Important Concepts in the Seismic Design: Dos and Don'ts

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Introduction & Summary of the Course:

While conceiving a new construction project, an architect or designer should give thorough thought to the form, shape, and material of the structure, as well as the functional and cost requirements, to avoid a critical failure during an earthquake. Often, architects conceive wonderful and imaginative forms and shapes to create an aesthetic and functionally efficient structure. Each of these choices has a significant bearing on the performance of the structure because of the associated vulnerability. The architect should interact with the structural engineer to conceive the most appropriate and seismically safe structure. A good configuration and a reasonable framing system can even overcome the poor quality of construction without greatly affecting the ultimate performance. Decisions made at the conceptual stage are difficult to modify, so it is essential that their full consequences in terms of performance and costs are understood as early as possible.

The basic factors contributing to the proper seismic behavior of a building, in a rational conceptual design of the structural system, are simplicity, symmetry of the building, ductility, and transfer of the lateral loads to the ground without excessive rotation. Complex structural systems that introduce uncertainties in the analysis and detailing, or that rely on effectively non-redundant load paths, can lead to unanticipated and potentially undesirable structural behavior. The behavior of a structure during an earthquake depends largely on the form of the superstructure and on how the earthquake forces are carried to the ground. For this reason the overall form, regular configuration, flow of loads, and framing system of building may be of serious concern if not taken care of in the first stage of planning.

The first nine sections of this course deal with the fundamental principles that should be observed strictly at the conceptual planning stage of a building since these have a great impact on the overall performance of the building during ground motion. Next, functional planning and the framing systems are discussed. The type of framing system opted will govern the load transfer mechanism for gravity and lateral loads and may dictate the choice of particular materials for construction to be used for good performance and economy. The course ends with the desirable properties of construction materials for earthquake-resistant structures.

Important Concepts Affect the Overall Performance of the Building during Earthquake.

1. Continuous Load Path

One of the most fundamental considerations in earthquake-resistant design is a clear, direct, and continuous load path. At least one (preferably more) continuous load path with adequate strength, stiffness, and ductility should be provided from the origin of the initial load manifestation to the final lateral load-resisting elements. In case a particular load path becomes degraded in strength or stiffness during an earthquake, the other one will serve as a backup. Buildings with more than one load path display redundancy. It has been observed that proper selection of the load-carrying system is essential to good performance under any loading. A properly selected structural system tends to be relatively forgiving of oversights in analysis, proportion, detail, and construction.

Buildings are generally composed of horizontal and vertical structural elements. The horizontal elements are usually diaphragms, such as floor slab, and horizontal bracing in special floors; and the vertical elements are the shear walls, braced frame, and moment-resisting frames. Horizontal forces produced by seismic motion are directly proportional to the masses of building elements and are considered to act at the centers of the mass of these elements. The earthquake forces developed at different floor levels in a building are brought down along the height to the ground through the shortest path. The general path for load transfer, in a conceptual sense, is opposite to the direction in which seismic loads are delivered to the structural elements. Thus, the path for load transfer is as follows— inertia forces generated in an element, such as a segment of exterior curtain wall, are delivered through structural connections to a horizontal diaphragm; the diaphragm distributes these forces to vertical components; and finally, the vertical elements transfer the forces into the foundations and eventually to the ground (Fig. l).

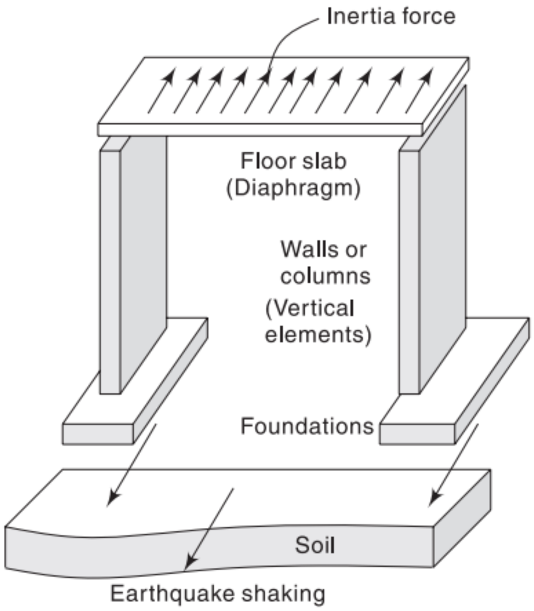


Figure 1. Flow of seismic inertia forces through the structural components

A deviation or discontinuity in this load-transfer path results in poor performance of the building. Failure to provide adequate strength, stiffness, and ductility of individual elements in the system or failure to tie individual elements together can result in distress or complete collapse of the system. One of the earliest lessons from earthquakes was the realization that structural and non-structural elements must be adequately tied to the structural system. Concrete diaphragms, with appropriate struts, ties, and boundary elements, should be provided with adequate reinforcement to transmit the seismic forces.

2. Overall Form

A structure is designed to transfer the seismic forces to the ground safely. However well the structure may have been designed, it is said to be acceptable only if it meets all the established configuration-related requirements from the observed failures during past earthquakes. Buildings having simple, regular, and compact layouts, incorporating a continuous and redundant lateral force-resisting system, tend to perform well during earthquakes and, thus, are desirable. While planning a particular structure, the guiding principles to be borne in mind are as follows. The structure should have the following characteristics:

(a) have a direct and continuous load path

(b) be simple and symmetrical
(c) not be too elongated in plan or elevation, i.e., the size should be moderate
(d) have uniform and continuous distribution of strength, mass, and stiffness
(e) have horizontal members which form hinges before the vertical members
(f) have sufficient ductility
(g) have stiffness related to the sub-soil properties

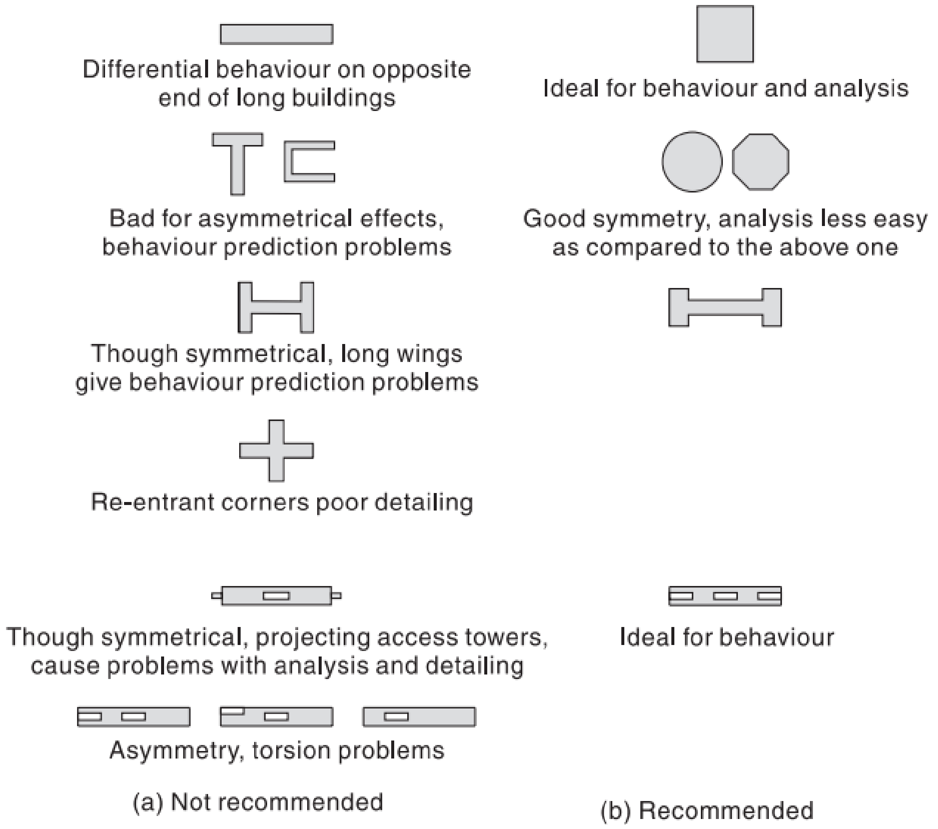
These principles are discussed in detail in the sections that follow.

3. Simplicity, Uniformity, and Symmetry

Buildings with a uniform and symmetrical distribution of mass, strength, and stiffness in plan and elevation perform better in earthquakes than those lacking these characteristics. A simple and symmetrical structure in plan, e.g., a square or circular shape, will have the greatest chance of survival for the following reasons:

a) The ability to understand the overall earthquake behavior of a structure is markedly greater for a simple one than it is for a complex one.
b) The ability to understand structural details is considerably greater for simple structures than it is for complicated ones.
c) Uniformity in plan improves dynamic performance of a structure during an earthquake by suppressing torsional response

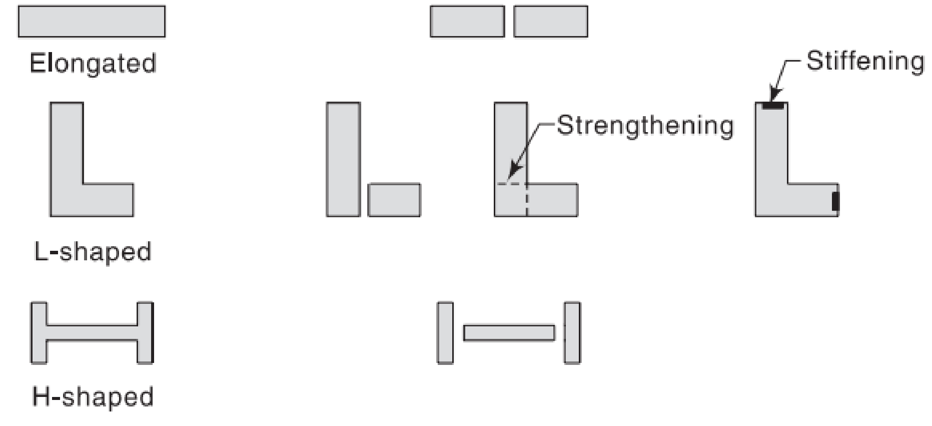
Buildings regular in plan and elevation, without re-entrant corners or discontinuities in transferring the vertical loads to the ground, display good seismic behavior as well. It is important that the plan of a structure is symmetrical in both directions. In general, buildings with simple geometry in plan as shown in Fig. 2(b) perform well during earthquakes. Buildings with re-entrant corners, such as U, V, T, and + shapes in plan [Fig. 2(a)], may sustain significant damage during earthquakes and should be avoided. H-shapes, although symmetrical, should not be encouraged either. The probable reason for the damage is the lack of proper detailing at the corners, which is complex. To check the bad effects of these interior corners in the plan, the building can be broken into parts using a separation joint at the junction. There must be enough clearance at the separation joints so that the adjoining portions do not pound each other. Figure 3 shows such cases of elongated, L-shaped and H-shaped buildings.



(a) Not recommended

(b) Recommended

Figure 2. Geometrical plans of typical buildings.

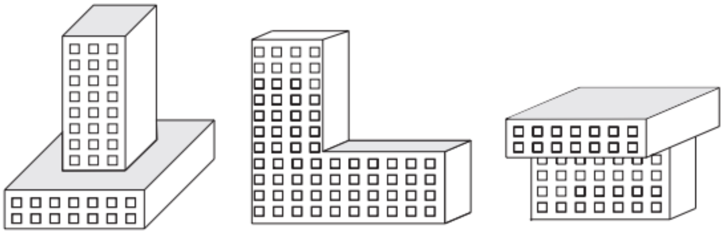


(a) Not recommended

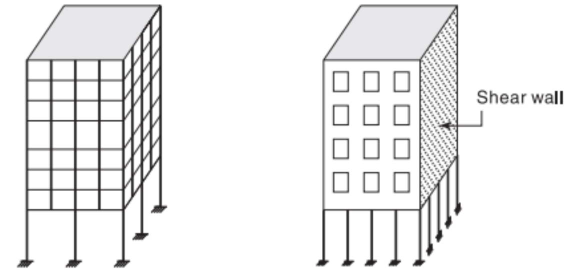
(b) Recommended

Figure 3. Broken layout concept

A building having a simple plan but a lack of symmetry in the columns or walls (more partition walls in the shorter direction than in the longer direction), or an irregularity in the elevation (Fig. 4), produces torsional effects, which are difficult to assess properly and can be destructive. External lifts and stairwells provide similar dangers; they tend to act on their own in earthquakes, making it difficult to predict force concentrations, torsions, and out-of-balance forces. To avoid torsional deformation, the center of stiffness of a building should coincide with the center of mass. It is desirable to have symmetry both in the building configuration, as well as in the structure, in order to satisfy this condition. The torsions of unsymmetrical structures can lead to a failure of corner columns and walls at the perimeter of the building. The twisting effect of buildings is discussed in Section 7.



(a) Setback—Effect of setback cannot be predicted by normal code

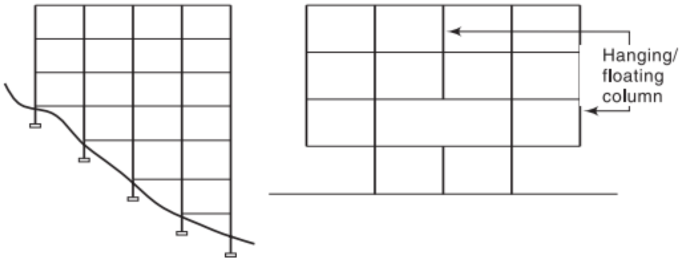


Intermediate and ground storey relatively taller

(b) Soft storey

Shear wall not carried in the ground storey

(c) Soft storey



(d) Sloping ground

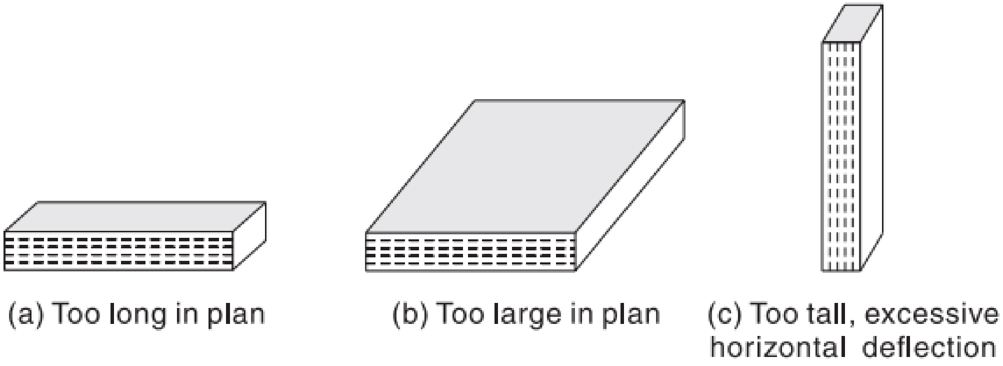
(e) Hanging or floating columns

Figure 4. Discontinuation in vertical configuration of buildings

Vertical and plan irregularities result in building responses significantly different from those assumed in the equivalent static force procedure. A building with an irregular configuration may be designed to meet all codal requirements but it will not perform well compared to a building with a regular configuration. If the building has an odd shape that is not properly considered in the design, good details and construction are of secondary value. Although the code gives certain recommendations for assessing the degree of irregularity, and corresponding penalties and restrictions, it is important to understand that these recommendations are to discourage and to make the designer aware of the potential detrimental effects of irregularities.

4. Elongated Shapes

A building may be too long, have too large an area in the plan, or maybe too slender. None of these shapes should be encouraged as such shaped buildings do not perform well during strong ground motion. Buildings of great length or plan area may not respond to earthquakes in the way calculated. Analysis customarily assumes that the ground moves as a rigid mass over the base of the building, but this is a reasonable assumption only for a small area. Also, the ground is assumed to be elastic and the propagation of seismic waves is not instantaneous. If different parts of the building are being shaken out of step with each other, additional, incalculable stresses are being imposed, and this effect increases with size. Thus, buildings that are too long in plan [Fig. 5(a)] may be subjected to different earthquake movements simultaneously at the two ends, leading to disastrous results. As an alternative, such buildings can be broken into a number of separate square buildings as shown in Fig. 3(b). Further, buildings such as warehouses, have large plan areas [Fig. 5(b)], will, in addition, be subjected to excessive horizontal seismic forces that will have to be carried by the columns and walls.


(a) Too long in plan

(b) Too large in plan

(c) Too tall, excessive horizontal deflection

Figure 5. Elongated shapes—one of the overall dimensions much lesser or much smaller than the other

In tall buildings [Fig. 5(c)] with a large height-to-base ratio (slenderness ratio > 4), the horizontal movement of the floors during ground shaking is large. For buildings with a slenderness ratio of less than 4, the movement is reasonable. The slenderer a building, the worse the overturning effects of an earthquake. The axial column force due to the overturning moment in such buildings tends to become unmanageably large. Also, the compressive and pull-out forces acting on the foundation increase tremendously.

5. Stiffness and Strength

Building with a uniform distribution of stiffness and strength in plan and elevation generally performs well during earthquakes. Strength is the property of an element to resist force. Stiffness is the property of an element to resist displacement. When two elements of different stiffnesses are forced to deflect the same amount, the stiffer element will carry more of the total force because it takes more force to deflect it. Stiffness greatly affects the structure’s uptake of earthquake-generated forces. On the basis of stiffness, the structure may be classified as *brittle* or *ductile*. A brittle structure, having greater stiffness, proves to be less durable during an earthquake, while a ductile structure performs well in earthquakes.

Sudden changes in stiffness and strength between adjacent stories are very common. Such changes are associated with setbacks (in penthouses and other small appendages), changes over the height of a structural system (e.g., discontinuous shear walls), changes in story height, changes in materials, and unanticipated participation of non-structural components. A common problem with such discontinuities is that inelastic deformations tend to concentrate in or around the discontinuity. These sudden changes in stiffness, strength, or mass in either vertical or horizontal planes of a building can result in the distribution of lateral loads and deformations different from those that are anticipated for a uniform structure. A sudden change of lateral stiffness up a building is not advised for the following reasons:

(a) Even with the most sophisticated and expensive computerized analysis, the earthquake stress cannot be determined adequately.
(b) The structural detailing poses practical problems.
Drastic changes in the vertical configuration as shown in Fig. 4 cause changes in stiffness and strength between adjacent stories of a building and should be avoided. Such discontinuity in the vertical configuration of a building is not recommended. Failures due to discontinuity of vertical elements of the lateral load-resisting systems have been among the most notable and spectacular.

Buildings with vertical setbacks as shown in Fig. 4(a) cause a sudden jump of earthquake forces at the level of discontinuity. A large vibrational motion takes place in some portions and a large diaphragm action is required at the border to transmit forces from the top to the base. It may be noted that the effects of setbacks cannot be predicted by normal code equivalent static analysis.

Uniformity of strength and stiffness in elevation helps to avoid the formation of weak or soft stories. Buildings that have fewer columns or walls in a particular story, or that have an unusually tall story [Fig. 4(b)] are prone to damage or collapse. One of the most common forms of discontinuity of vertical elements occurs when shear walls that are present in upper floors are discontinued in the lower floors. The result is the frequent formation of a soft story that concentrates damage. Figure 4(c) shows a building having shear walls (RCC walls for carrying earthquake forces) that do not go all the way to the ground, but terminate at an intermediate story level. It is advocated that the stiffness of the lower story, the so-called soft story, be reduced so that a reduced dynamic force is transmitted to the superstructure. However, this argument is based on simple elastic analysis. When realistic inelastic and geometrical non-linear effects are taken into account, the plastic deformations tend to concentrate on the soft story and may cause the entire building to collapse.

The unequal height of the columns [Fig. 4(d)] causes twisting and damage to the short columns of the building. It is because shear force is concentrated in the relatively stiff short columns that fail before the long columns. In a structural frame, long columns can be turned into short columns by the introduction of spandrels. Buildings with columns that hang or float on beams at an intermediate story [Fig. 4(e)] have discontinuities in the load transfer path.

The most common form of vertical discontinuity arises because of the unintended effects of nonstructural elements. The problem is most severe in structures having relatively flexible lateral load-resisting systems because in such cases the nonstructural component can comprise a significant portion of the total stiffness. A common cause of failure is the infilled frames. If properly designed, the infill can improve the performance of the frame due to its stiffening and strengthening action. However, soft stories may result if infills are omitted in a single story (often the first story). Even if infills are placed continuously and symmetrically throughout the structure, a soft story may be formed if one or more infill panels should fail.

Partial height frame infills are also common. In this form of construction, an infill extends between columns, from the floor level to the bottom of the window line, leaving a relatively short portion of the column exposed in the upper portion of the story. The shear required to develop flexural yield in the shortened column can be substantially higher than for the full-length column. If the designer has not considered this effect of the infill, shear failure of this so-called *captive column* can result before flexural yield. Complete collapse of the column (and building) can occur if it is not well equipped with transverse steel. This form of distress is a common cause of building damage and collapse during earthquakes.

Apparent vertical irregularities can occur due to the interaction between adjacent structures having inadequate separation. A tall building adjacent to a shorter building may experience irregular response due to the effects of impact between the two structures. This effect can be exacerbated by local column damage due to the pounding of the roof of the small building against the columns of the taller one.

Mass, stiffness, and strength plan irregularities can result in significant torsional response. The inelastic torsional response cannot, at present, be rectified with the results of elastic analysis. Techniques for inelastic analysis of complete building systems that take torsion into account are largely unavailable and unverified. Given such uncertainties and difficulties with analytical techniques, the buildings should be designed to have substantial torsional resistance, near symmetry, and compactness of plan. A building will have a maximum chance of survival if it conforms to the following:

(a) The load-bearing elements should be uniformly distributed. This checks the torsion in the building.
(b) The columns and walls should be continuous and without offsets from the roof to the foundation.
(c) The beams should be free of offsets.
(d) Columns and beams should be coaxial.
(e) Beams and columns should be of equal widths. This promotes good detailing and aids the transfer of moments and shear through the junction of the members concerned.
(f) To avoid stress concentration, there should not be a sudden change of cross-section of any member.
(g) The structure should be as continuous (redundant) and monolithic as possible.

The earthquake resistance of an economically designed structure depends on its capacity to absorb apparently excessive energy input, mainly by repeated plastic deformation of its members. Hence, the more continuous and monolithic the building is, the more plastic hinges and shear and thrust routes are available for energy absorption. This requires the structure to be highly redundant.

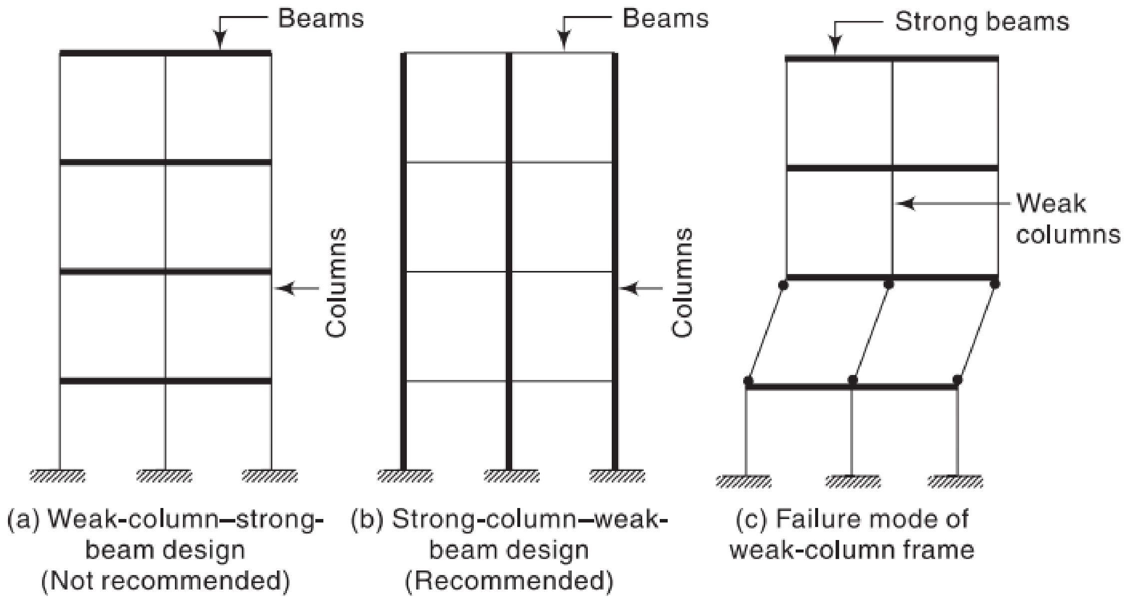
6. Horizontal and Vertical Members

In a framed structure, horizontal members, i.e., beams and slabs, should fail prior to the vertical members, i.e., columns. Beams and slabs generally do not fall down even after severe damage at plastic hinge positions, whereas columns will rapidly collapse under vertical loading once sufficient spalling has taken place. Hence, continuous beams on light columns [Fig. 6(a)] are not appropriate in earthquake-prone regions, and weak-beam–strong-column [Fig. 6(b)] arrangement should be the choice. It is very important in that it postpones the complete collapse of a structure. The following are the reasons for having strong columns and allowing prior yielding of the beams in flexure.

(a) Failure of a column means the collapse of the entire building.

(b) In a weak-column structure, plastic deformation is concentrated in a particular story, as shown in Fig. 6(c), and a relatively large ductility factor is required.

(c) In both shear and flexural failures of columns, degradations are greater than those in the yielding of beams.



(a) Weak-column–strong-beam design (Not recommended)

(b) Strong-column–weak-beam design (Recommended)

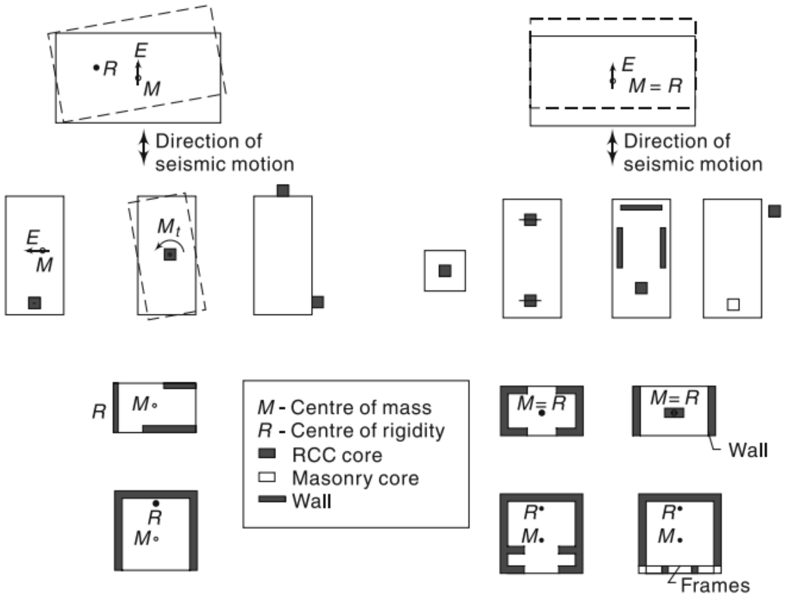
(c) Failure mode of weak-column frame

Figure 6. Weak-beam–strong-column concept

7. Twisting of Buildings

Torsional forces from ground motion are not usually of great concern unless the building has an inherently low torsional strength. Twist in buildings causes different portions at the same floor level to move horizontally by different amounts. Irregularities of mass, stiffness, and strength in a building can result in significant torsional response. However, torsion arises from eccentricity in the building layout—when the centre of mass of the building does not coincide with its centre of rigidity. If there is torsion, the building will rotate about its centre of rigidity due to the torsional moment about the centre of structural resistance. The torsional response may be inadequately represented by a linear dynamic analysis, because yielding caused by lateral-torsional response can reduce the stiffness on one side of a building and further increase the eccentricity between mass and stiffness centers.

The recommended plan configurations of buildings to avoid torsional moments due to the distribution of mass and stiffness of elements are illustrated in Fig. 7. This additional torsion will have to be dealt with along with the torsional component of ground motion. This may cause a large increase in the lateral forces acting on bracing elements and on other parts of the structure, in proportion to their distances from the center of rotation.



(a) Not recommended
(These plan configurations
give rise to torsion)

(b) Recommended

Figure 7. Distribution of mass and stiffness of elements in plan

Torsion in buildings during earthquakes can be most simply explained by analogy with a rope swing. Consider a wooden cradle tied with coir ropes to a sturdy branch of a tree. Buildings behave like this swing, except that they are anchored at the bottom rather than at the top. That is to say that buildings are essentially inverted swings. The walls and columns are like ropes, the ground is like the branch of the tree to which the ropes are tied, and the upper floors or stories are like the wooden cradle. In a single-story building, the roof acts as the wooden cradle [Fig. 8(a)] of a swing and in multi-story buildings, the upper floors act as a stack of wooden cradles suspended by the ropes at regular intervals [Fig. 8(b)].

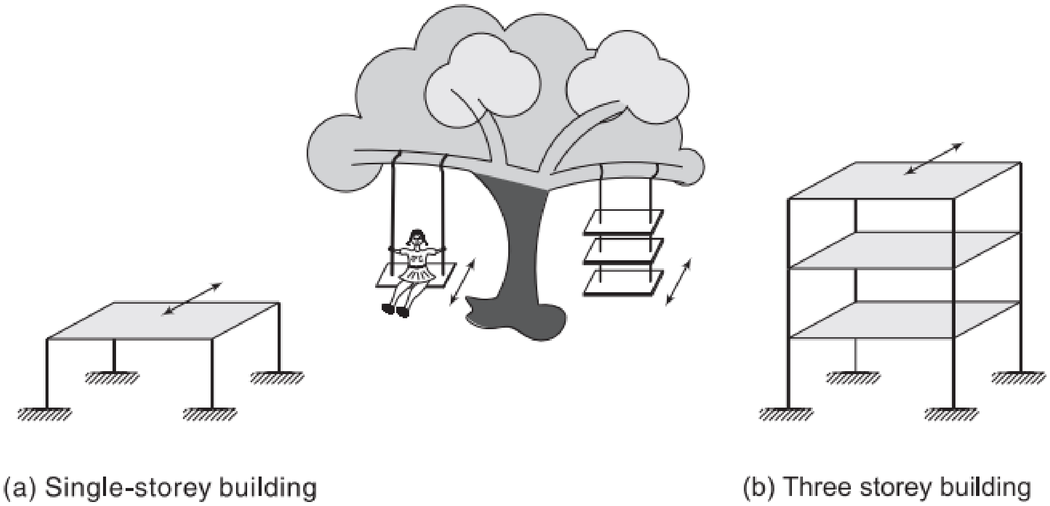
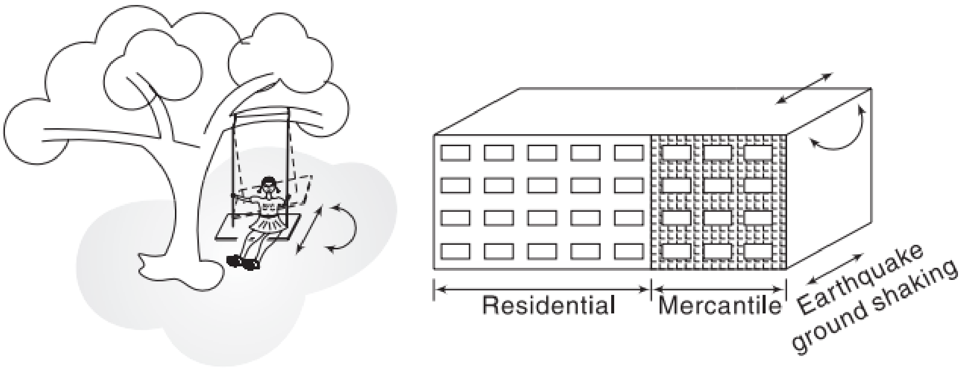


Figure 8. Horizontal shaking of single- and three-story buildings and their simulation with rope and swing

Now consider a rope swing tied symmetrically with two equal ropes. If one sits in the middle of the cradle, it will swing back and forth in a symmetric fashion without any sideways swinging or tilting. Similarly, when a symmetric building, loaded uniformly, is shaken by an earthquake, it swings back and forth such that all points on a floor move horizontally in the same direction and by the same amount at any given time. However, if one sits on the cradle of the swing on any one side, it tilts, causing the ropes and, thus the swing to twist [Fig. 9(a)]. Similarly, if the mass on the structure of a building is more on one side than on the other [Fig. 9(b)], then the lighter side is displaced by a greater amount when the building is subjected to ground movement. This is to say that the building undergoes horizontal displacement as well as rotational motion. To understand this sort of motion better, try sitting on a park swing on one side of the cradle and swinging fast. Instead of swinging back and forth, the swing will turn about its center of mass, causing the rope to twist. This is the kind of motion an unequally loaded structure undergoes. And although the ropes of a swing are flexible enough to twist under torsion and then come back to their original position, the walls and columns of a building are not.

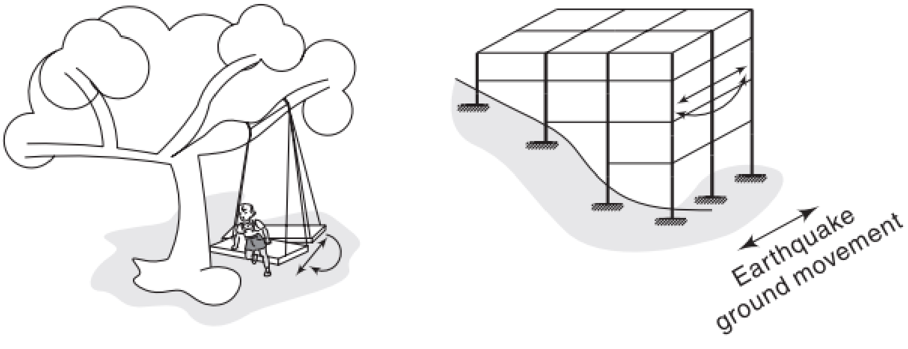


(a) Swing with equal ropes, unequally loaded

(b) Structure unequally loaded in plan

Figure 9. Torsional vibration of a structure with even vertical members

A rope swing with unequal rope lengths [Fig. 10(a)] on either side will undergo motion similar to that described above. The structural counterparts of this are buildings on slopes. These have unequal columns as shown in Fig. 10(b) and the floors experience twisting about a vertical axis because of the varying stiffness of columns. Buildings having walls only on two sides and thin columns along the other also experience twist as shown in Fig. 11. The twist induces more damage in the columns and walls on the side that moves more. The best way to minimize twist is by ensuring that buildings have symmetry in plan with respect to vertical members and loads.



(a) Swing with unequal ropes

(b) Structure with unequal vertical members

Figure 10. Torsional vibration of a structure with uneven vertical members loaded unequally in plan

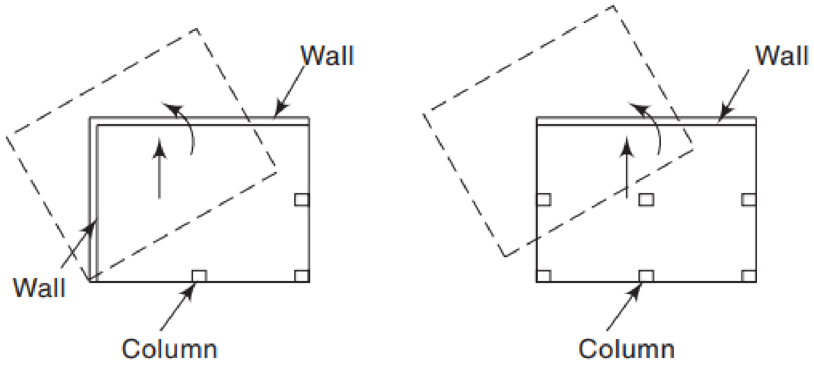


Figure 11. Twisting due to walls on two/one sides (in plan)

8. Ductility

Ductility is the capacity of building materials, systems, structures, or members to undergo large inelastic deformations without significant loss of strength or stiffness. It is an essential attribute of a structure that must respond to strong ground motions. It serves as the shock absorber in a building, for it reduces the transmitted force to a sustainable magnitude. The resultant sustainable force is traditionally used to design a hypothetically elastic representation of the building. Therefore, the survivability of a structure under strong seismic action relies on the capacity to deform beyond the elastic range, and to dissipate seismic energy through plastic deformation.

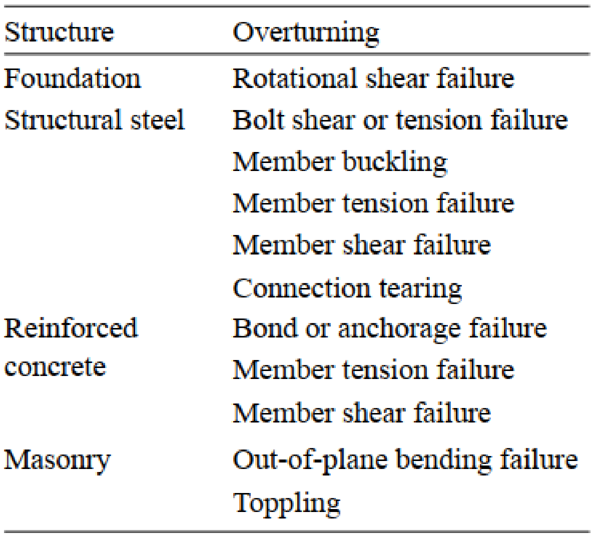
Formally, ductility refers to the ratio of the displacement just prior to ultimate displacement or collapse, to the displacement at first damage or yield. This is a very important characteristic of a building since it greatly reduces the effect or *response* that is produced in the structure by an earthquake. This is because the building is set in vibration by the energy of an earthquake. This vibration, as well as the accompanying deflection, is reduced by the energy that is absorbed by the large inelastic deflections of a ductile structure. Some materials, such as steel and wood, are inherently ductile, while others, such as masonry and concrete, are brittle and fail suddenly. Building elements constructed with ductile materials have a *reserve capacity* to resist earthquake overloads. Therefore, buildings constructed with ductile elements, such as steel and adequately reinforced concrete, tend to withstand earthquakes much better than those constructed with brittle materials such as unreinforced masonry.

One way of achieving ductility in structural members is by designing elements, with known limits, which deform in a ductile manner. For example, in RCC members, the amount and location of steel should be such that the failure of the member occurs by steel reaching its strength in tension before concrete reaches its strength in compression. This is referred to as *ductile failure*. In RCC buildings the seismic inertia forces generated at floor levels are transferred through the various beams and columns to the ground. The correct building components need to be made ductile. The failure of a beam causes localized effects. However, the failure of a column can affect the stability of the whole building. Therefore, it is better to make the beams ductile rather than the columns. Such a design method is known as strong column–weak-beam design method.

Ductility can also be achieved by avoiding any possibility of brittle failure (Table 1). As an example, a tension bolt in a steel beam–column connection should be at a safe stress level when the beam has reached its ultimate moment. For the entire structural system to be ductile, the following requirements must be met.

(a) Any mode of failure should involve the maximum possible redundancy.
(b) Brittle-type failure modes, such as overturning, should be adequately safeguarded so that ductile failure occurs first.

Table 1. Types of brittle failure



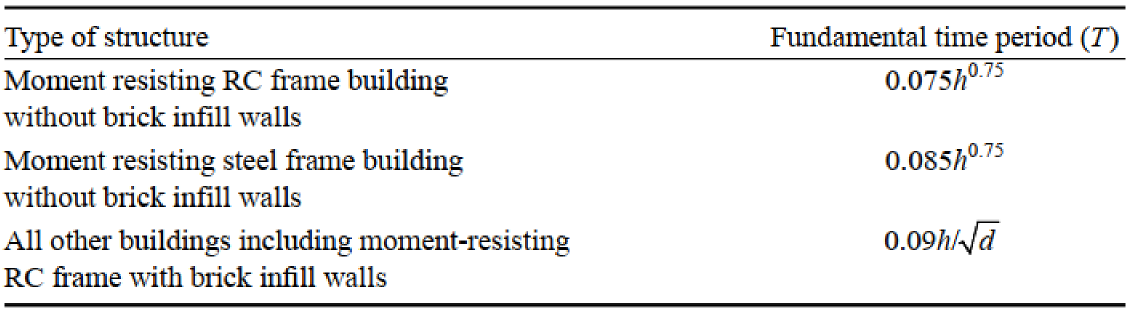
Structure	Overturning
Foundation	Rotational shear failure
Structural steel	Bolt shear or tension failure
	Member buckling
	Member tension failure
	Member shear failure
	Connection tearing
Reinforced concrete	Bond or anchorage failure
	Member tension failure
	Member shear failure
Masonry	Out-of-plane bending failure
	Toppling

Ductility is often measured by hysteretic behaviour of critical components, such as a column–beam assembly of a moment frame. The hysteretic behaviour is usually examined by observing the cyclic moment–rotation (or force–deflection) behaviour of the assembly. The slopes of the curves represent the stiffness of the structure, and the enclosed areas are sometimes full and flat, or they may be lean and pinched. Structural assemblies with curves enclosing a large area representing large dissipated energy are regarded as superior systems for resisting seismic loading.

9. Flexible Building

Whether a structure should be stiff or flexible has always been a point of discussion. The ground shaking during an earthquake contains a group of many sinusoidal waves of different frequencies having periods in the range of 0.03 to 33 s. The base of the building swings back and forth when the ground shakes. The building oscillates back and forth horizontally and after some time comes back to the original position. The time taken (in seconds) for one complete back and forth motion is called the *fundamental natural period T* of the building; the higher the flexibility, the greater the value of *T*. The fundamental time periods of some structures are given in Table 2. Depending upon the value of *T* for the building and the characteristics of earthquake ground motion, some buildings are shaken more than the others. In a stiff (rigid) building, every part moves by the same amount as the ground; for a flexible building, different parts move by different amounts.

Table 2. Fundamental time period of some of the structures

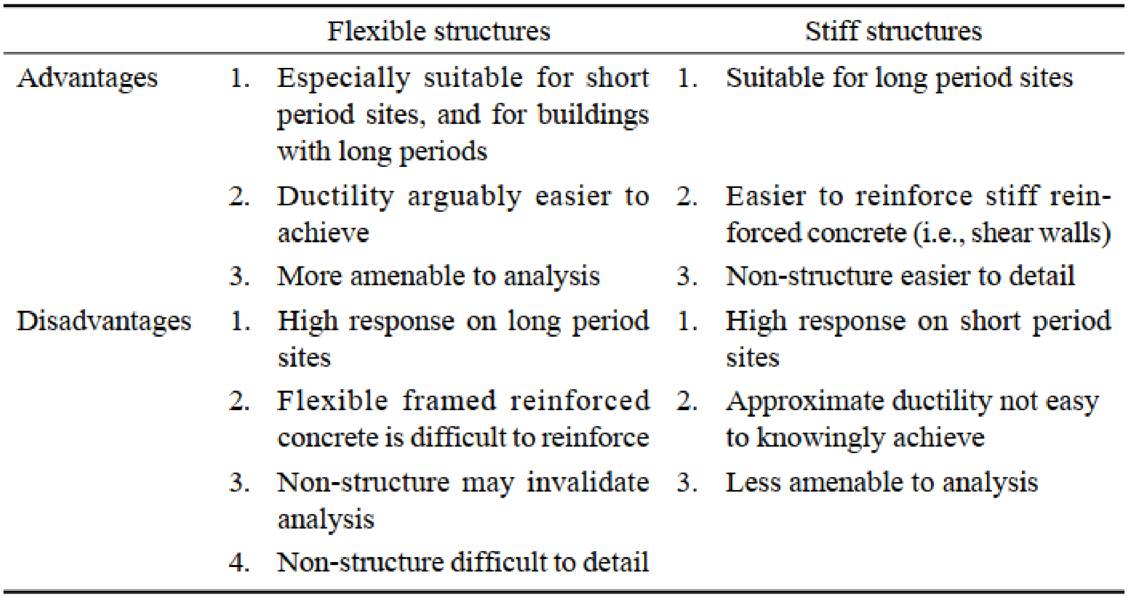


Type of structure	Fundamental time period (T)
Moment resisting RC frame building without brick infill walls	$0.075h^{0.75}$
Moment resisting steel frame building without brick infill walls	$0.085h^{0.75}$
All other buildings including moment-resisting RC frame with brick infill walls	$0.09h/\sqrt{d}$

Ideally, a flexible structure with moment-resisting frames (beam and column type) is built so that the non-structural elements such as partitions and infill walls are isolated from the frame movements. This is necessary because a flexible structure tends to exhibit large lateral deflections, which induce damage in nonstructural members. Even the lifts and shaft walls are completely separated. There is no extra safety margin provided by the non-structure as in traditional construction. In tall buildings, oscillations due to wind gusts can cause discomfort to the occupants, and a stiff structure is desirable. For a flexible structure, materials such as masonry are not suitable and steel work is the usual choice. For greater stiffness, diagonal braces or RCC shear wall panels may be incorporated in steel frames. Concrete can be readily used to achieve almost any degree of stiffness. The non-structures such as partitions may greatly stiffen a flexible structure and, hence, must be allowed in the structural analysis.

Depending on the situation, either a flexible or a stiff structure can be made to work, but the advantages and disadvantages of the two forms need careful consideration. These advantages and disadvantages are given in Table 3.

Table 3. Flexible structures vs stiff structures

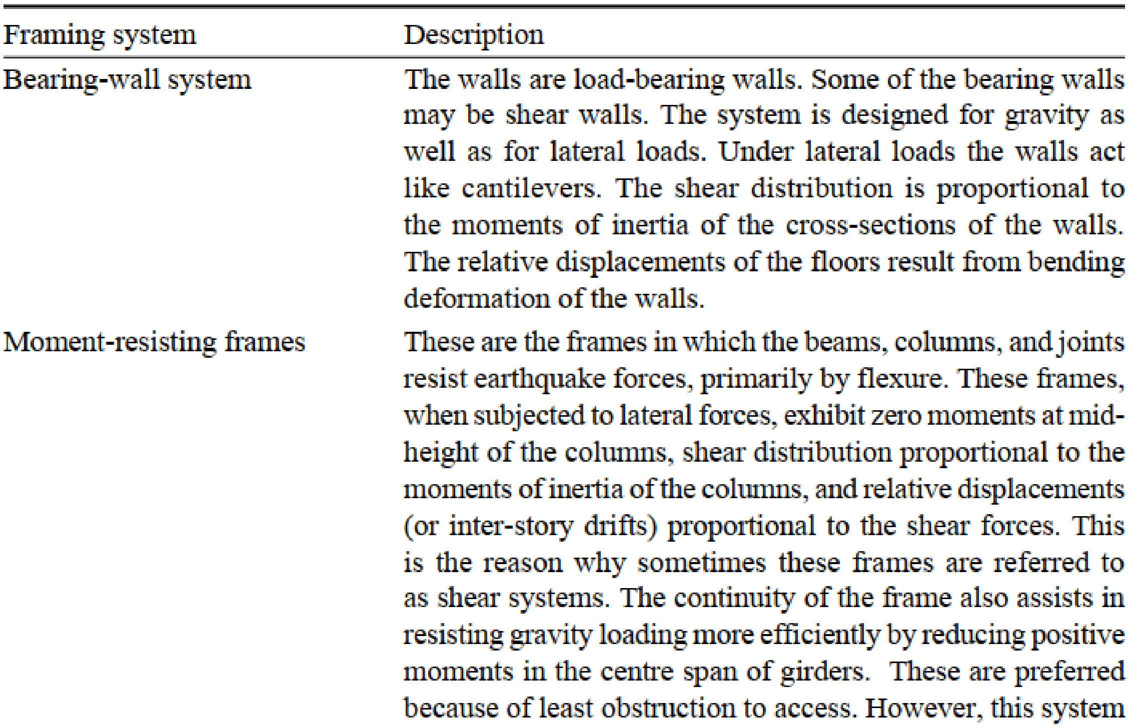
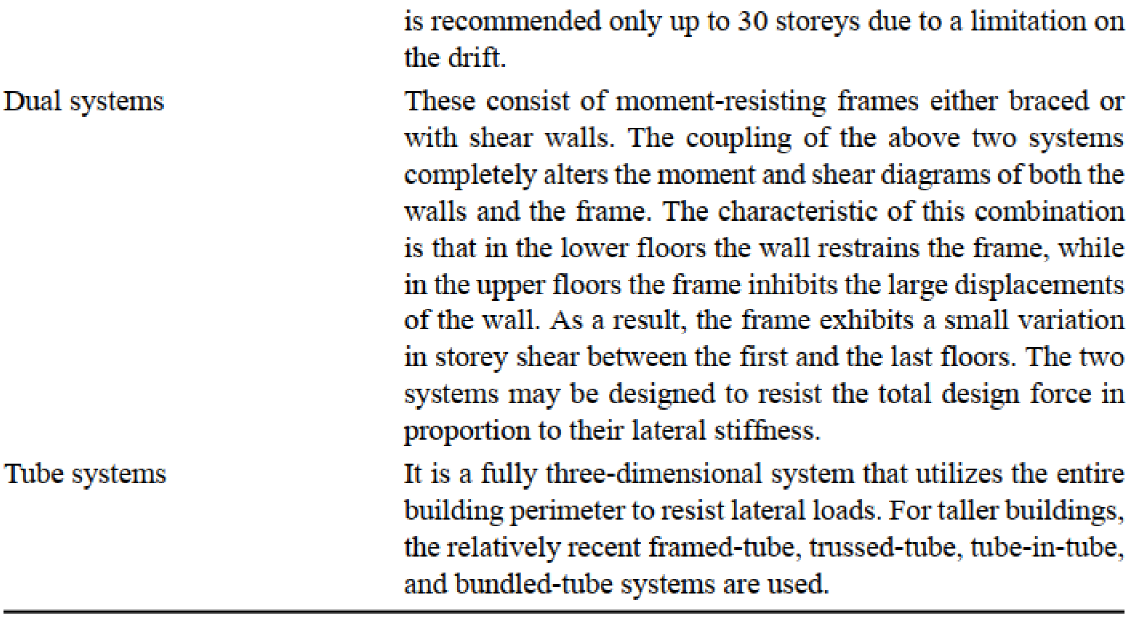


	Flexible structures	Stiff structures
Advantages	1. Especially suitable for short period sites, and for buildings with long periods	1. Suitable for long period sites
	2. Ductility arguably easier to achieve	2. Easier to reinforce stiff reinforced concrete (i.e., shear walls)
	3. More amenable to analysis	3. Non-structure easier to detail
Disadvantages	1. High response on long period sites	1. High response on short period sites
	2. Flexible framed reinforced concrete is difficult to reinforce	2. Approximate ductility not easy to knowingly achieve
	3. Non-structure may invalidate analysis	3. Less amenable to analysis
	4. Non-structure difficult to detail	

10. Functional Planning

The functional planning of a building affects the way in which it can accommodate its structural skeleton. The principal categories of buildings from the point of view of a lateral load-resisting system are as given in Table 4 and are discussed in the section to follow. The vertical divisions of the building create problems, making it difficult to avoid irregularities in mass or stiffness. However, the service cores and exterior cladding provide an opportunity to incorporate shear walls or braced panels. One of the main objectives in preliminary planning is to establish the optimum locations for service cores and for stiff structural elements that should be continuous to the foundation. The initial structural and architectural plans may be in conflict, but it is essential to arrive at a satisfactory compromise at the concept planning stage itself.

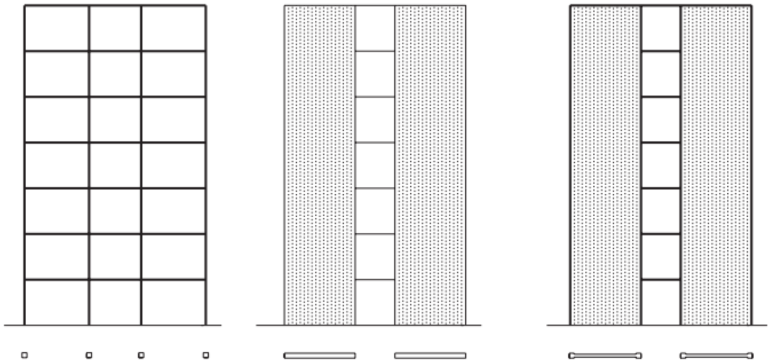
Table 4. Lateral load-resisting systems

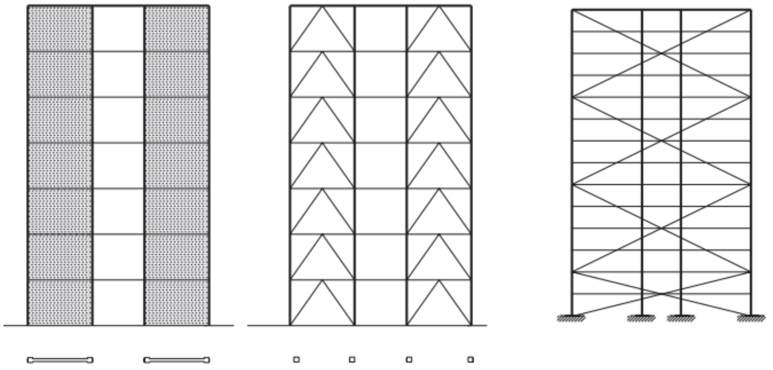
Framing system	Description
Bearing-wall system	The walls are load-bearing walls. Some of the bearing walls may be shear walls. The system is designed for gravity as well as for lateral loads. Under lateral loads the walls act like cantilevers. The shear distribution is proportional to the moments of inertia of the cross-sections of the walls. The relative displacements of the floors result from bending deformation of the walls.
Moment-resisting frames	These are the frames in which the beams, columns, and joints resist earthquake forces, primarily by flexure. These frames, when subjected to lateral forces, exhibit zero moments at mid-height of the columns, shear distribution proportional to the moments of inertia of the columns, and relative displacements (or inter-story drifts) proportional to the shear forces. This is the reason why sometimes these frames are referred to as shear systems. The continuity of the frame also assists in resisting gravity loading more efficiently by reducing positive moments in the centre span of girders. These are preferred because of least obstruction to access. However, this system is recommended only up to 30 storeys due to a limitation on the drift.
Dual systems	These consist of moment-resisting frames either braced or with shear walls. The coupling of the above two systems completely alters the moment and shear diagrams of both the walls and the frame. The characteristic of this combination is that in the lower floors the wall restrains the frame, while in the upper floors the frame inhibits the large displacements of the wall. As a result, the frame exhibits a small variation in storey shear between the first and the last floors. The two systems may be designed to resist the total design force in proportion to their lateral stiffness.
Tube systems	It is a fully three-dimensional system that utilizes the entire building perimeter to resist lateral loads. For taller buildings, the relatively recent framed-tube, trussed-tube, tube-in-tube, and bundled-tube systems are used.

11. Framing Systems

The load-bearing wall system is the most common building system for low-rise structures where gravity loads are the dominant loads. However, this system is inherently weak in resisting lateral loads, and is seldom recommended for multistorey buildings. The framework of a multi-story building consists of a number of beams and columns built monolithically, forming a network. The ability of a multi-story building to resist the lateral forces depends on the rigidity of the connections between the beams and the columns. When the connections are fully rigid, the structure as a whole is capable of resisting the lateral forces. The moment-resisting frame is thus the fundamental structural system. However, if the strength and stiffness of a frame are not adequate, the frame may be strengthened by incorporating load-bearing walls, shear walls, and/or bracings (Fig. 12). Shear walls and bracings are also useful in preventing the failure of non-structural components by reducing drift. Shear walls are walls situated in advantageous positions in a building that can effectively resist lateral loads originating from earthquakes or winds. These may be made of RCC, steel, composite, and masonry. RCC shear walls are most commonly used in multi-story structures.



(a) Pure frame (b) Load bearing shear walls (c) Shear wall with columns



(d) Infilled shear walls (e) Braced frames (f) Whole building braced

Figure 12. Lateral load-resisting systems

The flat slab system is one of the most favorite reinforced concrete structural forms with the architects. It provides architectural flexibility, maximum usage of space, easier formwork, and shorter construction period. However, the flat slab systems need special attention as these perform poorly under earthquake loading and are less efficient. This is primarily due to the absence of deep beams or shear walls in this form of construction. When subjected to even moderate earthquakes, the excessive deformations cause damage to the non-structural members creating panic.

For buildings taller than about forty storeys, the effect of lateral forces becomes increasingly intense, and *tube systems* become economical. Tube systems may be classified as *framed-tube*, *trussed-tube*, *tube-in-tube*, and *bundled-tube* systems. In the framed-tube system [Fig. 13(a)], closely spaced columns are tied at each floor level by deep spandrel beams, thereby creating the effect of a hollow tube, perforated by openings for windows. This system represents a logical evolution of the conventional framed structure, possessing the necessary lateral stiffness with excellent torsional qualities, while retaining the flexibility of planning. The trussed-tube system shown in Fig. 13(b) is an advancement over the framed tube system. The diagonal members, along with girders and columns, form a truss system that imparts a great deal of stiffness to the building. The tube-in-tube system [Fig. 13(c)] consists of an exterior tube that resists the bending moment due to lateral forces and an interior slender tube, which resists the shear produced by the lateral forces. The bundled-tube system [Fig. 13(d)] is made up of a number of tubes separated by shear walls; the tubes rise to various heights and each tube is designed independently.

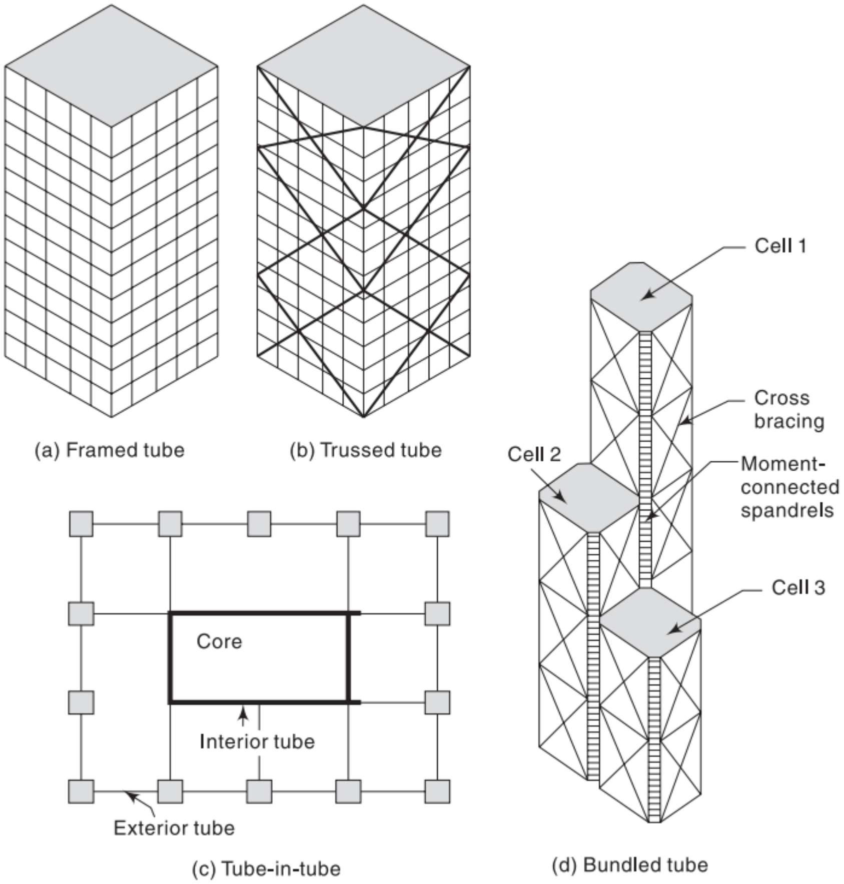


Figure 13. Types of tube structures

In a multi-story building, the moment-resisting frames, along with shear walls [Fig. 14(a)] or the bracing, work to resist lateral forces. Frames deform in a predominantly shear mode [Fig. 14(b)], where the relative story deflection depends on the shear applied at the storey level. The walls deform in an essentially bending mode [Fig. 14(c)]. A structural framework with load-bearing walls hence exhibits an intermediate form of behaviour as shown in Fig. 14(d). In the lower part of the building, the walls resist the greater part of the shear force, but the shear gradually decreases in higher storeys. If flexural deformation occurs in a load-bearing wall, the adjacent boundary beam undergoes a large deformation and should have adequate ductility. Also, adjacent columns are subjected to large axial force, so the difficulties arise, both in designing the column cross-section and in dealing with the pull-out force on the foundation. To overcome this situation, the building may be braced or shear walls may be provided, as shown in Fig. 12.

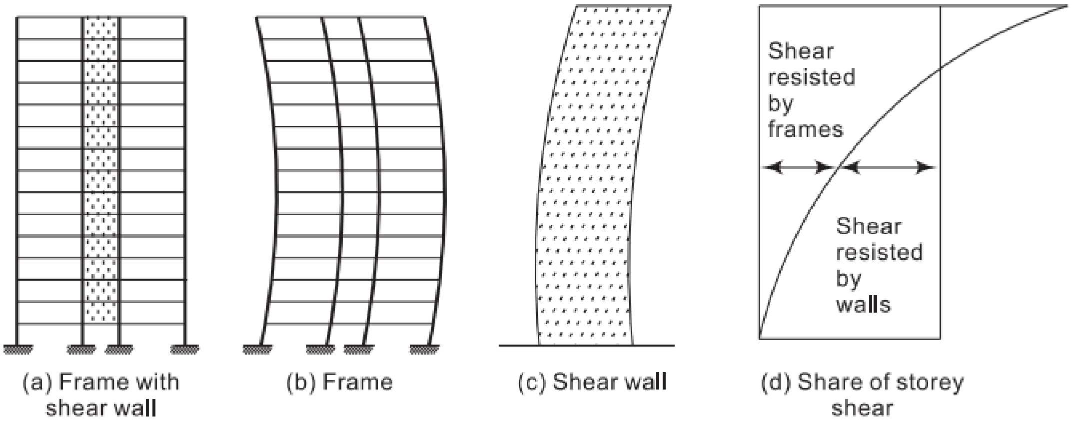


Figure 14. Contribution of frames and shear walls to storey shear

The framed-tube system combines the behavior of a true cantilever, such as a shear wall, with that of a beam–column frame. Overturning under the lateral load is resisted by the tube form, causing compression and tension in the columns. The shear from the lateral load is resisted by bending in columns and beams, primarily in the two sides of the building parallel to the direction of the lateral load.

12. Effect of Non-structural Elements

Non-structural elements such as claddings, infill walls, partition walls, etc., interfere with the free deformation of the structure and thus become structurally very responsive in earthquakes. If the material used in construction is flexible, the non-structures will not affect the structure significantly. However, these are often made with brittle materials like bricks, concrete blocks, etc., and so affect the overall behaviour of the structure in the following ways: -

(a) The natural period of vibration of the structure may be reduced and may cause a change in the intake of seismic energy and, consequently, a change in the seismic stresses of the structure.
(b) The lateral stiffness of the structure may redistribute, changing the stress distribution.
(c) The structure may suffer pre-mature failure, usually in shear or by pounding.
(d) non-structures may suffer excessive damage due to shear forces or pounding.

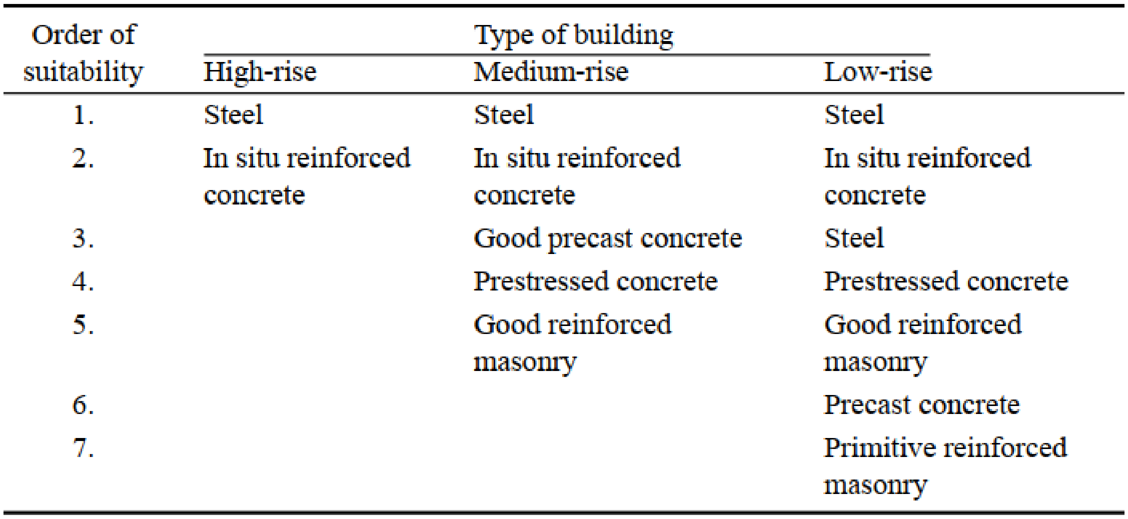
The more flexible the basic structure, the worse the above effects will be. The structure will suffer pronounced effects if the non-structural elements are asymmetric or not the same on successive floors. There are two approaches to deal with such problems in structures and to create low seismic response. One way is to include these shear elements into the official structure, as analyzed, and to detail accordingly. This approach is suitable for stiff buildings. The other way is to prevent the non-structural elements from contributing their shear stiffness to the structure. This approach is appropriate particularly for a flexible structure. To achieve this objective, gaps against the structure, up the sides, and along the top of the element are made, which are later filled with a flexible material.

13. Choice of Construction Materials

In the determination of the form of a structure, the choice of material is often an important factor. Some of the common construction materials in use are clay bricks, stones, timber, cement-concrete, and steel. The choice is usually dictated by the availability, economic consideration, or by the architect in case of general constructions in regions of low seismicity (zone II). Brick or stone masonry is strong in compression but weak in tension, and the same is true for cement concrete. Reinforced masonry is relatively superior with regard to the strength to-weight ratio, degradation, and deformability, and it is also less expensive. Concrete, although the most favourable building material, produces beams that are brittle in shear, and columns brittle both in compression and shear. However, proper ductile detailing improves the behaviour and performance of the member. Introduction of concrete shear walls improves to a large extent the behaviour of RCC buildings under strong ground motions. RCC structures are inferior to steel structures with respect to strength-to-weight ratio, degradation, and deformability. In the prestressed concrete structures, the introduction of prestressing adversely affects the deformability and hence the seismic characteristics of the building. Prestressed concrete is used for medium- and low-rise buildings. For tall buildings, steel is generally preferable. There is little to choose between RCC and steel for medium-rise buildings as long as the structures are well designed and detailed. Steel has an edge over concrete, since it has high strength-to-mass ratio and steel members are ductile both in flexure and shear. Steel, though expensive, is the ultimate choice to make a building ductile. Steel is most suitable for high-rise structures. However, it is not often used for low- to medium-rise buildings because of high cost. Timber, because of its high strength-to-weight ratio performs well for low-rise buildings. However, wooden structures are inferior in fire resistance.

The order of suitability of various construction materials, recommended for various types of buildings is given in Table 5. However, it is far from fixed, as it will depend on qualities of locally available materials, skill of the labor available, construction method, and the quality control exercised.

Table 5 Structural materials in appropriate order of suitability



Order of suitability	Type of building		
	High-rise	Medium-rise	Low-rise
1.	Steel	Steel	Steel
2.	In situ reinforced concrete	In situ reinforced concrete	In situ reinforced concrete
3.		Good precast concrete	Steel
4.		Prestressed concrete	Prestressed concrete
5.		Good reinforced masonry	Good reinforced masonry
6.			Precast concrete
7.			Primitive reinforced masonry

For the purpose of earthquake resistance (for structures in zones III, IV, and V), construction materials should have the following desirable properties:

(a) High ductility: High plastic deformation capacity can enhance the load carrying capacity of the members.
(b) High strength-to-weight ratio: Since the inertial force is a function of mass of the structure, it is advantageous to use light and strong materials or structural systems.
(c) Orthotropy and homogeneity: The basic physical model in seismology is that of a perfectly elastic medium in which the infinitesimal strain approximation of elastic theory is adopted. Anisotropy imperfections in elasticity and inhomogeneities modify the responses predicted by simpler theories and thus are undesirable.
(d) Ease in making full strength connections: Since both ductile and brittle members can result from a combination of, e.g., brittle concrete and ductile steel, performance of structural elements cannot be evaluated by materials alone. Further, the structural continuity at connections is of great importance in evaluating the behavior of an entire structural system.
(e) Cost: A building plan is often discarded because of high cost despite its superior physical quality. The cost of the overall structure should be reasonable.

Summary

This course explains how the quality of a structure depends on the form of the structure and how careful planning at the conceptual stage can improve its seismic performance. There are two main fundamental requirements for seismic performance levels of buildings. First, the no-collapse condition that requires the structure to retain its full vertical load-bearing capacity. Moreover, the structure must be left with sufficient lateral strength and stiffness to protect life even during strong aftershocks. Second, the damage limitation performance level including the cost of damage and the total cost of the structure should not be disproportionately high. The factors such as redundancy, simplicity, and symmetry with a minimum of changes in the section, stiffness, strength, flexibility, and ductility of structures, when accounted for in the conceptual design assist in meeting the no-collapse and the damage-limitation requirements. Although, these are qualitative in nature, yet are sound principles to be observed during planning stage for good performance of a building. Suitable framing systems conforming to the principles of earthquake resistant configuration, which eliminate vulnerabilities in the structural system, are described. The chapter ends with an introduction to the desirable properties of the materials to be used for earthquake-resistant construction.

Example 1:

A building having non-uniform distribution of mass is shown in Fig 15. Locate its center of mass?

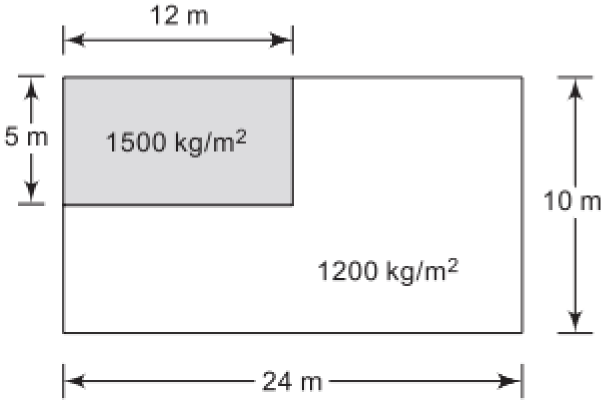


Figure 15. Plan

Solution

Let us divide the roof slab into three rectangular parts as shown in Fig 16. Mass of part I is 1500 kg/m2, while that of other two parts is together 1200 kg/m^2. Let origin be at point A, and the coordinates of the center of mass be at (X,Y).

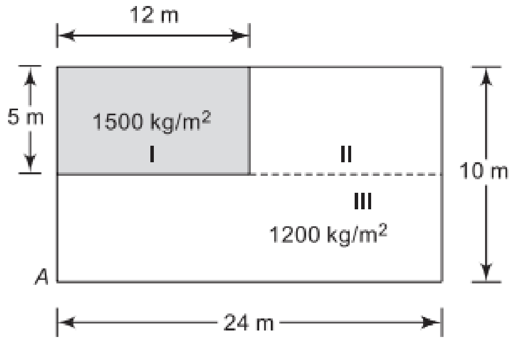


Figure 16. Plan

$$X = \frac{(12\times5\times1500)\times6+(12\times5\times1200)\times18+(24\times5\times1200)\times12}{(12\times5\times1500)+(12\times5\times1200)+(24\times5\times1200)}$$

$$= 11.65 \text{ m}$$

$$Y = \frac{(12\times5\times1500)\times7.5+(12\times5\times1200)\times7.5+(24\times5\times1200)\times2.5}{(12\times5\times1500)+(12\times5\times1200)+(24\times5\times1200)}$$

$$= 5.15 \text{ m}$$

Hence, coordinates of center of mass are (11.65, 5.15).

Example 2:

The plan of a simple one-story building is shown in Fig. 17. All the columns and the beams have same cross-sections. Obtain its center of stiffness?

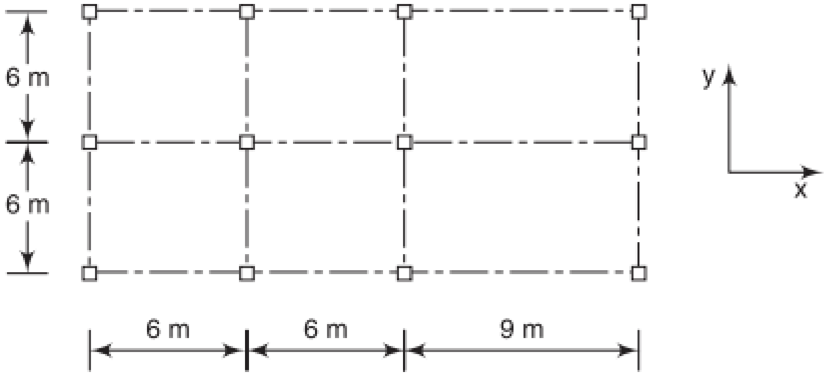


Figure 17. Plan

Solution

In the y-direction there are three identical frames located at uniform spacing. Hence, the coordinate of center of stiffness is located symmetrically, i.e., at y = 6.0 m from the left bottom corner. In the x-direction, there are four identical frames having equal stiffness. However, the spacing is not uniform. Let the lateral stiffness of each transverse frame be k, and the coordinates of the center of stiffness be (X, Y)

$$X = \frac{k \times 0 + k \times 6 + k \times 12 + k \times 21}{k + k + k + k} = 9.75$$

Hence, the coordinates of center of stiffness are (9.75, 6.0).

References

1. ASCE, 2022, Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-22, American Society of Civil Engineers, Structural Engineering Institute, Reston, Virginia.

2. ASCE, 2017, Seismic Evaluation and Retrofit of Existing Buildings, ASCE/SEI 41-17, American Society of Civil Engineers, Structural Engineering Institute, Reston, Virginia.

3. Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary, ACI, Farmington Hills, Michigan, USA.

4. FEMA, 2018b, Seismic Performance Assessment of Buildings, Methodology and Implementation, FEMA P-58 Series, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

5. FEMA-306, ‘Evaluation of earthquake damaged concrete and masonry wall buildings’, ATC-43 Project, Applied Technology Council, California.