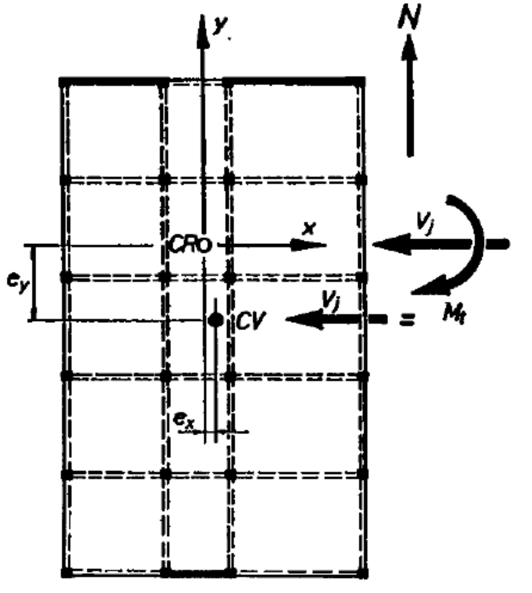


(d) Eccentricities

GROSS SEISMIC RESPONSE-RESPONSE IN PLAN

- For example, the position of the shear force within the third story is determined by point CV in figure (d), where this shear force is shown to act in the east-west direction.

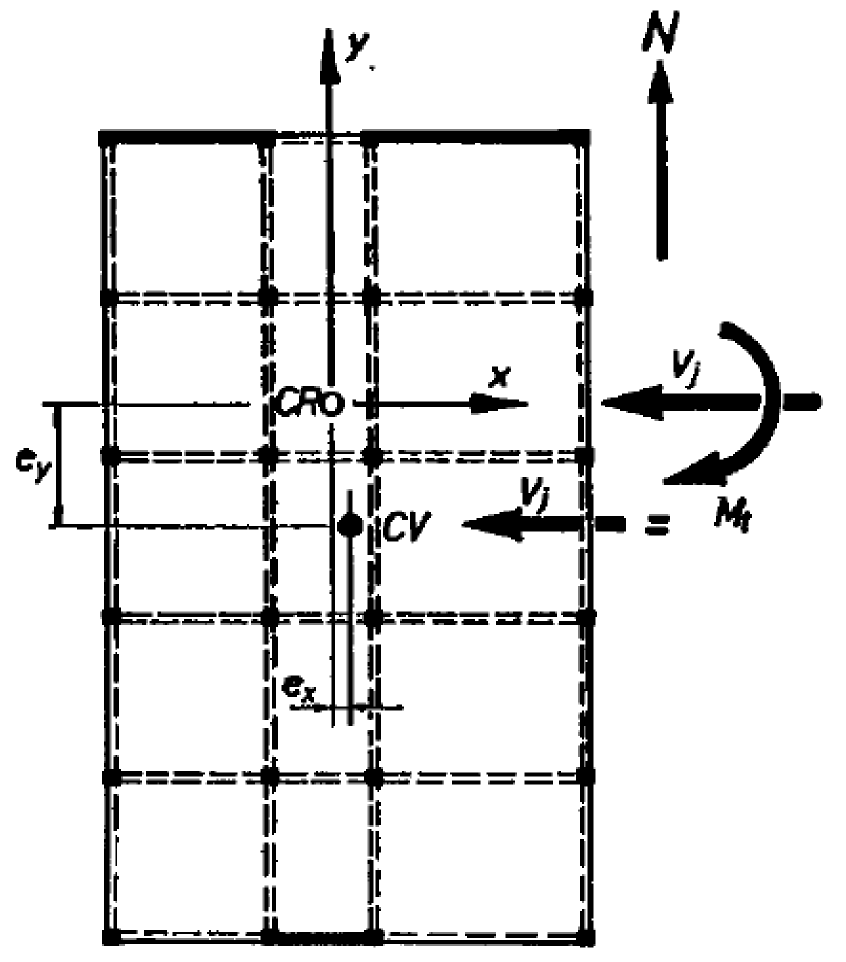




(d) Eccentricities

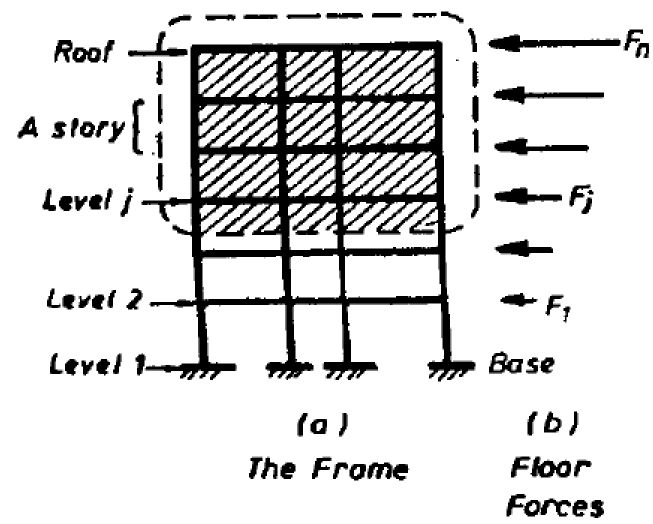
GROSS SEISMIC RESPONSE-RESPONSE IN PLAN

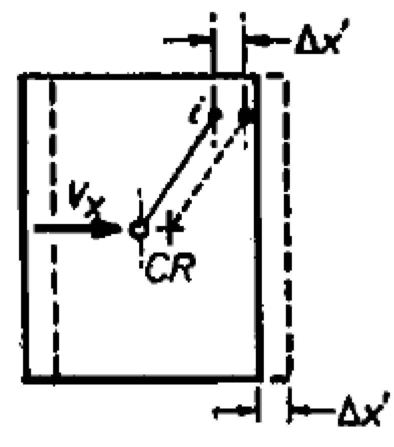
- Depending on the direction of an earthquake-induced acceleration at any instant, the force passing through this point may act in any direction.
- For a building of the type shown in figure (d), it is sufficient, however, to consider seismic attacks only along the two principal axes of the plan.



(d) Eccentricities

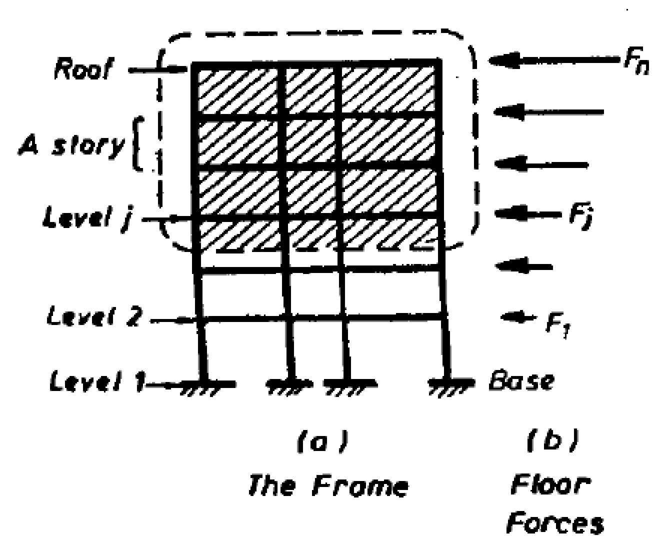
- **Center of Rigidity:** If, as a result of lateral forces, one floor of the building in figure translates horizontally as a rigid body relative to the floor below, as shown in figure (a), a 'constant inter-story displacement Δx' will be imposed on all frames and walls in that story.
- Therefore, the induced forces in these elastic frames and walls, in the relevant east-west planes, will be proportional to the respective stiffness's.

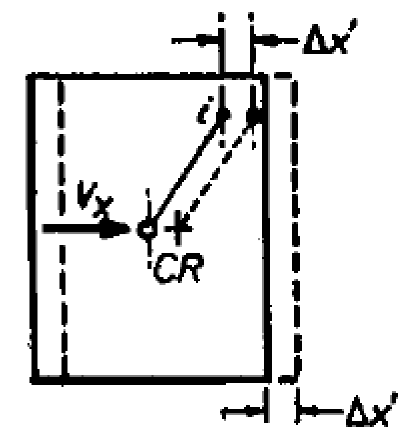




(a) Translation

- **Center of Rigidity:** The resultant total force, $\boldsymbol{V_j}=\boldsymbol{V_x}$, induced by the translational displacements Δx', will pass through the center of rigidity (CR) in previous figure (d).

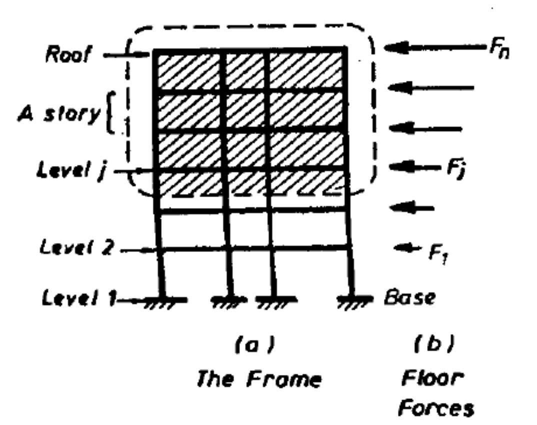


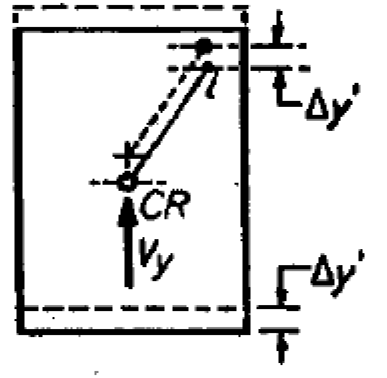


(a) Translation

GROSS SEISMIC RESPONSE-RESPONSE IN PLAN

- Similarly, a relative floor translation to the north, shown as Δy' in Fig (b), will induce corresponding forces in each of the four frames Fig. (d), the resultant of which, V_y, will also pass through point CR.
- This point, defined as the center of rigidity or center of stiffness, locates the position of a story shear force V_j which will cause only relative floor translations.
- The position of the center of rigidity may be different in each story.
- It is relevant to story shear forces applied in any direction in a horizontal plane.





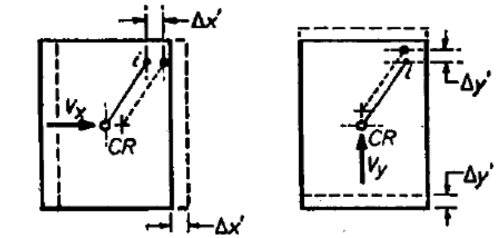
(b) Translation

GROSS SEISMIC RESPONSE-RESPONSE IN PLAN

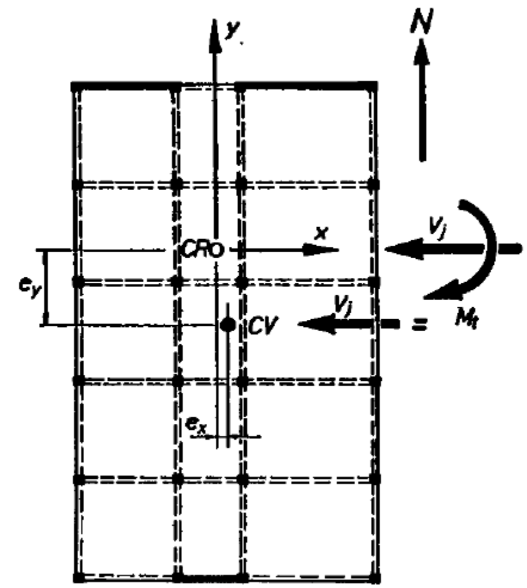
- Such a force may be resolved into components, such as V_x and Vy shown in Fig. (a) and (b), which will cause simultaneous story translations Δx' and Δy', respectively.

- Since the story shear force in Fig (d) acts through point CV rather than the center of rigidity CR, it will cause floor rotation as well as relative floor translation.

- For convenience, V_j may be replaced by an equal force acting through CR, thus inducing pure translation, and a moment $M_t = e_y \times V_j$ about CR, leading to rigid floor rotation, as shown in Fig. (c).



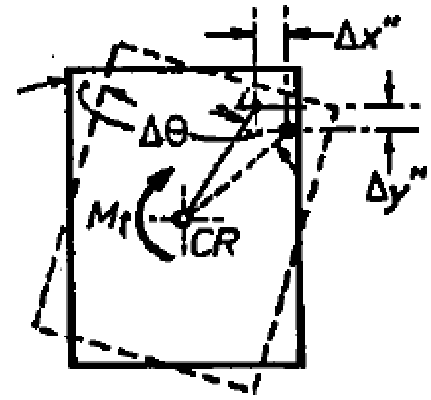
(a) Translation (b) Translation



(d) Eccentricities

GROSS SEISMIC RESPONSE-RESPONSE IN PLAN

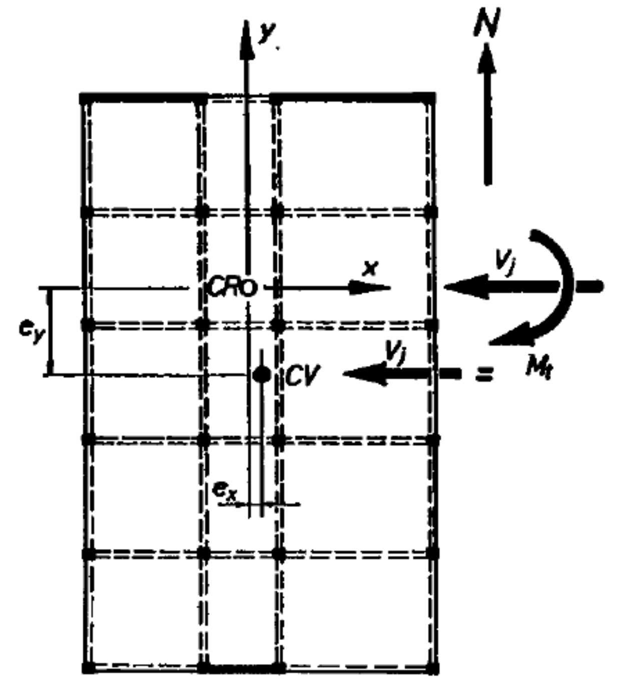
- The angular rotation Δθ is termed story twist.
- It will cause additional interstory displacements $\Delta_{x''}$ and $\Delta_{y''}$ in lateral force resisting elements in both principal directions, x and y.
- The displacements due to story twist are proportional to the distance of the element from the center of rotation, [i.e., the center of rigidity (CR)].
- Displacements due to story twist, when combined with those resulting from floor translations, can result in total element inter-story displacements that may be difficult to accommodate.



(c) Twist

GROSS SEISMIC RESPONSE-RESPONSE IN PLAN

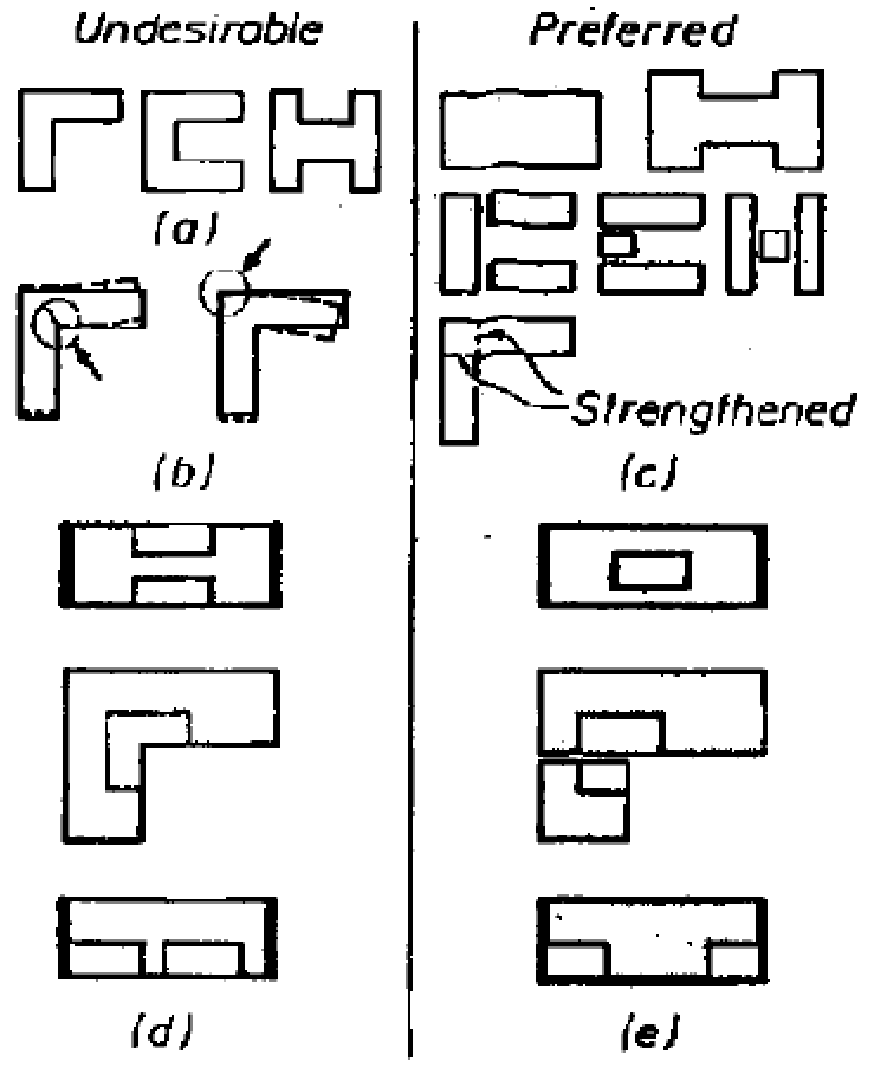
- For this reason the designer should attempt to minimize the magnitude of story torsion M_t
- This may be achieved by a deliberate assignment of stiffness's to lateral force-resisting components, such as frames or walls, in such a way as to minimize the distance between the center of rigidity (CR) and the line of action of the story shear force (CV).
- To achieve this in terms of floor forces, the distance between the center of rigidity and the center of mass should be minimized.



(d) Eccentricities

INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE

- An aspect of seismic design of equal ,if not greater importance than structural analysis, is the choice of building configuration.
- By observing the following fundamental principles, relevant to seismic response, more suitable structural systems may be adopted.
- Simple, regular plans are preferable. Building with articulated plans such as T and L shapes' should be avoided or be subdivided into simpler forms



INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE

- Symmetry in plan should be provided where possible. Gross lack of symmetry may lead to significant torsional response, the reliable prediction of which is often difficult.
- Much greater damage due to earthquakes has been observed in buildings situated at street corners, where structural symmetry is more difficult to achieve, than in those along streets, where a more simple rectangular and often symmetrical structural plan could be utilized.

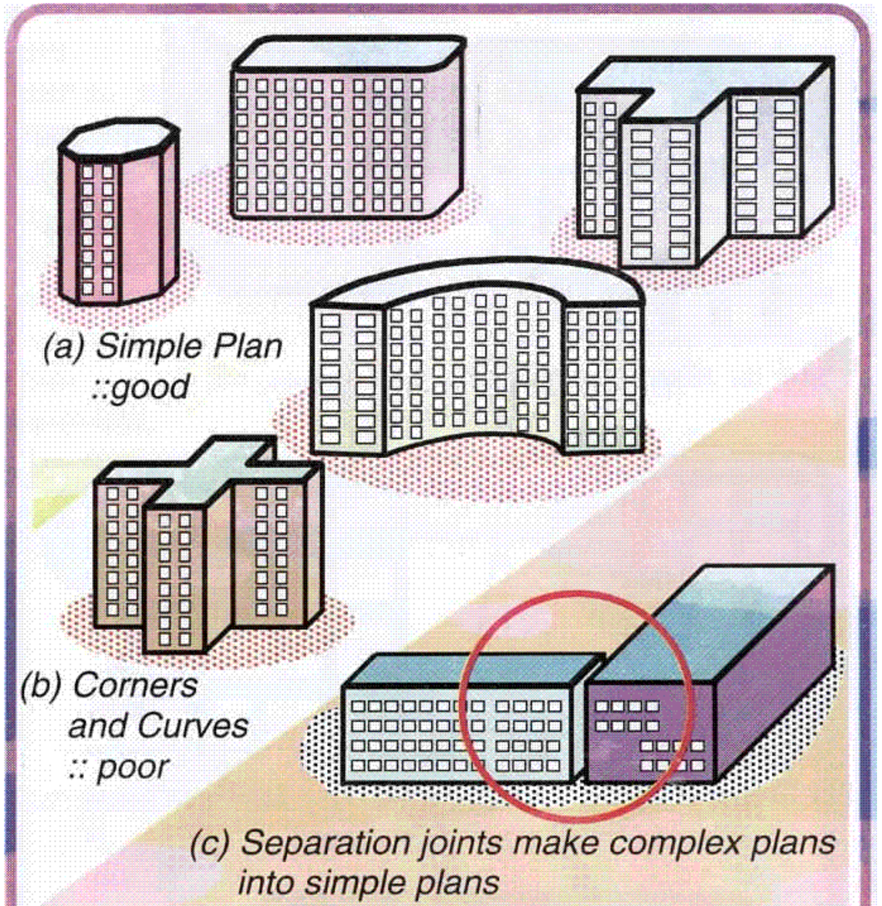
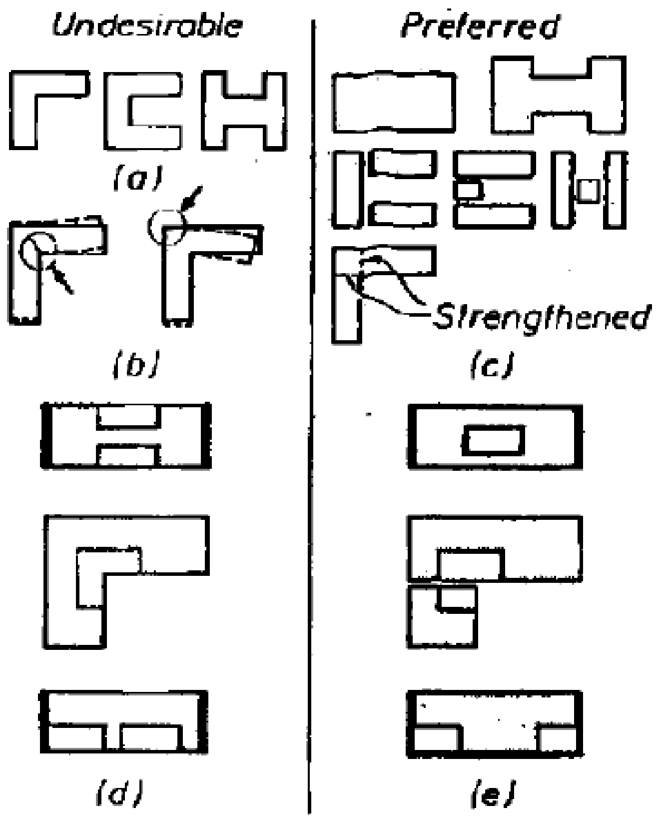


Figure 2: Simple plan shape buildings do well during earthquakes.

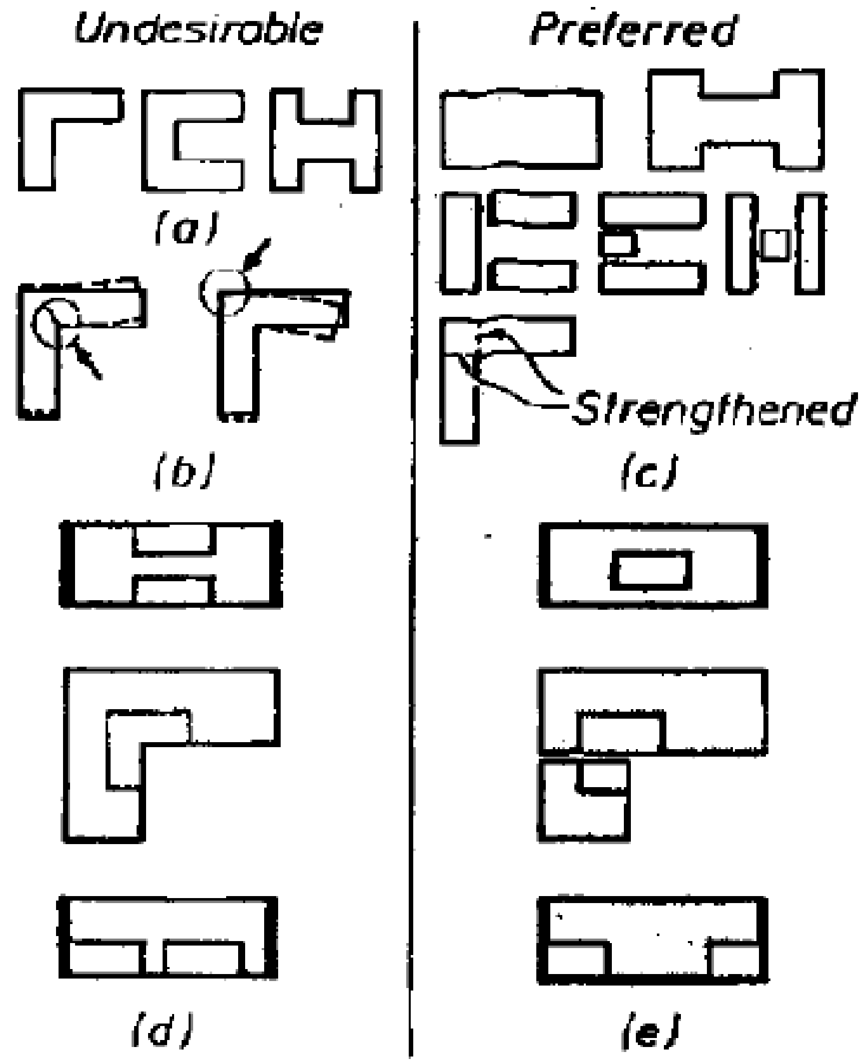
INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE

- An integrated foundation system should tie together all vertical structural elements in both principal directions.
- Foundations resting partly on rock and partly on soils should preferably be avoided.
- Lateral-force-resisting systems within one building, with significantly different stiffness's such as structural walls and frames, should be arranged in such a way that at every level symmetry in lateral stiffness is not grossly violated.
- Thereby undesirable torsional effects will be minimized.



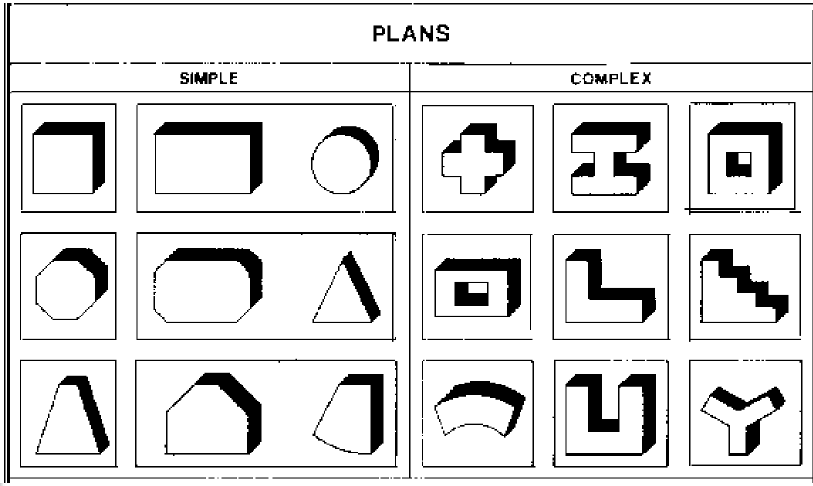
INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE

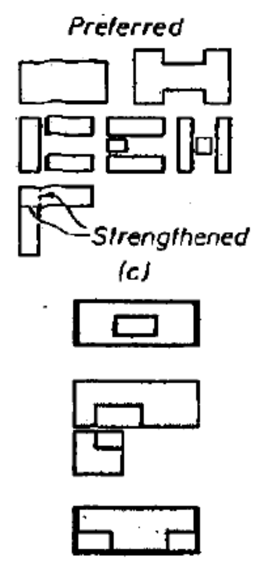
- Regularity should prevail in elevation, in both the geometry and the variation of story stiffness's.
- The principles described above are examined in more detail in the following section.



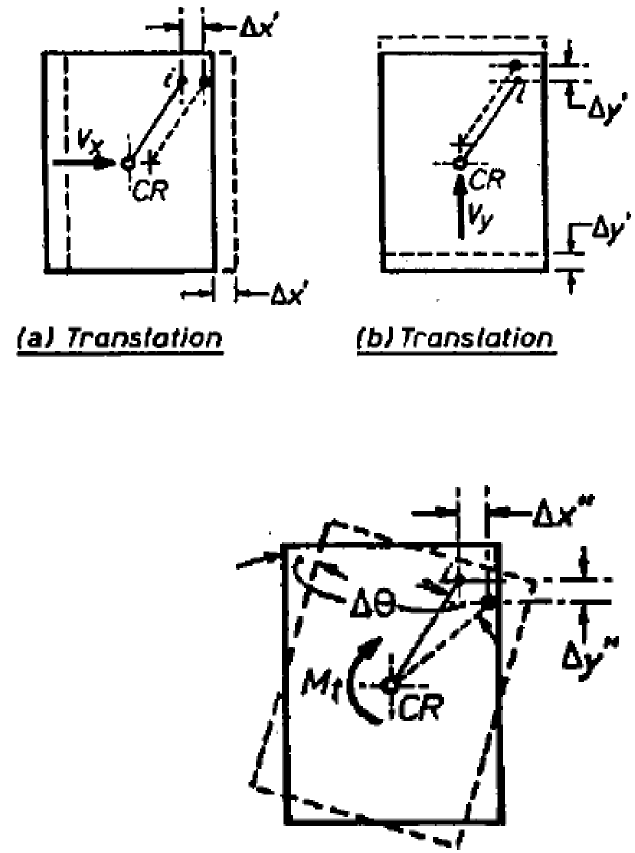
INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-ROLE OF FLOOR DIAPHRAGM

- Simple and preferably symmetrical building plans hold the promise of more efficient and predictable seismic response of each of the Structural components.
- A prerequisite for the desirable interaction within a building of all lateral-force-resisting vertical components of the structural system is an effective and relatively rigid interconnection of these components at suitable levels.
- This is usually achieved with the use of floor systems, which generally possess large in-plane stiffness.





- Vertical elements will thus contribute to the total lateral force resistance, in proportion to their own stiffness.
- With large in-plane stiffness, floors can act as diaphragms.
- Hence a close to linear relationship between the horizontal displacements of the various lateral-force-resisting vertical structural elements will exist at every level.
- From rigid-body translations and rotations, shown in Fig., the relative displacements of vertical elements can readily be derived.

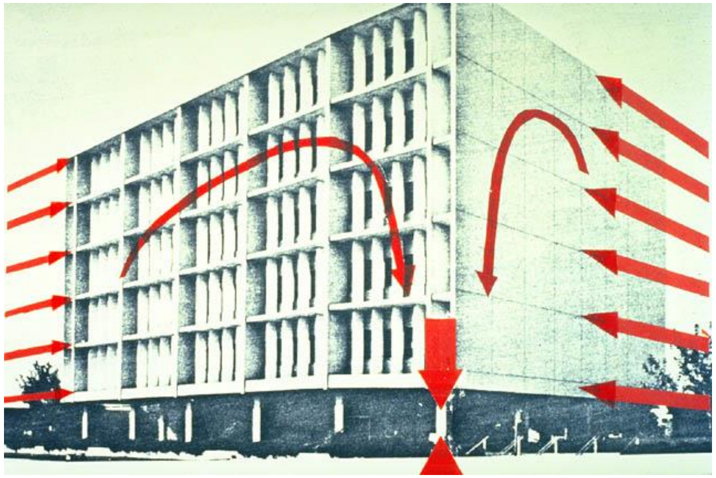


(a) Translation (b) Translation

(c) Twist

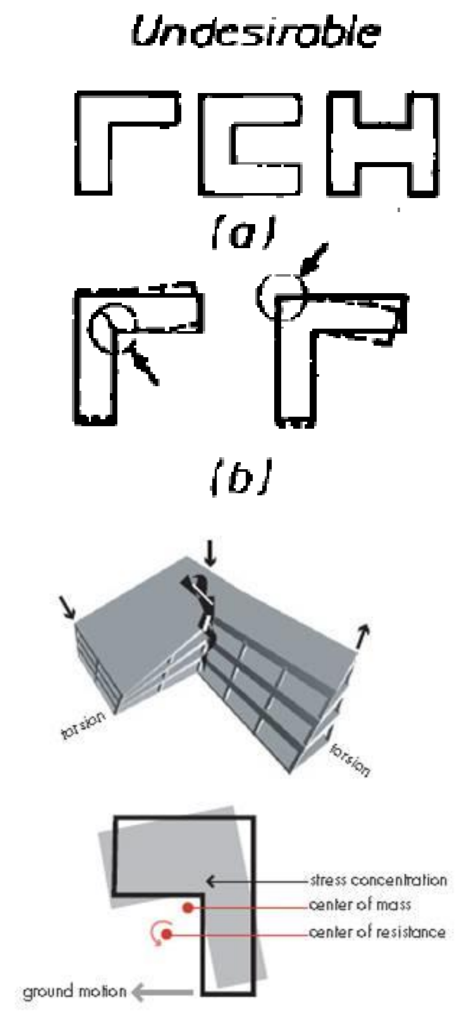
INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-ROLE OF FLOOR DIAPHRAGM

- Another function of a floor system, acting as a diaphragm, is to transmit inertia forces generated by earthquake accelerations of the floor mass at a given level to all horizontal-force-resisting elements.
- At certain levels, particularly in lower storey's, significant horizontal forces from one element, such as a frame, may need to be transferred to another, usually stiffer element, such as a wall.
- These actions may generate significant shear forces and bending moments within a diaphragm.



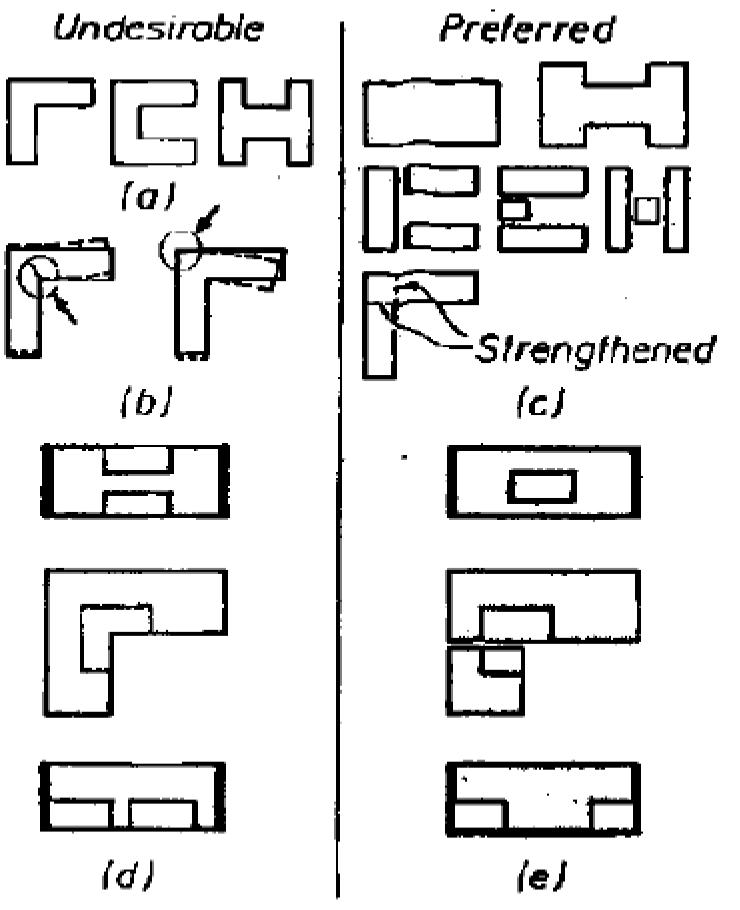
INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-ROLE OF FLOOR DIAPHRAGM

- In squat rectangular diaphragms, the resulting stresses will be generally insignificant.
- However, this may not be the case when long or articulated floor plans, such as shown in Fig. (a)have to be used.
- The correlation between horizontal displacements of vertical elements Fig. (b), will be more difficult to establish in such eases.
- Reentrant corners, inviting stress concentrations, may suffer premature damage. When such configurations are necessary, it is preferable to provide structural separations.



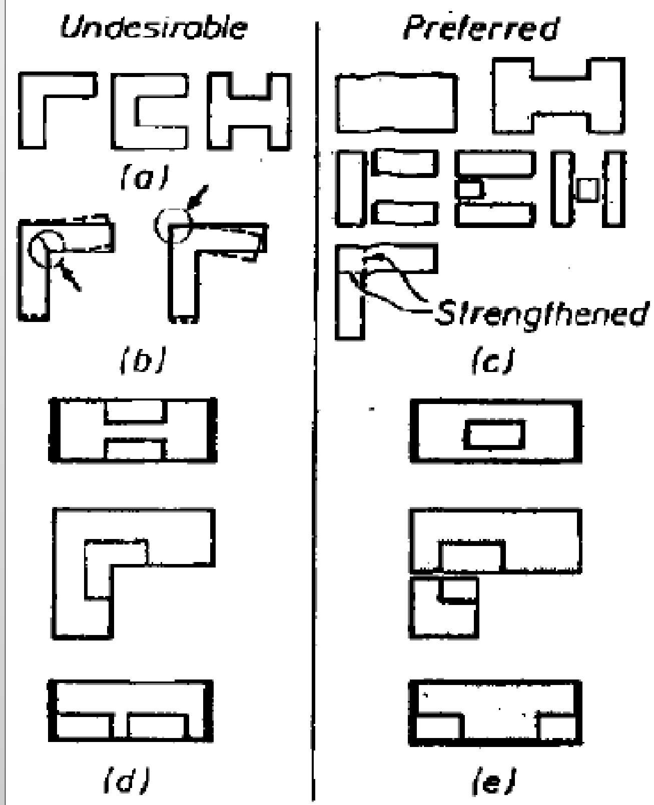
INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-ROLE OF FLOOR DIAPHRAGM

- This may lead to a number of simple, compact, and independent plans, as shown in Figure.
- Gaps separating adjacent structures must be large enough to ensure that even during a major seismic event, no hammer- ing of adjacent structures will occur due to out-of-phase relative motions of the independent substructures.
- Inelastic deflections, resulting from ductile dynamic response, must be allowed.



INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-ROLE OF FLOOR DIAPHRAGM

- Diaphragm action may be jeopardized if openings, necessary for vertical traffic within a multistory building or other purposes, significantly reduce the ability of the diaphragm to resist in-plane flexure of shear, as seen in examples in Fig. (d).
- The relative importance of openings may be estimated readily from a simple evaluation of the flow of forces within the diaphragm, necessary to satisfy equilibrium criteria.
- Preferred locations for such openings are suggested in Fig. (e).

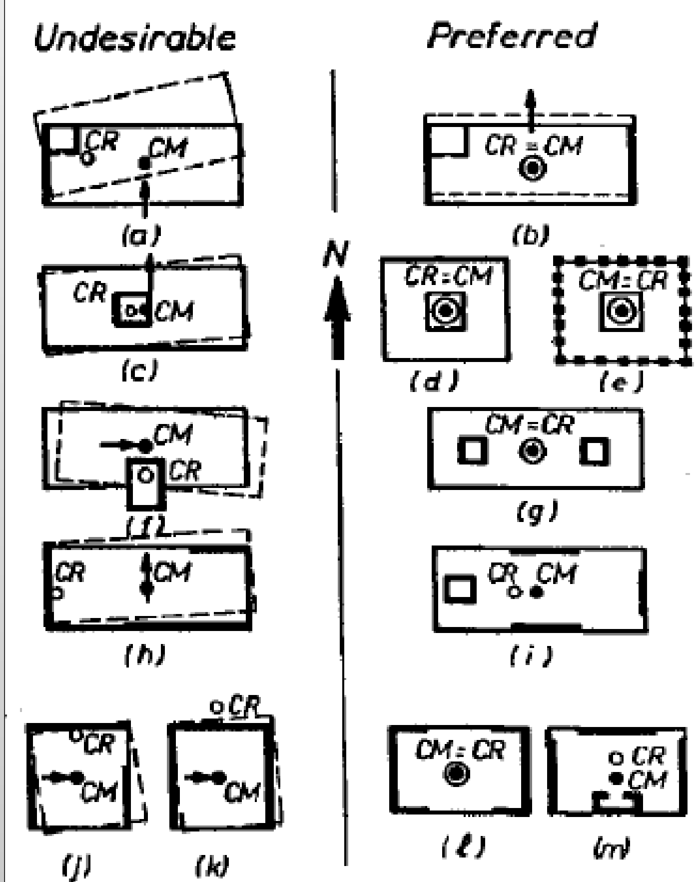


INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-ROLE OF FLOOR DIAPHRAGM

- As a general rule, diaphragms should be designed to respond elastically, as they are not suitable to dissipate energy through the formation of plastic regions.
- Using capacity design principles, to be examined subsequently, it is relatively easy to estimate the magnitudes of the largest forces that might be introduced to diaphragms.

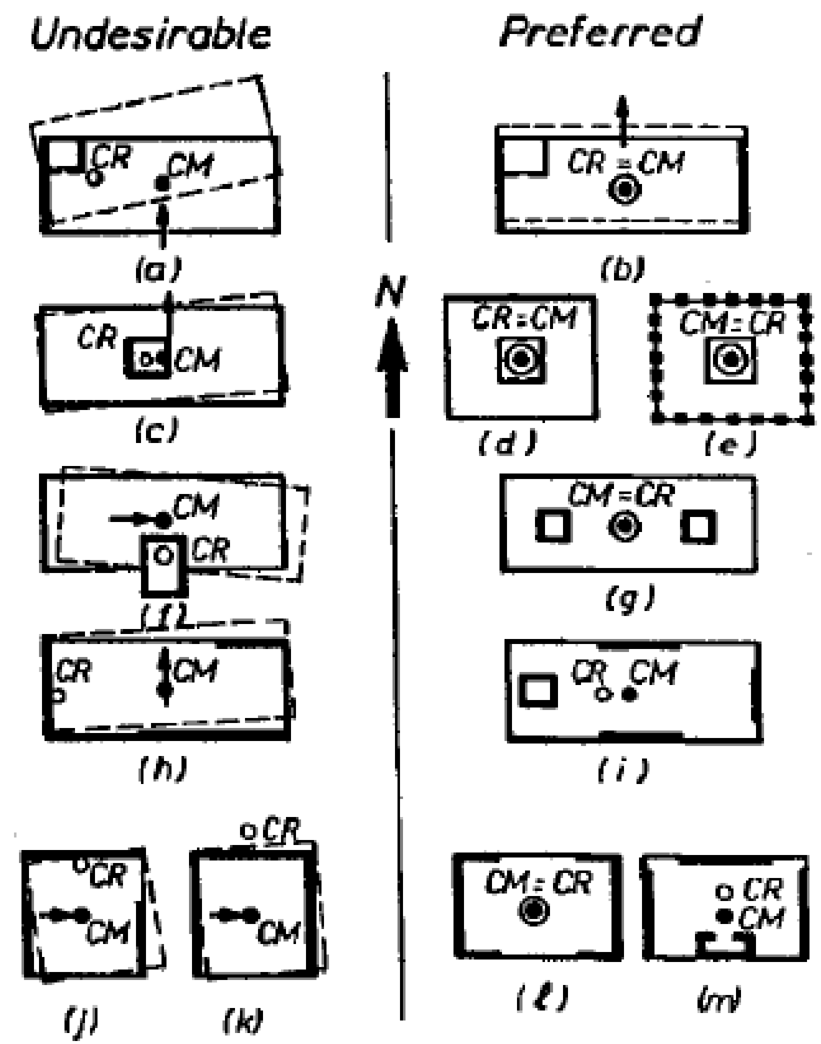
INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-TORSIONAL EFFECTS

- To avoid excessive displacements in lateral-force-resisting components that are located in adverse positions within the building plan, torsional effects should be minimized.
- This is achieved by reducing the distance between the center of mass (CM), where horizontal- seismic floor forces are applied, and the center of rigidity (CR).
- A number of examples for both undesirable positioning of major lateral force-resisting elements, consisting of structural walls and frames, and for the purpose of comparison, preferred locations, are given in Figure.



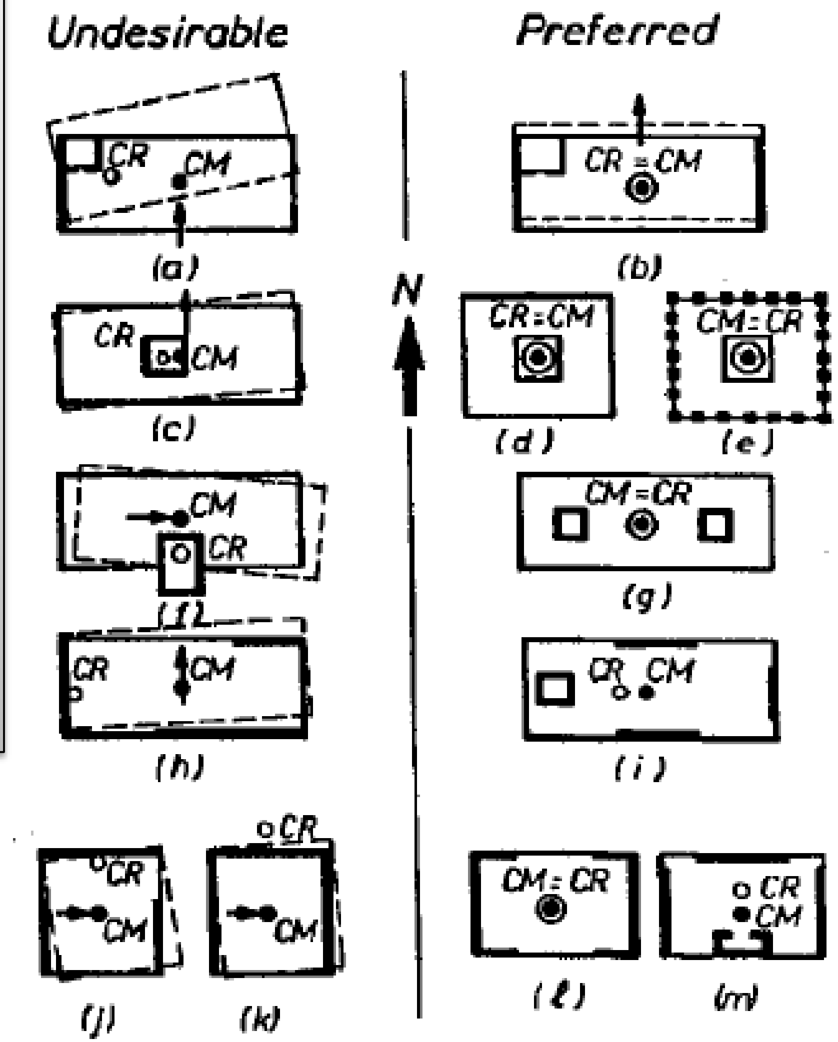
INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-TORSIONAL EFFECTS

- For the sake of clarity the positioning of frames required solely for gravity load resistance within each floor plan is generally not shown.
- While the primary role of the frames in these examples will be the support of gravity load, it must be appreciated that frames will also contribute to both lateral force resistance and torsional stiffness.



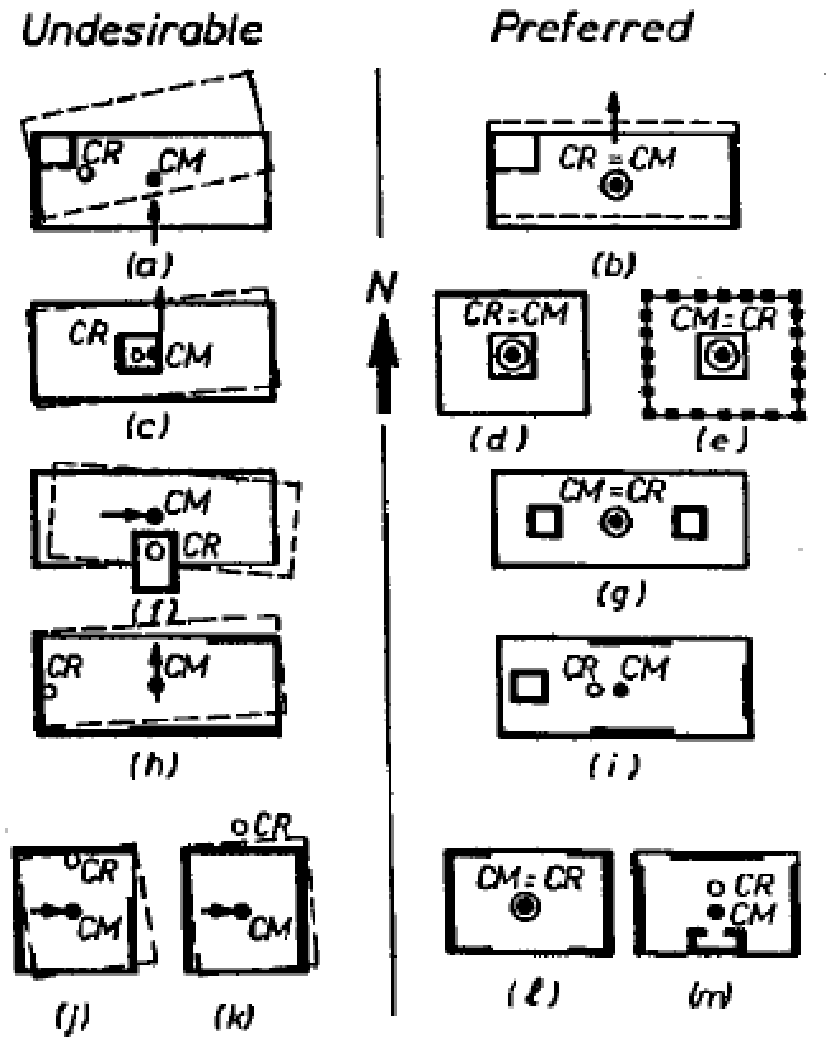
INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-TORSIONAL EFFECTS

- Figure (a) shows that because of the location of a still wall at the west end of a building, very large displacements, as a result of floor translations and rotations will occur at the east end.



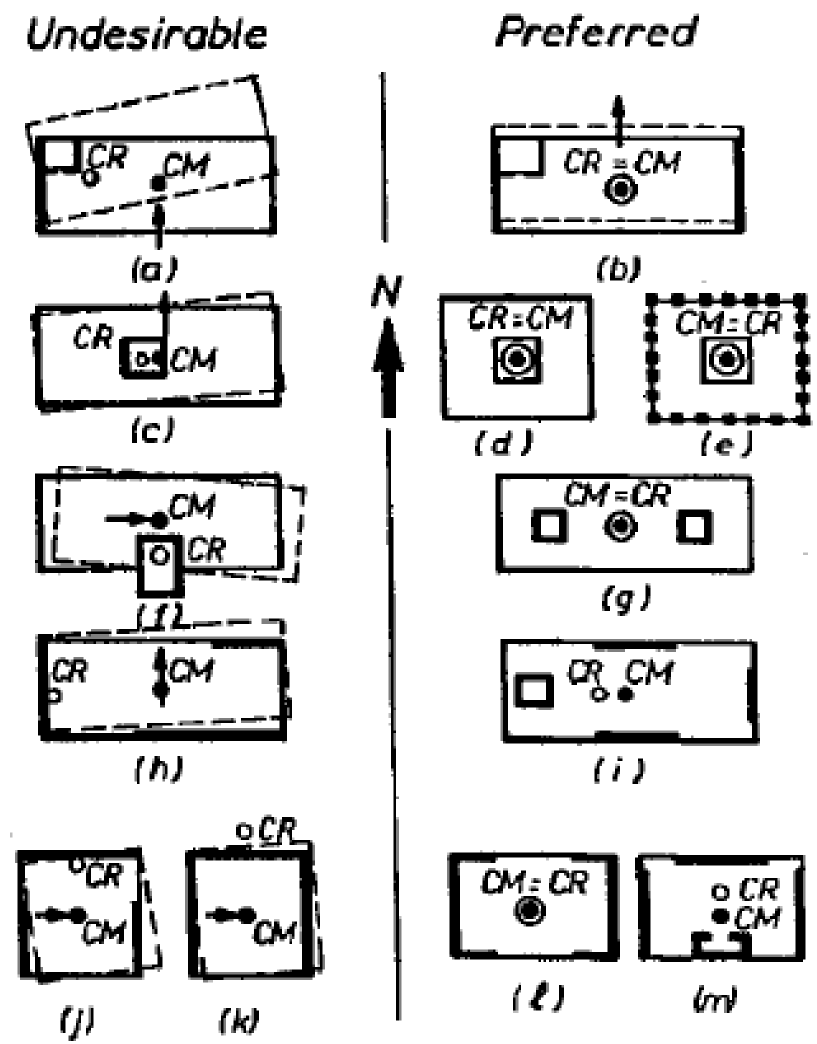
INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-TORSIONAL EFFECTS

- As a consequence, members of a frame located at the east end may be subjected to excessive inelastic deformations (ductility).
- Excessive ductility demands at such a location may cause significant degradation of the stiffness of a frame. This will lead to further shift of the center of rigidity and consequently to an amplification of torsional effects.



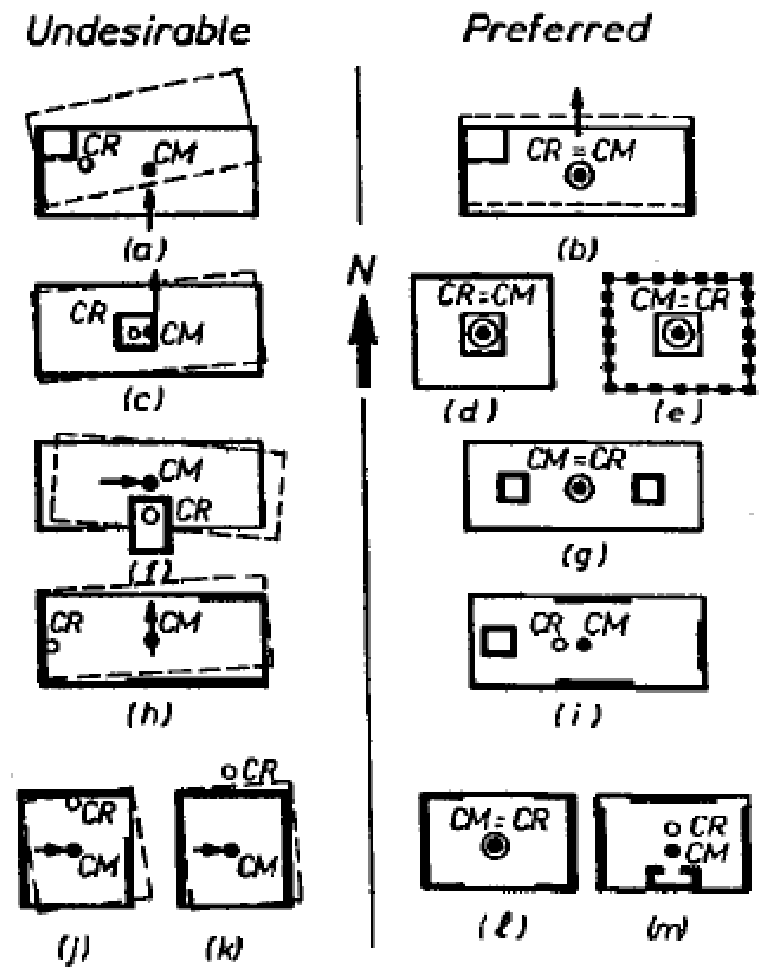
INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-TORSIONAL EFFECTS

- A much improved solution, shown in Fig. (b), where the service core has been made nonstructural and a structural wall added at the east end will ensure that the centers of mass and stiffness virtually coincide.



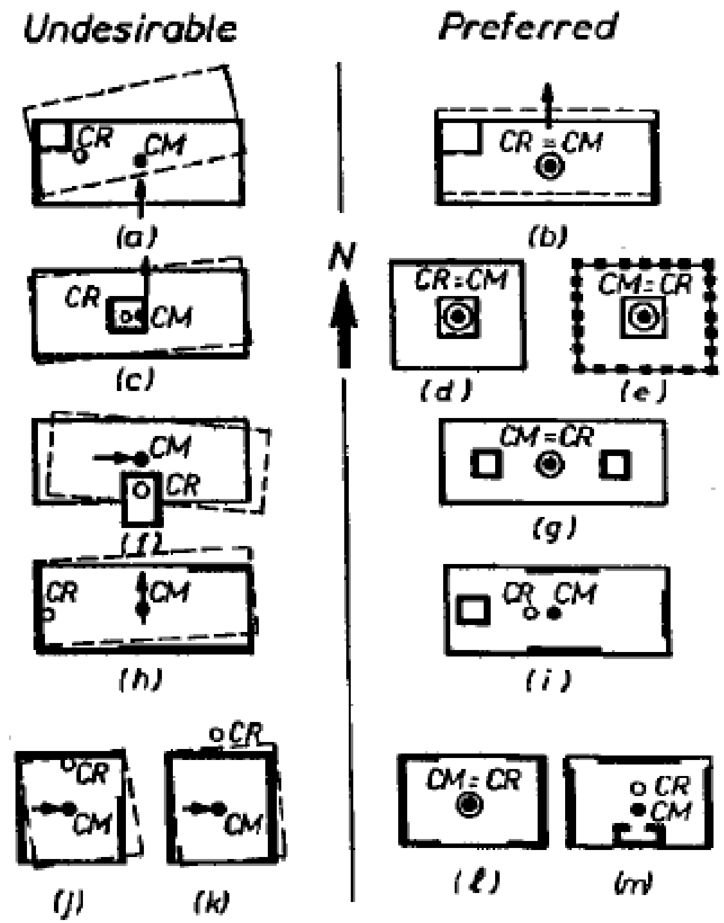
INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-TORSIONAL EFFECTS

- Hence only dominant floor translations, imposing similar ductility demands on all lateral force resisting frames or walls, are to be expected.
- Analysis may show that in some buildings torsional effects [Fig. (c)] may be negligible.
- However, as a result of normal variations in material properties and section geometry, and also due to the effects of torsional components of ground motion, torsion may arise also in theoretically perfectly symmetrical buildings.



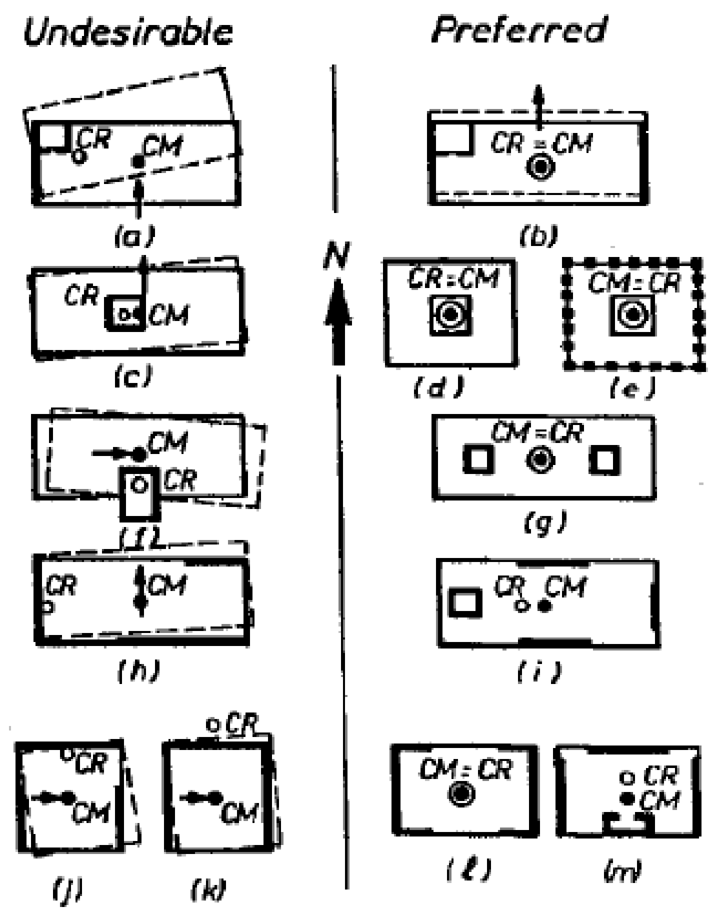
INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-TORSIONAL EFFECTS

- Hence codes require that allowance be made in all buildings for so-called “accidental” torsional effects.
- Although a reinforced concrete or masonry core, such as shown in Fig. (c), may exhibit good torsional strength, its torsional stiffness, particularly after the onset of diagonal cracking, may be too small to prevent excessive deformations at the east and west ends of the building.
- Similar twists may lead, however, to acceptable displacements at the perimeter of square plans with relatively large cores, seen in Fig. (d).



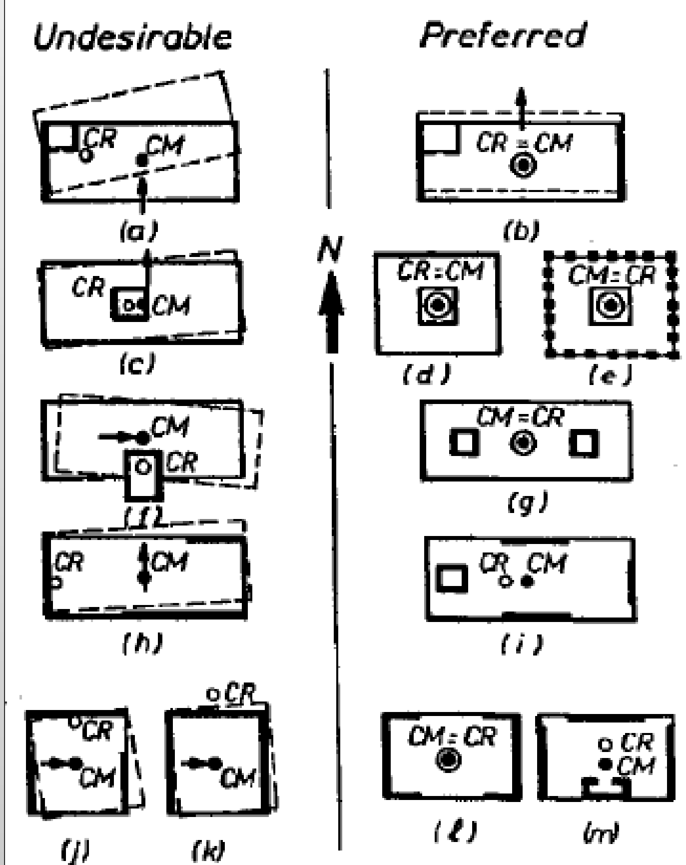
INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-TORSIONAL EFFECTS

- Closely placed columns, interconnected by relatively stiff beams around the perimeter of such buildings. [Fig. (e)], can provide excellent control of torsional response.
- The eccentrically placed service core, shown in Fig. (f), may lead to excessive torsional effects under seismic attack in the east-west direction unless perimeter lateral force resisting elements are present to limit torsional displacements.
- The advantages of the arrangement, shown in Fig. (g), in terms of response to horizontal forces are obvious.



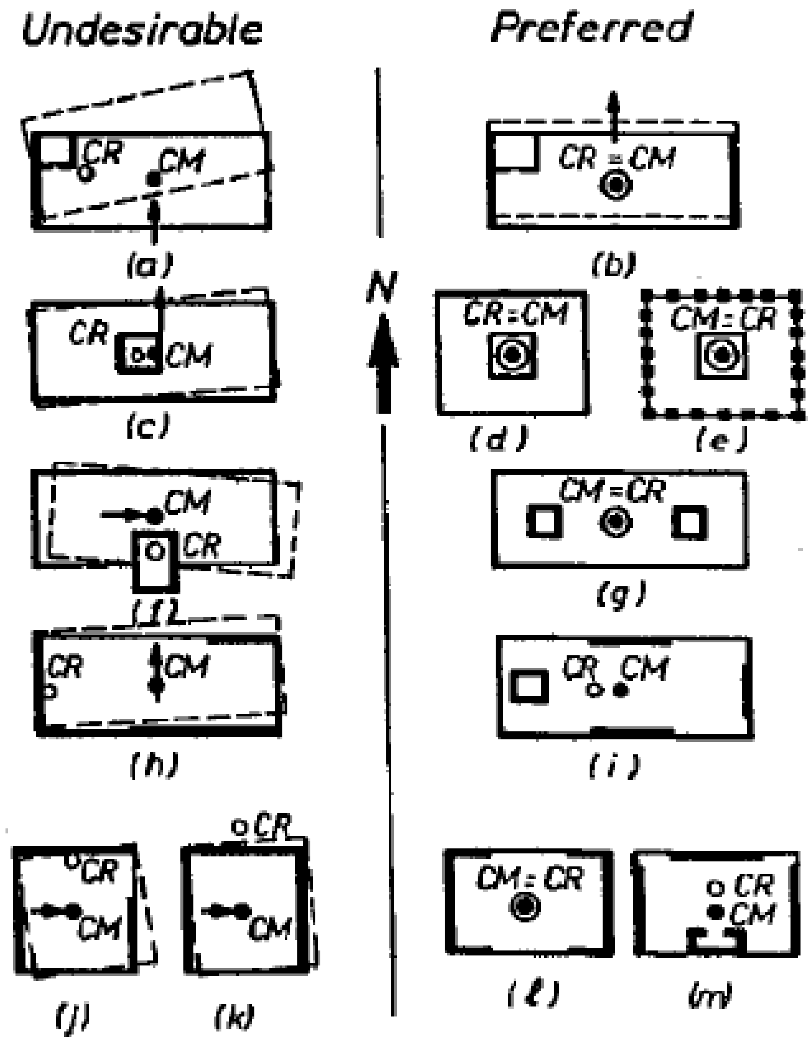
INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-TORSIONAL EFFECTS

- While the locations of the walls in Fig. (h), to resist lateral forces, it satisfactory, the large eccentricity of the center of mass with respect to the center of rigidity will result in large torsion when lateral forces are applied in the north-south direction.
- The placing of at least one stiff element at or close to each of the four sides of the buildings, as shown in Fig. (i), provides a particularly desirable structural arrangement.
- Further examples, showing wall arrangements with large eccentricities and preferred alternative solutions, are given in Fig. (j) to (m).



INFLUENCE OF BUILDING CONFIGURATGION ON SEISMIC RESPONSE-TORSIONAL EFFECTS

- Although large eccentricities are indicated in the examples of Fig. (j) and (k), both stiffness and the strength of these walls may well be adequate to accommodate torsional effects.
- The examples apply to structures where walls provide the primary lateral load resistance.
- The principles also apply to framed systems, although it is less common for excessive torsional effects to develop in frame structures.



CASE HISTORY-BUILDING A

3.7.1 Building A

Figure 3-44 Front elevation of Building A

CASE HISTROY-BUILDI

- Building A, shown in Figures 3-44 and 3-45, was located at the eastern outskirts of Golcuk (Turkey). Much of the first story of this moment-frame building (not seen in Figure 3-44) was located below grade.
- The grade level sloped down from the front to the back PM of the building. A sketch of the first-floor plan of the building is shown in Figure 3-46.
- Most of the hollow clay tile infill masonry failed during the earthquake but some remained intact at the rear of the building in the sixth story (see Figure 3-45).

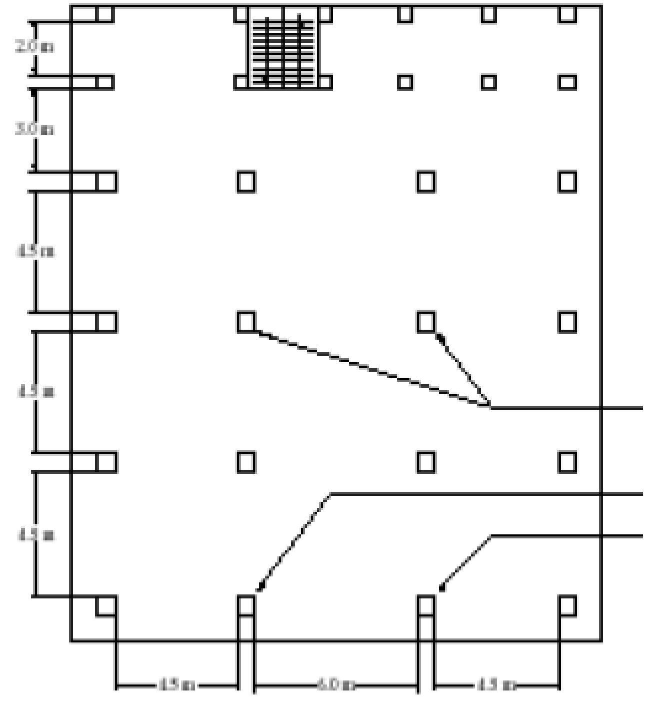
3.7.1 Building A

Figure 3-44 Front elevation of Building A

Figure 3-45 Rear elevation of Building A showing intact infill masonry walls

Component Failures

- Structural damage was concentrated in the first-story columns at the front of the building Figure 3-47) and around the stairwell at the rear of the building (Figure 3-48).
- Non ductile detailing was evident in each damaged component viewed by the reconnaissance team.



CASE HISTROY-BUILDING A

- The staircases in the rear stairwell were cast integrally with the exterior columns. The landings were located approximately 1 m below the beam-column joints (Figure 3-48).
- No transverse reinforcement was present in these joints. The lateral support provided by the landings and the staircases resulted in short column construction and led to shear failures immediately above the landings.

Figure 3-47 Damage to first story columns

Figure 3-48 Damage at the rear stairwell

CASE HISTROY-BUILDING A

- Figure 3-48 shows severe damage to the staircases that suggests that the staircases resisted significant lateral forces during the earthquake via strut action. The lateral stiffness of the staircases is

Figure 3-47 Damage to first story columns

Figure 3-48 Damage at the rear stairwell

CASE HISTROY-BUILDING A

- The lateral stiffness of the staircases is evinced by the damage they suffered but likely was not included in the earthquake analysis of the building (which is also common practice in the United States).

Figure 3-48 Damage at the rear stairwell

CASE HISTROY-BUILDING A

- The distribution of damage to columns in the first story is shown in Figure 3-46. Figures 3-49, 3-50, and 3-51 show column failures.
- Non-ductile detailing is evident, including widely spaced perimeter transverse ties with 90° hooks and no cross ties, and lap splices located at the floor level with no confining transverse reinforcement.

Figure 3-49 Shear failure of Column A (See Figure 3-46)

CASE HISTROY-BUILDING A

System Response

- A comprehensive performance-based evaluation methodology should be able to predict distributions of damage similar to that identified above assuming an accurate characterization of earthquake shaking.
- The performance of Building A brings into question the procedures currently adopted in the United States for system evaluation for the performance level of collapse prevention.

Figure 3-50 Axial failure of column B (See Figure 3-46)

CASE HISTROY-BUILDING A

- (In this report, “collapse” is defined in terms of the failure of the gravity load-resisting system.)
- As shown in Figures 3-46 and 3-47, the first and third rows of columns were badly damaged but the second row of columns suffered no significant damage. All columns in the first three rows were the same size; rebar in the first and third rows of columns were essentially identical.

Figure 3-51 Axial failure at lap splice in Column C (See Figure 3-46)

CASE HISTROY-BUILDING A

- If the interior columns in the first row failed initially, conventional approaches would suggest that lateral forces were redistributed to other stiff components (including the second row of columns) and gravity loads were transferred to the undamaged columns in the first and second rows.
- The increase in the gravity and earthquake effects should have been greater on the second-row columns than on the third-row columns, yet the columns in the third row failed and the columns in the second row were undamaged.

Figure 3-51 Axial failure at lap splice in Column C (See Figure 3-46)

CASE HISTROY-BUILDING A

- New knowledge regarding the transfer of lateral loads and gravity from failed components to other components of a building frame is needed to obtain accurate estimates of building performance.
- Although several columns in the first story of the building failed in shear and axial compression, the building did not collapse.
- Clearly system response cannot be judged on the basis of the most highly loaded (forces or deformations) component in the building, as is the practice in FEMA 273, NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA 1997).

CASE HISTROY-BUILDING A

- The gravity load resisting system of the building did not collapse for a number of reasons that include

  (a)frame action in the stories above the damaged columns and

  (b) residual axial-load capacity in the heavily damaged columns.

- After the columns in the first row failed in shear and shortened, the slab and beam framing deflected in the shape of a catenary (see the sag in the floor slabs in Figure 3-44) and gravity loads were carried to the adjacent undamaged columns by axial tension in the beams and slabs.

CASE HISTROY-BUILDING A

- Vierendeel truss action in the upper stories also likely transferred gravity loads to adjacent undamaged columns.
- Provision for such redundancy in framing systems would reduce the likelihood of building collapse and substantially uncouple system-level response from component-level response.
- The catenary and Vierendeel truss mechanisms may be very effective in stabilizing the structure when interior columns are lost. To ensure that beams and slabs are able to maintain catenary deflections, bottom reinforcement should be continuous through any columns that may fail under lateral loads.

CASE HISTROY-BUILDING A

- Recent studies (Moehle et al. 2000) have shown that columns heavily damaged in shear are still capable of supporting axial loads.
- Residual axial strength in these columns would reduce the need to redistribute gravity loads as described in the previous paragraph. The failed columns in the first row were squat so that after failure in shear, the upper segments of the columns bore on the lower segments, albeit not concentrically. (Contrast this behavior with that described earlier for narrow columns; see **Figure 3-32**).

CASE HISTROY-BUILDING A

- The core concrete in the failed columns in the third row continued to carry gravity loads after the earthquake because the cores of the columns remained partially intact.
- The use of transverse reinforcement in the amount needed to keep the core of a column intact at large deformation would further reduce the likelihood of building collapse.

CASE HISTROY-BUILDING A

a. damage from out-of-plane deformation

b. unseating of beam-slab system from column

Figure 3-32 Damage and failures at ends of moment-frame columns

BACK

CASE HISTROY-BUILDING A

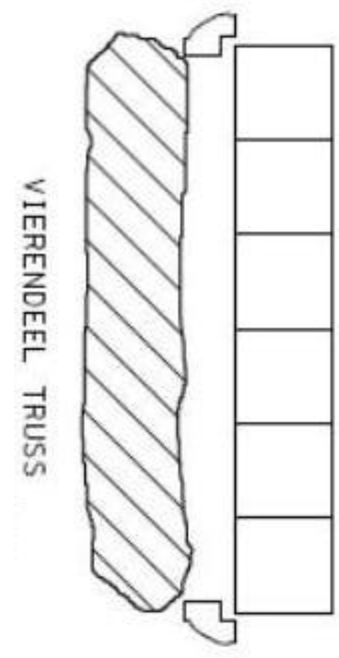
3.7.1 Building A

Figure 3-44 Front elevation of Building A

BACK

CASE HISTROY-BUILDING A

- The Vierendeel truss/girder is characterized by having only vertical members between the top and bottom chords and is a statically indeterminate structure.
- Hence, bending, shear and axial capacity of these members contribute to the resistance to external loads.
- The use of this girder enables the footbridge to span larger distances and present an attractive outlook. However, it suffers from the drawback that the distribution of stresses is more complicated than normal truss structures



BACK