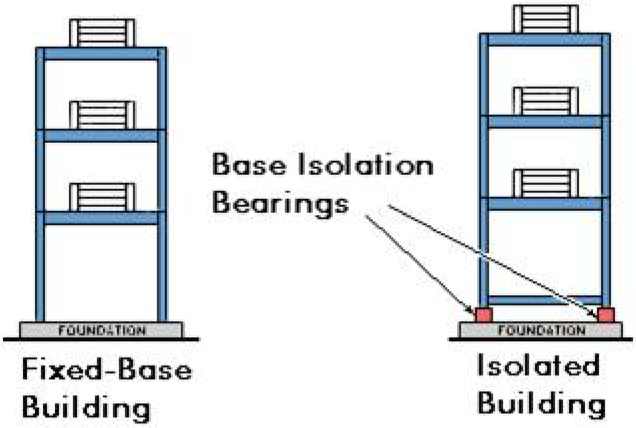
BASE ISOLATION

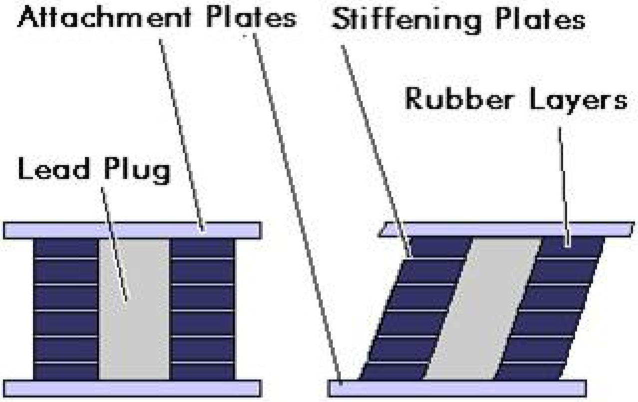
Introduction: The conventional approach to earthquake resistant design of buildings depends upon providing the building with strength, stiffness and inelastic deformation capacity which are great enough to withstand a given level of earthquake generated force. This is generally accomplished through the selection of an appropriate structural configuration and the careful detailing of structural members, such as beams and columns, and the connections between them. The basic approach underlying more advanced techniques for earthquake resistance is not to strengthen the building, but to reduce the earthquake generated forces acting upon it. Among the most important advanced techniques of earthquake resistant design and construction are base isolation and energy dissipation devices.

Base Isolation



(fig. 1)

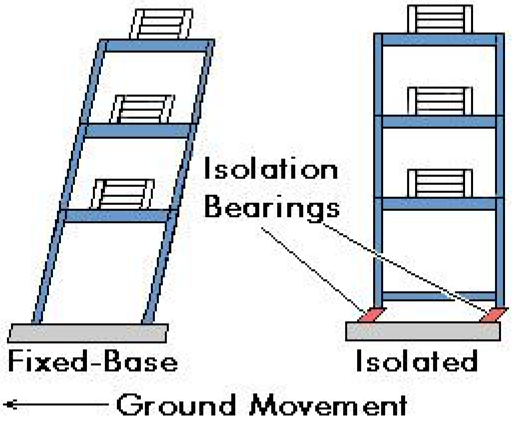
It is easiest to see this principle at work by referring directly to the most widely used of these advanced techniques, which is known as base isolation. A base isolated structure is supported by a series of bearing pads which are placed between the building and the building's foundation.(See Figure 1) A variety of different types of base isolation bearing pads have now been developed. For example, lead–rubber bearings. These are among the frequently used types of base isolation bearings. (See Figure 2) A lead–rubber bearing is made from layers of rubber sandwiched together with layers of steel. In the middle of the bearing is a solid lead 'plug.' On top and bottom, the bearing is fitted with steel plates which are used to attach the bearing to the building and foundation. The bearing is very stiff and strong in the vertical direction, but flexible in the horizontal direction.



(fig. 2)

Earthquake Generated Forces

To get a basic idea of how base isolation works, first examine Figure 3. This shows an earthquake acting on both a base isolated building and a conventional, fixed–base building. As a result of an earthquake, the ground beneath each building begins to move. In Figure 3, it is shown moving to the left.



(fig. 3)

Each building responds with movement which tends toward the right. We say that the building undergoes displacement towards the right. The building's displacement in the direction opposite the ground motion is actually due to inertia. The inertial forces acting on a building are the most important of all those generated during an earthquake. It is important to know that the inertial forces which the building undergoes are proportional to the building's acceleration during ground motion. It is also important to realize that buildings don't actually shift in only one direction.

Because of the complex nature of earthquake ground motion, the building actually tends to vibrate back and forth in varying directions. So, Figure 3 is really a kind of "snapshot" of the building at only one particular point of its earthquake response. In addition to displacing toward the right, the un–isolated building is also shown to be changing its shape from a rectangle to a parallelogram (the building is deforming). The primary cause of earthquake damage to buildings is the deformation which the building undergoes as a result of the inertial forces acting upon it.

Indian Seismic Codes

Seismic codes are unique to a particular region or country. They take into account the local seismology, accepted level of seismic risk, building typologies, and materials and methods used in construction. Further, they are indicative of the level of progress a country has made in the field of earthquake engineering.

The first formal seismic code in India, namely IS 1893, was published in 1962. Today, the Bureau of Indian Standards (BIS) has the following seismic codes:

IS 1893 (Part I), 2002, Indian Standard Criteria for Earthquake Resistant Design of Structures (5th Revision)

IS 4326, 1993, Indian Standard Code of Practice for Earthquake Resistant Design and Construction of Buildings (2nd Revision)

IS 13827, 1993, Indian Standard Guidelines for Improving Earthquake Resistance of Earthen Buildings

IS 13828, 1993, Indian Standard Guidelines for Improving Earthquake Resistance of Low Strength Masonry Buildings

IS 13920, 1993, Indian Standard Code of Practice for Ductile Detailing of Reinforced Concrete Structures Subjected to Seismic Forces

IS 13935, 1993, Indian Standard Guidelines for Repair and Seismic Strengthening of Buildings

The regulations in these standards do not ensure that structures suffer no damage during earthquake of all magnitudes. But, to the extent possible, they ensure that structures are able to respond to earthquake shakings of moderate intensities without structural damage and of heavy intensities without total collapse.

IS 1893 (part-1) 2003 : Criteria for earthquake resistant design of structures

Part.1 General provision and buildings. This standard deals with assessment of sesmic loads on various structures and earthquake resistant design of buildings. Its basic provisions are applicable to buildings, elevated structures, Industrial and stack like structures, bridges, concrete masonry and earth dams, embankments and retaining walls and other structures.

This standard contains provisions that are general in nature and applicable to all structures. It also contains provisions that are specific to buildings only. It covers general principles anddesign criteria, load combinations, design spectrum, main attributes of buildings dynamic analysis, apart from seismic zoning map and coefficients of important towns, showing epicenters, map showing tectonic features and lithological map of India.

The important aspects covered by this standard are as follows:

They are same as explained under IS 1893-1984.

IS 4326. Earthquake resistant design and construction of buildings

Code of practice : This standard provides guidance in selection of materials, special features of design and construction for earthquake resistant buildings including masonry construction, timber construction, pre fabricated construction etc.

In this standard, it is intended to cover the specifed features of design and construction for earthquake resistance of buildings of conventional type.

The general principles to be observed in the construction of such earthquake resistant buildings as specified in this standard are lightness, continuity of construction, avoiding reinforced projecting and suspended parts. Buildings configuration, strength in various directions, stable foundations, Ductibility of structures, connection to non-structural parts and fire safety of structures.

Special construction features like separation of adjoining structures, foundation design, crumple section, Roofs and floors and stair cases have been elaborated in this standard. It also covers the details pertaining to the type of construction, masonry construction with rectangular masonry units, masonry bearing walls, opening in bearing walls, seismic strengthening arrangements, framing of thin load bearing walls, reinforcing details for hollow block masonry flooring or roofing with precast components and timber construction. This is already discussed.

IS 13827-1993 : Improving earthquake resistance of earthen Buildings Guidelines

The guidelines covered in this standard deal with the design and construction aspects for improving earthquake resistance of earthen houses with out the use of stabilizers such as lime, cement, asphalt etc.

The provisions of this standard are applicable to seismic zone III, IV and V. No special provisions are considered for zone I and II. However consdering inherently weak against water, and earthquake, earthen buildings should be avoided preferably in flood prone, high rain fall areas and seismic zone IV and V.

It has been recommended that such buildings should be light, single storeyed and simple rectangular in plan. Qualitative tests for the suitability of soil have been suggested.

Guidelines for block or adobe construction, Rammed earth construction seismic strengthening of bearing wall buildings. Internal bracing inearthen houses and earthen constructions with wood or cane structure have been elaborated in this standard.

IS 13828-1993. Improving Earthquake resistance of low strength Masonry buildings-Guidelines

This standard covers the special fetures of design and construction for improving earthquake resistance of buildings of low strength masonry.

The provisions of this standard are applicable in all seismic zones-No special provisions are considered necessary for buildings in seismic zones I and II if cement sand mortar not leaner than 1:6 has been used in the masonry and through stones or bonding lelements are used in stone walls.

The various provisions of IS 4326-1993 regarding general principles, special construction features types of constructio, categories of buildings and masonry construction with rectangular masonry units, buildings of low strength are dealt with in this standard. However there are certain restrictions, exceptions and additional details, which are specifically included here in. This is already discussed.

IS 13920-1993. Ductile detailing of reinforced concrete structures subjected to seismic forces-Code of Practice

This standard covers the requirements for designing and detailing of monolithic R.C.C. buildings so as to give then adequate toughness and ductility toresist severe earthquake shocks with out collapse.

The provision for reinforced concrete construction given in this standard apply specifically to monolithic reinforced conrete construction; precast and/ or prestressed concrete members may be used only if they can provide the same level of ductility as that of a monolithic reinforced concrete construction during or after an earthquake.

Provisions on minimum and maximum reinforcement have been elaborated which include, the requirements of beams for longitudinal reinforcement in beams at joint face, splices and anchorage requirements. Provisions also have been included for calculation of disign shear force and for detailing of transverse reinforcements in beams.

Material specifications are indicated for lateral force resisting elements of frams. The provisions are also given for detailing of reinforcement in the wall web, boundary elements, coupling beams, around openings, at construction joints and for the development, splicing and anchorage of reinforcement.

IS 13935-1993 repair and seismic strengthening of buildings- Guidelines.

This standard covers the selection of materials and techniques to be used for repair and seismic strengthening of damaged buildings during earthquake and retorfittings for up grading of seismic resistance of existing buildings.

The provisions of this standard are applicable to seismic zones III, IV and V of IS 1893-1984, which are based on damage intensities VII and more on MSK scales.

The buildings affected by earthquake may suffer both structural as well as non-structural damages. This standard lays down guidelines for non-structural/architectural as well as structural repairs, seismic strengthening and seismic retrofitting of existing buildings. Guidelines have been given for selection of materials for repair work such as cement, steel epoxy resins, epoxy mortar, quick setting cement mortar, and special techiques such as shot crete, mechanical anchorage etc.. Seismic Strengthening techniques for the modification of roofs or floors, inserting new walls, strengthening existing walls, masonry arches, random rubble masonry walls, strengthening long walls, strenghtening reinforced concrete members and strengthening of foundations have neen elaborated in detail.

STRUCTURAL SYSTEMS

Structural systems are categorized based on the material of construction (e.g., concrete, masonry, steel), by the way in which lateral forces induced by earthquake shaking are resisted by the structure (e.g., by walls or frames), and by the relative quality of seismic-resistant design and detailing provided.

The Provisions recognizes four broad categories of structural system:
- Bearing wall systems,
- Building frame systems,
- Moment-resisting frame systems
- Dual systems,

In bearing wall systems, structural walls located throughout the structure provide the primary vertical support for the building's weight and that of its contents as well as the building's lateral resistance. Bearing wall buildings are commonly used for residential construction, warehouses, and low-rise commercial buildings of concrete, masonry and wood construction.

Building frames are a common structural system for buildings constructed of structural steel and concrete. In building frame structures, the building's weight is typically carried by vertical elements called columns and horizontal elements called beams. Lateral resistance is provided either by diagonal steel members (termed braces) that extend between the beams and columns to provide horizontal rigidity or by concrete, masonry, or timber shear walls that provide lateral resistance but do not carry the structure's weight. In some building frame structures, the diagonal braces or walls form an inherent and evident part of the building design as is the case for the high-rise building. In most buildings, the braces or walls may be hidden behind exterior cladding or interior partitions.

Moment-resisting frame systems are commonly used for both structural steel and reinforced concrete construction. In this form of construction, the horizontal beams and vertical columns provide both support for the structure's weight and the strength and stiffness needed to resist lateral forces. Stiffness and strength are achieved through the use of rigid connections between the beams and columns that prevent these elements from rotating relative to one other. Although somewhat more expensive to construct than bearing wall and braced frame structural systems, moment-resisting frame systems are popular because they do not require braced frames or structural walls, therefore permitting large open spaces and facades with many unobstructed window openings.

Moment Resisting Frame

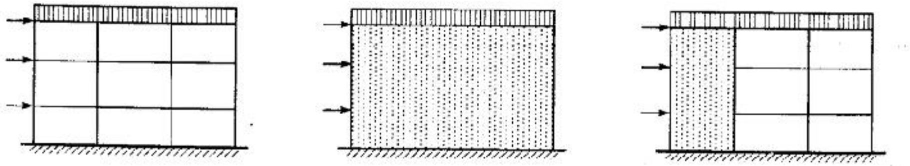
In building frame system, the members shown in Figure (a) (columns and beams) and joints of frame are resisting the earthquake forces, primarily by flexure. This system is generally preferred by architects because they are relatively unobtrusive compared to the shear walls or braced frames, but there may be poor economic risk unless special damage control measures are taken. Slab column frames are not recommended as a lateral load resisting system.

Building with Shear Wall or Bearing Wall System

This system supports all or most of the gravity loads as well as lateral loads. In general, a bearing wall system has a comparably lower value for R since the system lacks redundancy and has a poor inelastic response capacity see Figure (b). In severe seismic zones, these bearing wall systems are required to be specially detailed as per IS 4326: 1993. This system is not much preferred by the architects.

Building with Dual System

This system consists of shear wall (or braced frame) and moment resisting frame such that (i) the two systems are designed to resist the total design force in proportion to their lateral stiffness considering the interaction of the dual system at all floor levels; and (ii) the moment resisting frames are designed to independently resist at least 25% of design seismic base shear. In general, a dual system comparably has a higher value of R since a secondary lateral support system is available to assist the primary nonbearing lateral support system as shown in Figure 1(c). This system is somewhat less restrictive architecturally.



(a) Moment resisting frames

(b) Bearing wall system

(c) Building with dual system

Different types of building systems.

DYNAMIC CHARACTERISTICS OF BUILDINGS

Buildings oscillate during earthquake shaking. The oscillation causes inertia force to be induced in the building. The intensity and duration of oscillation, and the amount of inertia force induced in a building depend on features of buildings, called their *dynamic characteristics*, in addition to the characteristics of the earthquake shaking itself. The important dynamic characteristics of buildings are *modes of oscillation* and *damping*. A mode of oscillation of a building is defined by associated *Natural Period* and *Deformed Shape* in which it oscillates.

Natural Period

Natural Period T_n of a building is the time taken by it to undergo one complete cycle of oscillation. It is an inherent property of a building controlled by its mass m and stiffness k. These three quantities are related by

$$T_n = 2\pi\sqrt{\frac{m}{k}};$$

its units are seconds (s). Thus, buildings that are heavy (with larger mass m) and flexible (with smaller stiffness k) have larger natural period than light and stiff buildings. Buildings oscillate by translating along X, Y or Z directions, or by rotating about X, Y or Z axes, or by a combination of the above (Figure 1). When a building oscillates, there is an associated shape of oscillation.

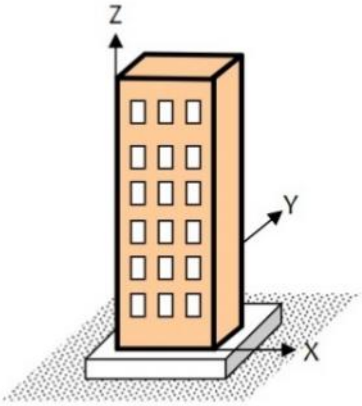


Figure 1: *Cartesian coordinates of a regular building*: Buildings oscillate by translating along X, Y or Z directions or/and by rotating about X, Y or Z axes

The reciprocal ($1/T_n$) of natural period of a building is called the *Natural Frequency* f_n; its unit is Hertz (Hz). The building offers least resistance when shaken at its natural frequency (or natural period). Hence, it undergoes larger oscillation when shaken at its natural frequency than at other frequencies (Figure 2). Usually, natural periods (T_n) of 1 to 20 storey normal reinforced concrete and steel buildings are in the range of 0.05 - 2.00s. In building design practice, engineers usually work with T_n and not f_n. Resonance will occur in a building, only if frequency at which ground shakes is steady at or near any of the natural frequencies of building and applied over an extended period of time. But, earthquake ground motion has departures from these two conditions. First, the ground motion contains a basket of frequencies that are continually and randomly changing at each instant of time. There is no guarantee that the ground shaking contains the same frequency (and that too close to f_n of the building) throughout or even for a sustained duration. Second, the small duration for which the ground shaking occurs at frequencies close to f_n of the building, is insufficient to build resonant conditions in most cases of the usual ground motions. Hence, usually, increased response occurs, but not resonance, when earthquake shaking carries energy in frequencies close to f_n of the building that is randomly fed to the building during earthquake shaking.

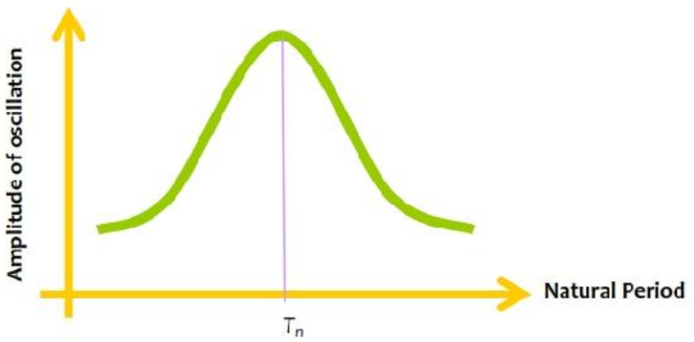


Figure 2: *Natural frequency of a building*: Amplitude of oscillation (or any response) of building increases when the building is shaken at or near its natural frequency

(1) *Effect of Stiffness*

Increasing the column size increases both stiffness and mass of buildings. But, when the percentage increase in stiffness as a result of increase in column size is larger than the percentage increase in mass, the natural period reduces. Hence, the usual discussion that increase in column size reduces the natural period of buildings, does not consider the simultaneous increase in mass; in that context, buildings are said to have shorter natural periods with increase in column size.

(2) *Effect of Mass*

Mass of a building that is *effective* in lateral oscillation during earthquake shaking is called the *seismic mass of the building*. It is the sum of its seismic masses at different floor levels. Seismic mass at each floor level is equal to full dead load plus appropriate fraction of live load. The fraction of live load depends on the intensity of the live load and how it is connected to the floor slab. Seismic design codes of each country/region provide fractions of live loads to be considered for design of buildings to be built in that country/region.

(3) *Effect of Unreinforced Masonry Infill Walls in RC Frames*

In many countries, the space between the beams and columns of building are filled with unreinforced masonry (URM) infills. These infills participate in the lateral response of buildings and as a consequence alter the lateral stiffness of buildings. Hence, natural periods (and modes of oscillation) of the building are affected in the presence of URM.

In conventional design practice, the masses of the infill walls are considered, but their lateral stiffness are not. Modeling the infill wall along with the frame elements (*i.e.,* beams and columns) is necessary to incorporate additional lateral stiffness offered by URM infill walls. Lateral stiffness of buildings increases when URM infill walls are included in the analysis models. Thus, natural period of a building is *lower,* when *stiffness of URM* infill *is considered,* than when it *is not considered*. The extent of stiffness enhancement and change in natural period due to URM infills depends on the extent and spatial distribution of URM infills. Change in natural period is higher in shorter buildings as compared to tall buildings. This implies that seismic behaviour of shorter buildings is affected significantly as compared to that of taller buildings, when stiffness enhancement due to URM is considered.

In summary, natural periods of buildings depend on the distribution of mass and stiffness along the building (in all directions). Some major trends related to natural periods of buildings of regular geometrics are :

1. Natural periods of buildings reduce with increase in stiffness.
2. Natural periods of buildings increase with increase in mass.
3. Taller buildings have larger fundamental translational natural periods.
4. Buildings tend to oscillate in the directions in which they are most flexible and have larger translational natural periods.
5. Natural periods of buildings depend on amount and extent of spatial distribution of unreinforced masonry infill walls.

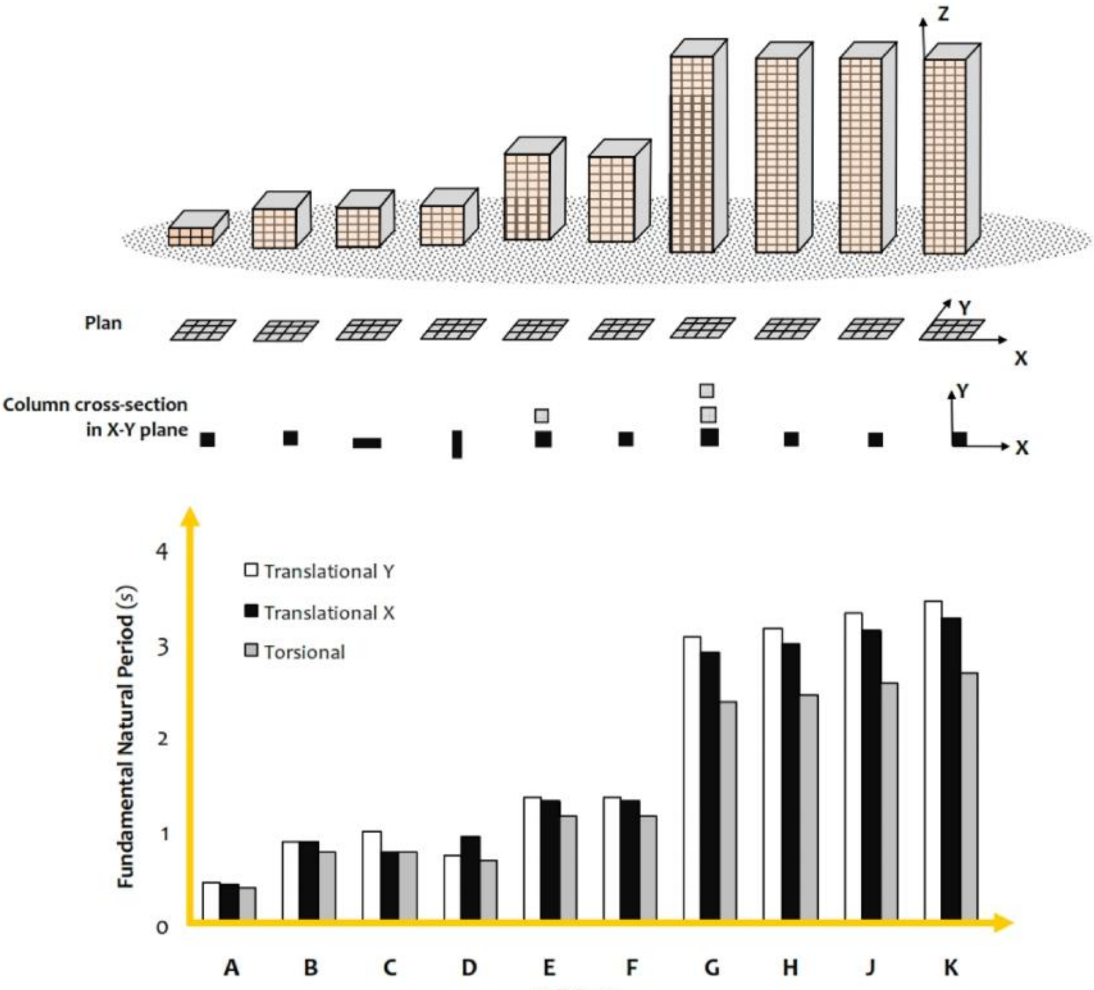


Figure 3: *Summary of natural periods of buildings considered*: Natural periods are influenced by mass and stiffness parameters of buildings

Damping

Buildings set to oscillation by earthquake shaking eventually come back to rest with time. This is due to dissipation of the oscillatory energy through conversion to other forms of energy, like heat and sound. The mechanism of this conversion is called *damping*.

In normal ambient shaking of building, many factors impede its motion, *e.g.*, drag from air resistance around the building, micro-cracking of concrete in the structural members, and friction between various interfaces in the building (like masonry infill walls and RC beams and columns). This damping is called *structural damping*.

But, under strong earthquake shaking, buildings are damaged. Here, reinforcement bars and concrete of the RC buildings enter nonlinear range of material behaviour. The damping that arises from these inelastic actions is called *hysteretic damping*; this further dampens oscillations of the building.

Another form of damping is associated with soil. This damping occurs when the soil strata underneath the building is flexible and absorbs energy input to the building during earthquake shaking, and sends it to far off distances in the soil medium. This is called *radiation damping*.

What are the Seismic Effects on Structures?

Inertia Forces in Structures

Earthquake causes shaking of the ground. So a building resting on it will experience motion at its base. From *Newton's First Law of Motion*, even though the base of the building moves with the ground, the roof has a tendency to stay in its original position. But since the walls and columns are connected to it, they drag the roof along with them. *This is much like the situation that you are faced with when the bus you are standing in suddenly starts; your feet move with the bus, but your upper body tends to stay back making you fall backwards!!* This tendency to continue to remain in the previous position is known as *inertia*. In the building, since the walls or columns are flexible, the motion of the roof is different from that of the ground (Figure 1).

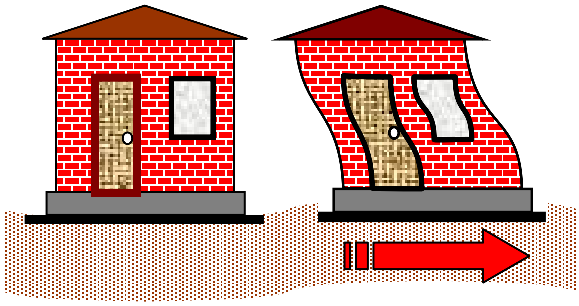


Figure 1: Effect of Inertia in a building when shaken at its base

Consider a building whose roof is supported on columns (Figure 2). *Coming back to the analogy of yourself on the bus: when the bus suddenly starts, you are thrown backwards as if someone has applied a force on the upper body.* Similarly, when the ground moves, even the building is thrown backwards, and the roof experiences a force, called *inertia force*. If the roof has a mass *M* and experiences an acceleration *a*, then from *Newton's Second Law of Motion*, the *inertia force* F_I is mass *M* times acceleration *a*, and its direction is opposite to that of the acceleration. Clearly, more mass means higher inertia force. Therefore, lighter buildings sustain the earthquake shaking better.

Effect of Deformations in Structures

The inertia force experienced by the roof is transferred to the ground via the columns, causing forces in columns. These forces generated in the columns can also be understood in another way. During earthquake shaking, the columns undergo relative movement between their ends. In Figure 2, this movement is shown as quantity **u** between the roof and the ground. But, given a free option, columns would like to come back to the straight vertical position, *i.e.,* columns resist deformations. In the straight vertical position, the columns carry no horizontal earthquake force through them. But, when forced to bend, they develop internal forces. The larger is the relative horizontal displacement **u** between the top and bottom of the column, the larger this internal force in columns. Also, the stiffer the columns are (*i.e.,* bigger is the column size), larger is this force. For this reason, these internal forces in the columns are called *stiffness forces*. In fact, the stiffness force in a column is the column stiffness times the relative displacement between its ends.

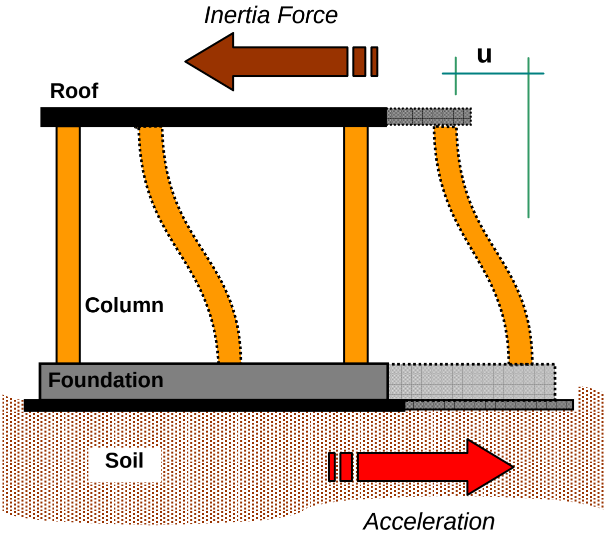


Figure 2: Inertia force and relative motion within a building

Horizontal and Vertical Shaking

Earthquake causes shaking of the ground in all three directions – along the two horizontal directions (*X and Y, say*), and the vertical direction (*Z, say)* (Figure 3). Also, during the earthquake, the ground shakes randomly *back and forth* (- and +) along each of these X, Y and Z directions. All structures are primarily designed to carry the gravity loads, *i.e.,* they are designed for a force equal to the mass *M* (this includes mass due to own weight and imposed loads) times the acceleration due to gravity *g* acting in the vertical downward direction (-Z). The downward force *Mg* is called the *gravity load*. The vertical acceleration during ground shaking either adds to or subtracts from the acceleration due to gravity. Since factors of safety are used in the design of structures to resist the gravity loads, usually most structures tend to be adequate against vertical shaking.

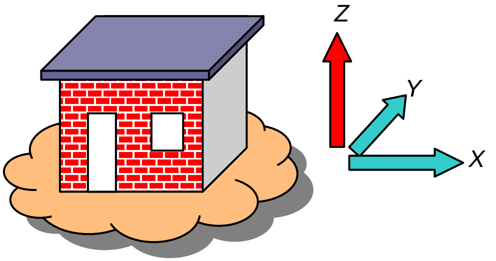


Figure 3: Principal directions of a building

However, horizontal shaking along X and Y directions (both + and – directions of each) remains a concern. Structures designed for gravity loads, in general, may not be able to safely sustain the effects of horizontal earthquake shaking. Hence, it is necessary to ensure adequacy of the structures against horizontal earthquake effects.

Flow of Inertia Forces to Foundations

Under horizontal shaking of the ground, horizontal inertia forces are generated at level of the mass of the structure (usually situated at the floor levels). These lateral inertia forces are transferred by the floor slab to the walls or columns, to the foundations, and finally to the soil system underneath (Figure 4). So, each of these structural elements (floor slabs, walls, columns, and foundations) and the connections between them must be designed to safely transfer these inertia forces through them.

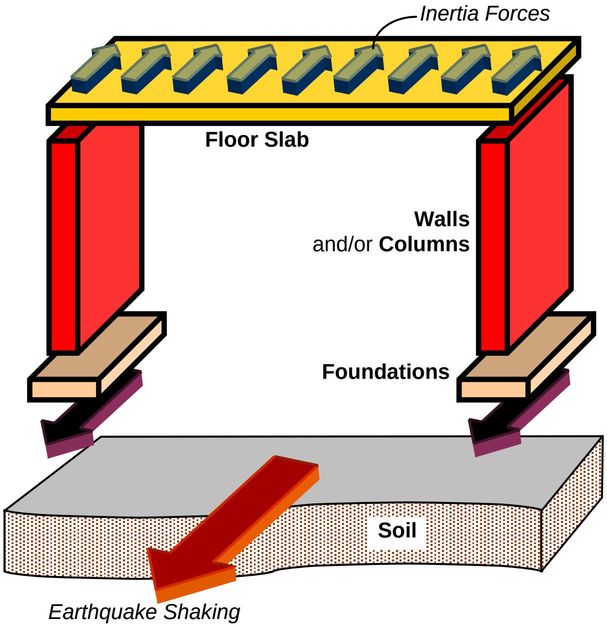


Figure 4: Flow of seismic inertia forces through all structural components.

Walls or columns are the most critical elements in transferring the inertia forces. But, in traditional construction, floor slabs and beams receive more care and attention during design and construction, than walls and columns. Walls are relatively thin and often made of brittle material like masonry. They are poor in carrying horizontal earthquake inertia forces along the direction of their thickness. Failures of masonry walls have been observed in many earthquakes in the past (*e.g.*, Figure 5a). Similarly, poorly designed and constructed reinforced concrete columns can be disastrous. The failure of the ground storey columns resulted in numerous building collapses during the 2001 Bhuj (India) earthquake (Figure 5b).

(a) Partial collapse of stone masonry walls during 1991 Uttarkashi (India) earthquake

(b) Collapse of reinforced concrete columns (and building) during 2001 Bhuj (India) earthquake

Figure 5: Importance of designing walls/columns for horizontal earthquake forces.

Seismic Behaviour of Unreinforced Masonry during Earthquakes

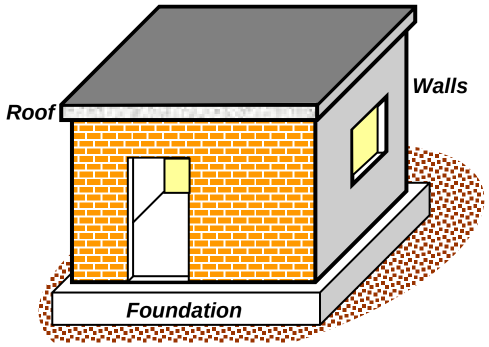
Behaviour of Brick Masonry Walls

Masonry buildings are brittle structures and one of the most vulnerable of the entire building stock under strong earthquake shaking. The large number of human fatalities in such constructions during the past earthquakes in India corroborates this. Thus, it is very important to improve the seismic behaviour of masonry buildings. A number of earthquake-resistant features can be introduced to achieve this objective.

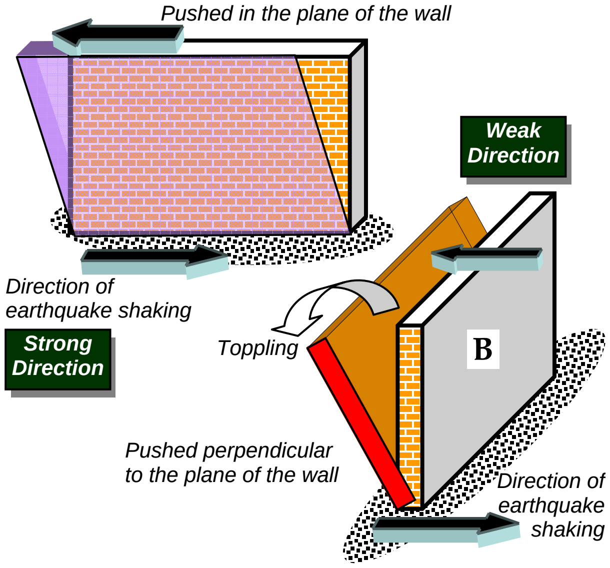
Ground vibrations during earthquakes cause inertia forces at locations of mass in the building. These forces travel through the roof and walls to the foundation. The main emphasis is on ensuring that these forces reach the ground without causing major damage or collapse. Of the three components of a masonry building (*roof*, *wall* and *foundation*) (Figure 1a), the walls are most vulnerable to damage caused by horizontal forces due to earthquake. A wall topples down easily if pushed horizontally at the top in a direction perpendicular to its plane (termed *weak direction*), but offers much greater resistance if pushed along its length (termed *strong direction*) (Figure 1b).

The ground shakes simultaneously in the vertical and two horizontal directions during earthquakes However, the horizontal vibrations are the most damaging to normal masonry buildings. Horizontal inertia force developed at the roof transfers to the walls acting either in the weak or in the strong direction. If all the walls are not tied together like a box, the walls loaded in their weak direction tend to topple (Figure 2a).

To ensure good seismic performance, all walls must be joined properly to the adjacent walls. In this way, walls loaded in their weak direction can *take advantage* of the good lateral resistance offered by walls loaded in their strong direction (Figure 2b). Further, walls also need to be tied to the roof and foundation to preserve their overall integrity.

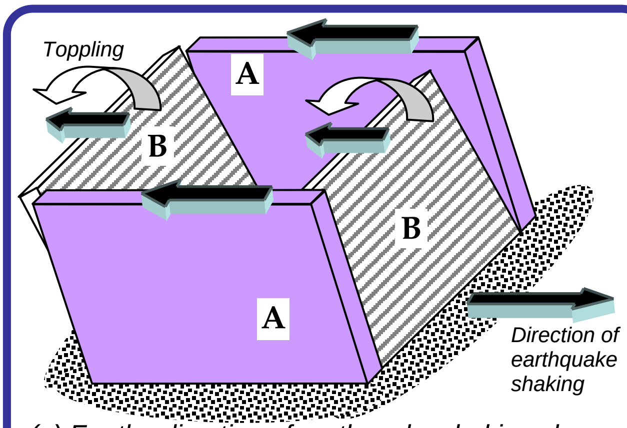


(a) Basic components of a masonry building

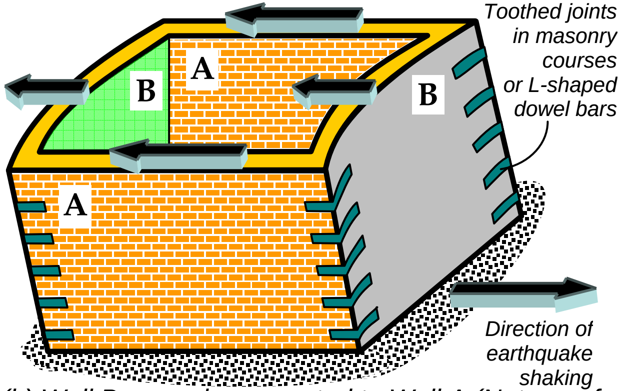


(b) Direction of force on a wall critically determines its earthquake performance

Figure 1: Basic components of a masonry building – *walls are sensitive to direction of earthquake forces*.



(a) For the direction of earthquake shaking shown, wall B tends to fail



(b) Wall B properly connected to Wall A (Note: roof is not shown): Walls A (loaded in strong direction) support Walls B (loaded in weak direction)

Figure 2: Advantage sharing between walls – *only possible if walls are well connected*.

How to Improve Behaviour of Masonry Walls

Masonry walls are slender because of their small thickness compared to their height and length. A simple way of making these walls behave well during earthquake shaking is by making them act together as a box along with the roof at the top and with the foundation at the bottom. A number of construction aspects are required to ensure this box action. Firstly, connections between the walls should be good. This can be achieved by (a) ensuring good interlocking of the masonry courses at the junctions, and (b) employing horizontal bands at various levels, particularly at the lintel level. Secondly, the sizes of door and window openings need to be kept small. The smaller the openings, the larger is the resistance offered by the wall. Thirdly, the tendency of a wall to topple when pushed in the weak direction can be reduced by limiting its length-to-thickness and height-to-thickness ratios (Figure 3). Design codes specify limits for these ratios. A wall that is too tall or too long in comparison to its thickness, is particularly vulnerable to shaking in its weak direction (Figure 3).

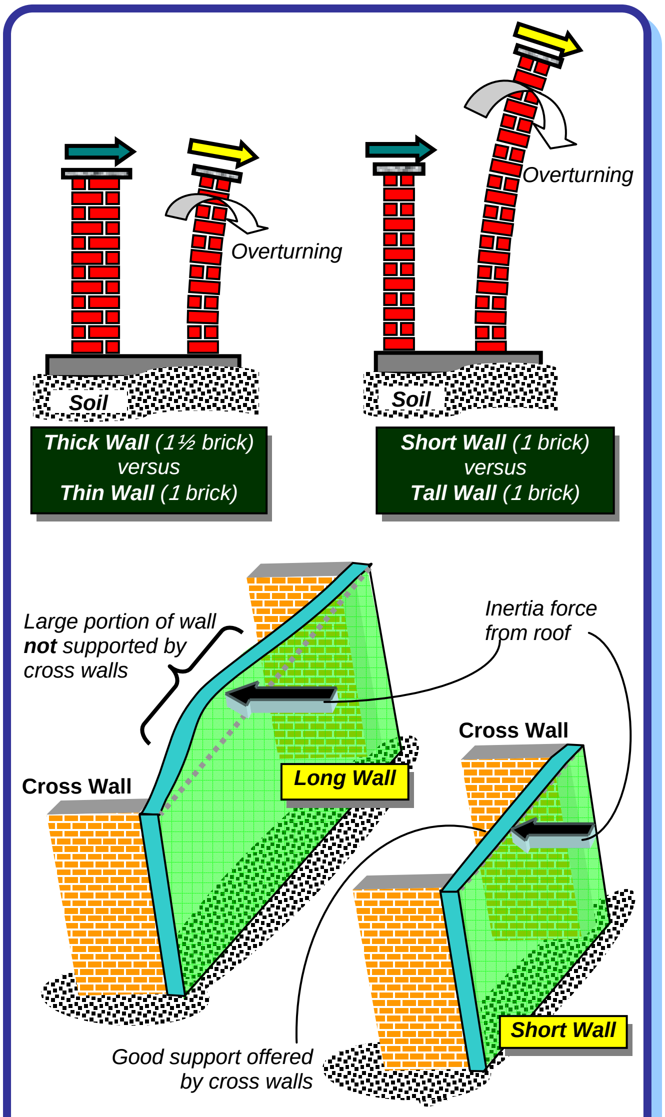


Figure 3: Slender walls are vulnerable – *height and length to be kept within limits*. *Note: In this figure, the effect of roof on walls is not shown.*

Choice and Quality of Building Materials

Earthquake performance of a masonry wall is very sensitive to the properties of its constituents, namely masonry units and mortar. The properties of these materials vary across India due to variation in raw materials and construction methods. A variety of masonry units are used in the country, *e.g.,* clay bricks (burnt and unburnt), concrete blocks (solid and hollow), stone blocks. *Burnt clay bricks* are most commonly used. These bricks are inherently porous, and so they absorb water. Excessive porosity is detrimental to good masonry behaviour because the bricks suck away water from the adjoining mortar, which results in poor bond between brick and mortar, and in difficulty in positioning masonry units. For this reason, bricks with low porosity are to be used, and they must be soaked in water before use to minimise the amount of water drawn away from the mortar.

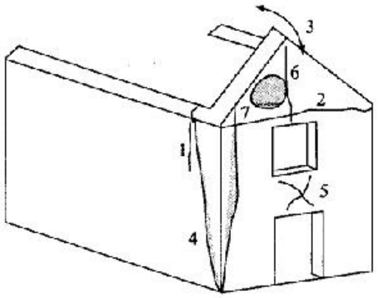
Various mortars are used, *e.g.,* mud, cement-sand, or cement-sand-lime. Of these, *mud mortar* is the weakest; it crushes easily when dry, flows outward and has very low earthquake resistance. *Cement-sand mortar with lime* is the most suitable. This mortar mix provides excellent workability for laying bricks, stretches without crumbling at low earthquake shaking, and bonds well with bricks. The earthquake response of masonry walls depends on the relative strengths of brick and mortar. Bricks must be stronger than mortar. Excessive thickness of mortar is not desirable. A 10mm thick mortar layer is generally satisfactory from practical and aesthetic considerations. Indian Standards prescribe the preferred types and grades of bricks and mortars to be used in buildings in each seismic zone.

FAILURE MODE OF MASONRY BUILDINGS

An appropriate selection of suitable retrofitting schemes depends entirely upon the failure mode of individual masonry construction. There are innumerable modes of failure of walls as observed by the reconnaissance team and documented in various published papers and reports. Although the type of construction, site of construction, structural typology of masonry buildings varies in different regions but the damage caused by seismic activity may be identified uniformly. The two most common modes of masonry failure may be called **out-of-plane failure** and **in-plane failure**. The structural walls perpendicular to seismic motion are subjected to out-of-plane bending results in out-of-plane failure featuring vertical cracks at the corners and in the middle of the walls. The structural walls parallel to seismic motion are subjected to in-plane forces *i.e.* bending and shear causes horizontal and diagonal cracks in the wall respectively. The other types of masonry failure are diaphragm failure, pounding, connection failure and failure of non-structural components. A brief discussion of each mode of masonry failure is described as under.

Out-of-plane Failure

Inadequate anchorage of the wall into the roof diaphragm and limited tensile strength of masonry and mortar unitedly causes out-of-plane failure of wall in un-reinforced masonry buildings, which are the most vulnerable. The resulting flexural stress apparently exceeds the tensile strength of masonry leading to rupture followed by collapse. Moreover long span diaphragms causes excessive horizontal flexure. Out-of-plane wall movement has been characterized as shown in Figure

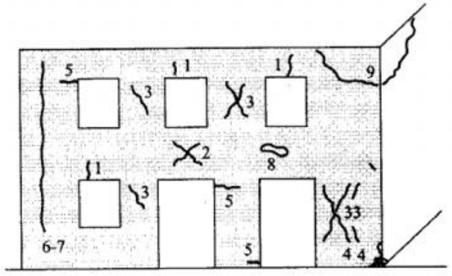


1. Vertical cracks in the corner and/or T walls
2. Horizontal cracks along the facade
3. Partial collapse of an exterior wall
4. Wythe separation
5. Cracks at lintel and top of slender piers
6. Cracks at the level of the roof
7. Masonry ejection

Out-of-plane failure characterization

In-plane Failure

In-plane failures of walls in un-reinforced masonry structures due to excessive bending or shear are most common as is evident from double diagonal (X) shear cracking. This cracking pattern frequently found in cyclic loading indicates that the planes of principal tensile stress in the walls remain incapable of withstanding repeated load reversals leading to total collapse. As the ground motion takes place for a short duration the walls are subjected to only one or two significant loading reversals and do not collapse totally. Fortunately by the time the shear cracks become unduly severe, the gravity load carrying capacity of the wall is not jeopardized. Diagonal tension *i.e.* "X" cracks occurs mainly in short piers, rocking (top and bottom) in slender piers. These cracks happen to be worse at lower storey. In-plane failures are characterized as in Figure



1. Vertical cracks on openings
2. Diagonal shear cracks on parapets and in doors and window lintels
3. Diagonal shear cracks in the masonry piers between openings
4. Crushing of corners of walls due to excess of compression stress
5. Horizontal flexure cracks on top and/or base of masonry piers
6. Vertical cracks at wall intersections
7. Passing through vertical cracks at wall intersections
8. Spalling of material at the location of floor beam due to pounding
9. Separation and expulsion of the intersection zone of two corner walls

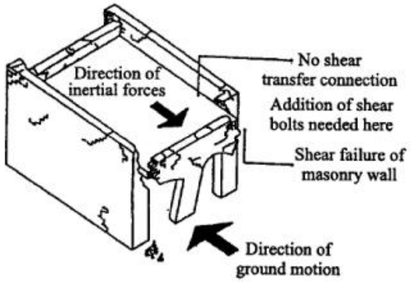
In-plane failure characterization

Diaphragm Failure

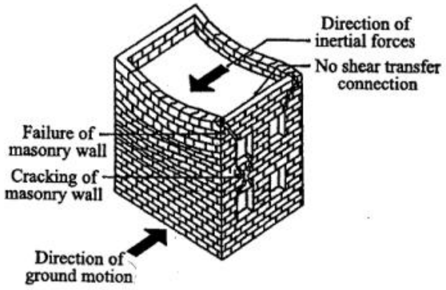
The failure of the diaphragm is a rare phenomenon in the event of seismic motion. Damage to the diaphragm never impairs its gravity load carrying capacity. Lack of tension anchoring produces a non-bending cantilever action at the base of the wall resulting from the push of diaphragm against the wall. The in-plane rotation of the diaphragms ends and the absence of a good shear transfer between diaphragms and reaction walls account for damage at the corners of the wall. Figure illustrates a wall failure resulting from excessive diaphragm flexibility. This problem remains non-existent in strengthened buildings and is very rare in anchored buildings. In strengthened buildings, separation remains worse at or near the centreline of the diaphragm.

Failure of Connection

Seismic inertial forces that originate in all elements of the building are delivered to horizontal diaphragms through structural connections. The diaphragms distribute these forces among vertical elements, which in turn transfer the forces to the foundation. Hence, an adequate connection capable to transfer the in-plane shear stress from the diaphragms to the vertical elements and to provide support to out-of-plane forces on these elements is essential between



Shear failure,



Characterization of failure,

the diaphragms and the vertical elements. This type of failure is characterized by diagonal cracks disposed on both the walls' edges causing separation and collapse of corner zones

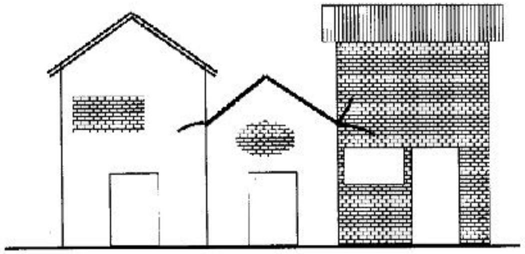
This phenomenon magnifies due to inadequately strengthened openings near the walls' edges and by floors insufficiently connected to the external walls.

Non-structural Components

The non-structural components in masonry buildings are parapet walls, partition walls, mumty, water tanks, canopies, projections, staircase etc. These non-structural elements behave like cantilevers if they remain unrestrained and are subjected to greater amplification as compared to ground motion becoming prone to failures

Pounding

When adjacent roof levels of two buildings and vertical brick work faces flush with one another, the pounding action causes structural distress due to out-of-plane vibrations. Such a failure is characterized as shown in Figure .

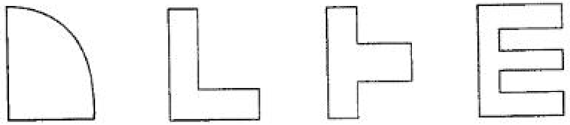


- Vertical cracks in the adjacent walls
- Diagonal cracks due to different levels in the structures

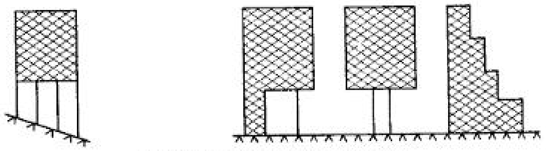
Planning Considerations as per IS 4326: 1993

BUILDING CONFIGURATION

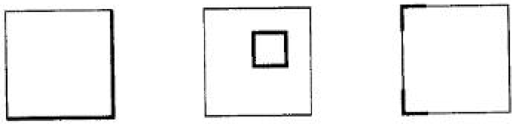
The second step in seismoresistant construction is the configuration of load resisting system of buildings. IS 1893 (Part 1): 2002 has recommended building configuration system in **Section 7** for the better performance of buildings during earthquakes. An important feature in building configuration is its regularity and symmetry in horizontal and vertical plane. Seismic behaviour of irregular shaped plans differs from regular shapes because the first can be subjected to their asymmetry and/or can present local deformations due to the presence of reentrant corners or excessive openings. Both effects give origin to undesired stress concentrations in some resisting members of the building. On the contrary, the ideal rectangular or square plan, structurally symmetric, with enough in-plane stiffness in its diaphragm, presents an ideal behaviour, because it has the same displacement at every point in the slab (Ravan and Lopez, 1996). Therefore, building shaped like a box, such as rectangular, both in plan and elevation, is inherently stronger than one that is L-shaped or U-shaped, that is a building with wings.



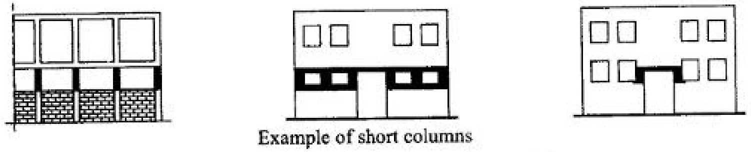
Example of plan irregularity



Example of vertical irregularity



Example of highly torsional configuration



Example of short columns

General building configuration problems

In order to minimize torsion and stress concentration, provisions given below

1. The building should have a simple rectangular plan and be symmetrical both with respect to mass and rigidity so that the centres of mass and rigidity of the building coincide with each other in which case no separation sections other than expansion joints are necessary. For provision of expansion joints reference may be made to IS 3414: 1968.
2. If symmetry of the structure is not possible in plan, elevation or mass, provision shall be made for torsional and other effects due to earthquake forces in the structural design or the parts of different rigidities may be separated through crumple sections. The length of such building between separation sections shall not preferably exceed three times the width.

Buildings having plans with shapes like, L, T, E and Y shall preferably be separated into rectangular parts by providing separation sections at appropriate places. Typical examples are shown in Fig. 1.

The buildings with small lengths of projections forming L, T, E or Y shapes need not be provided with separation section. In such cases the length of the projection may not exceed 15 to 20 percent of the total dimension of the building in the direction of the projection

For buildings with minor asymmetry in plan and elevation separation sections may be omitted.

Strength in Various Directions

The structure shall be designed to have adequate strength against earthquake effects along both the horizontal axes. The design shall also be safe considering the reversible nature of earthquake forces.

Foundations

The structure shall not be founded on such loose soils which will subside or liquefy during an earthquake, resulting in large differential settlements

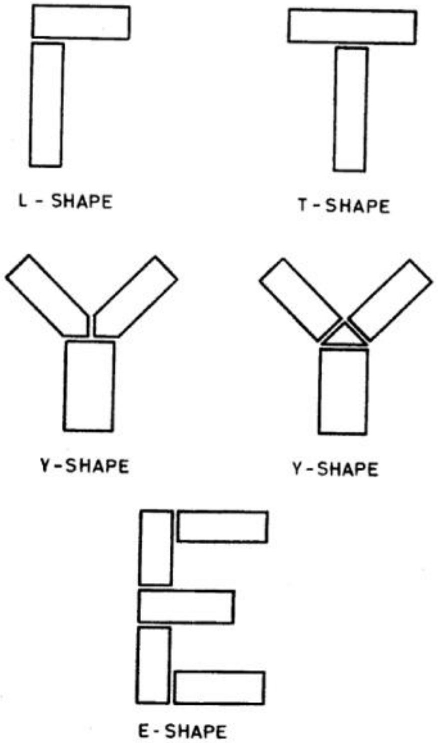


FIG. 1 TYPICAL SHAPES OF BUILDING WITH SEPARATION SECTIONS

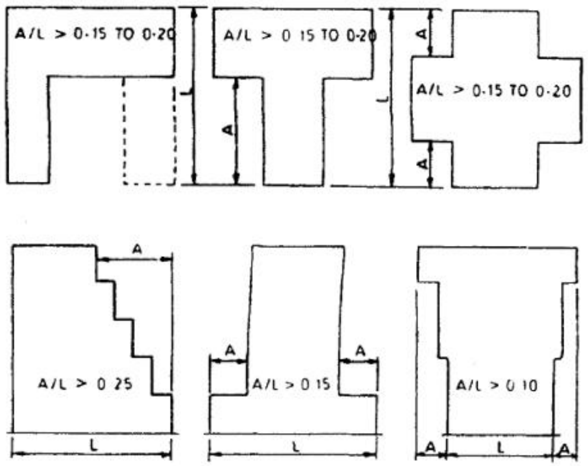


FIG. 2 PLAN AND VERTICAL IRREGULARITIES

PLANNING CONSIDERATIONS

Configuration is critical to good seismic performance of buildings. The important aspects affecting seismic configuration of buildings are overall geometry, structural systems, and load paths. Various issues related to seismic configuration are discussed in this section.

Overall Geometry

Buildings oscillate during earthquake shaking and inertia forces are mobilized in them. Then, these forces travel along different paths, called *load paths*, through different structural elements, until they are finally transferred to the soil through the foundation. The generation of forces based on basic oscillatory motion and final transfer of force through the foundation are significantly influenced by overall geometry of the building, which includes: (a) plan shape, (b) plan aspect ratio, and (c) slenderness ratio of the building.

(a) Plan Shape

The influence of plan geometry of the building on its seismic performance is best understood from the basic geometries of *convex*- and *concave*-type lenses. Buildings with former plan shape have direct load paths for transferring seismic inertia forces to its base, while those with latter plan shape necessitate indirect load paths that result in stress concentrations at points where load paths bend. Buildings with convex and simple plan geometries are preferred, because they demonstrate superior seismic performance than those with concave and complex plan geometries (Figure 1).

To illustrate the above concept, seven plan shapes are considered; six of them have complex plan geometries and one has the simple rectangular geometry (Figure 1).

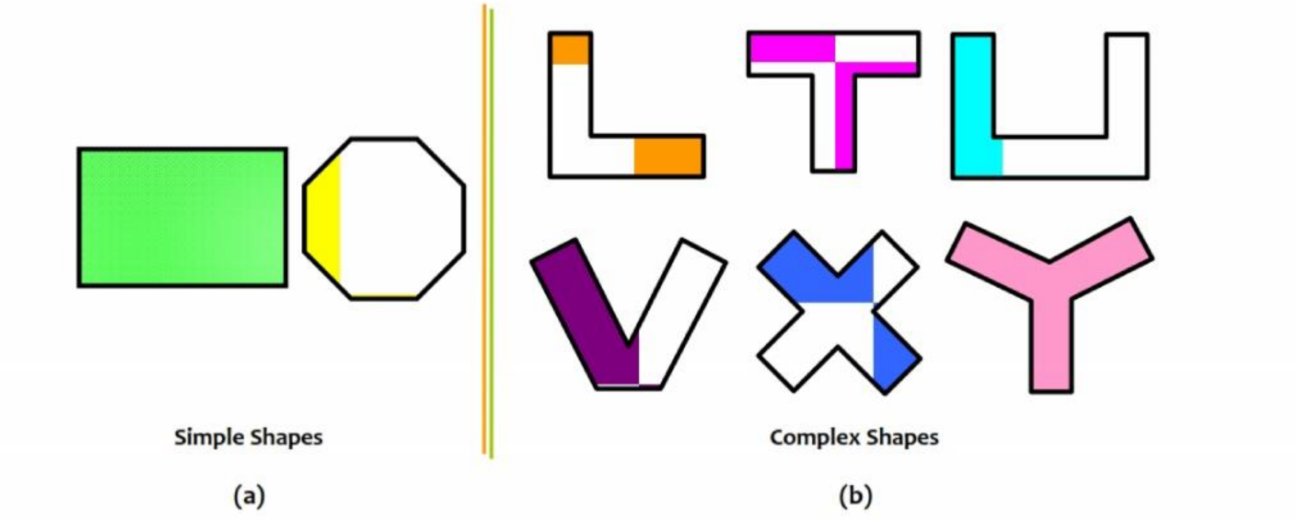
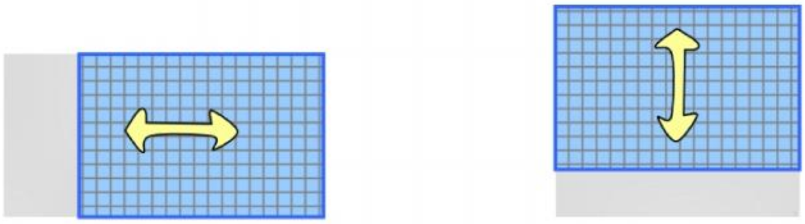


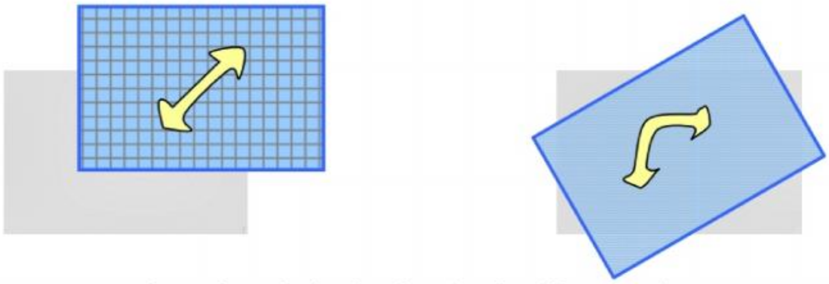
Figure .1: *Plan shapes of buildings*: Buildings with (a) simple shapes undergo simple acceptable structural seismic behaviour, while (b) those with complex shapes undergo complex unacceptable structural seismic behaviour

(1) Buildings with different shapes, but same Plan Area

Rectangular (or square) columns are good in resisting shear and bending moment about axes parallel to their sides. Thus, it is important to have buildings oscillating primarily along their sides – *translation along diagonals* or *torsional* motions are NOT good for seismic performance of columns, and hence, of buildings (Figure 2). Thus, it is desirable to have pure translation modes as the lower modes of oscillation and push torsional and diagonal translational modes to the higher ranks. Primarily, these undesirable (diagonal translation and torsional) modes arise when there is lack of symmetry in the plan shape of buildings along the sides. It is important to have regular plan shape of buildings.



Pure translational oscillatory motions



Diagonal translational and torsional oscillatory motions

Figure 2: *Oscillatory motions of buildings during earthquake shaking*: Diagonal translational and torsional oscillations are not preferred

(2) Buildings with different projections, but same Plan Shape

Long projections are not good! Projections, if required, must be short, although they still offer stress concentration at their re-entrant corners. Consider buildings with U-plan shape, but with different length of projections (Figure 3). The first three modes of oscillation in all the three buildings are same – two lateral translations and torsion, with similar natural periods.

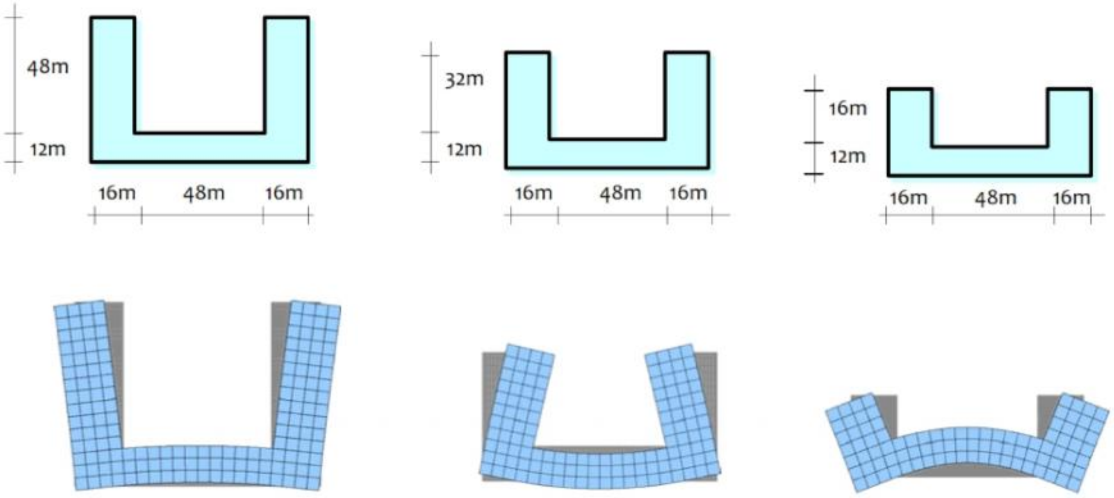


Figure 3: *Effect of projections*: The contribution of opening-closing modes of oscillation to overall response is least in building with smallest projection

In buildings with L-plan shape, the effect of two undesirable mode of oscillations, namely, diagonal translation and opening-closing modes can be avoided by having small projections, which dominate in buildings with large projections. Also, the diagonal translation mode is not seen in the building with small projecting arms, but the torsional mode is seen too early in the second and third mode shapes, which is undesirable.

Similarly, in buildings with V-plan shape, Y-plan shape and X-plan shape, the effect of two undesirable modes of oscillation. This is illustrated through results of buildings with V-plan shape, Y-plan shape and buildings with X-plan shape. But, again, due to the complex shape, torsional mode of oscillation is present in all buildings. And, torsion is the fundamental mode of oscillation in building with Y-plan shape and especially that with large projections.

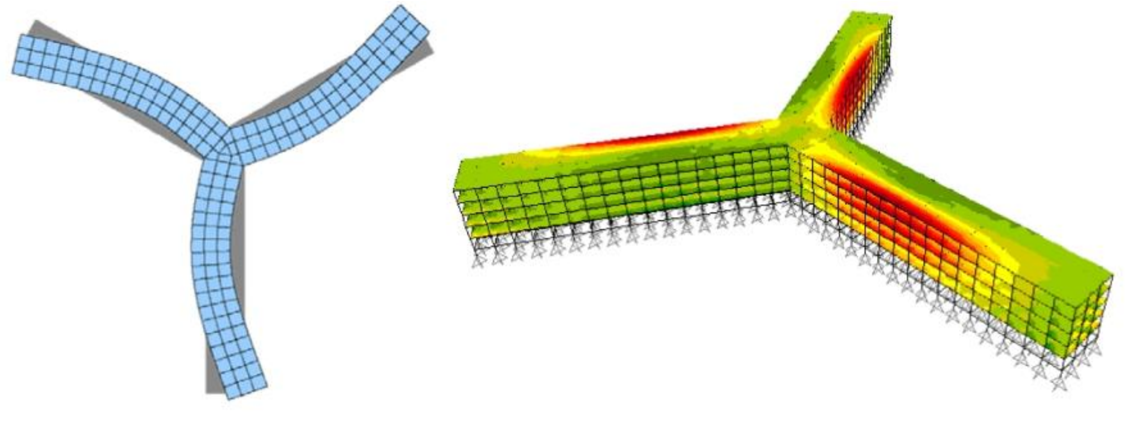


Figure 4: *Torsional mode of oscillation*: Torsional mode of oscillation in buildings with complex shape contribute significantly to overall building response if it has large natural period

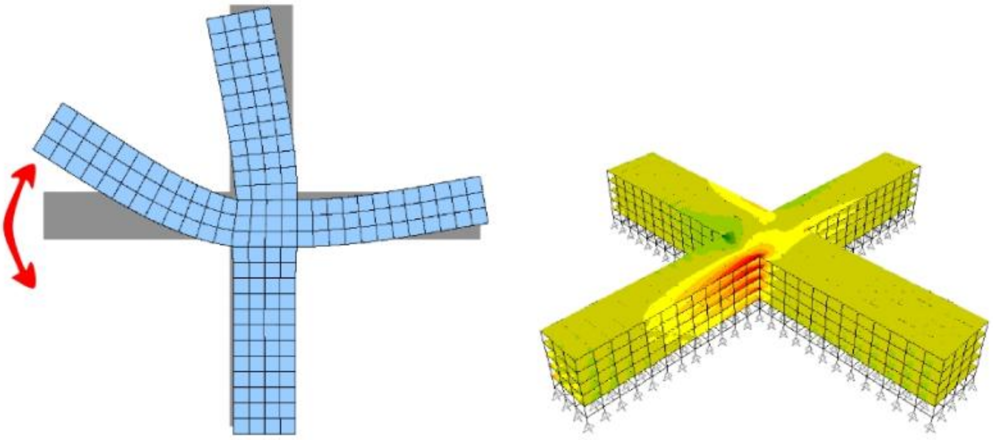


Figure 5: *Dog-tail-wagging mode of oscillation*: Dog-tail-wagging mode of oscillation in building with X-plan shape cause significant stress concentration at re-entrant corners

In summary, the important observations are

(1) Torsional modes of oscillations are predominant in buildings with L-, X- and Y-plan shapes, which should be avoided with suitable choice of structural configuration;
(2) Diagonal translation modes of oscillations are predominant in buildings with L-and X-plan shapes, which should be avoided with suitable changes in structural configuration;
(3) Opening-closing and dog-tail-wagging modes of oscillation are predominant in buildings with large projecting arms;
(4) Opening-closing and dog-tail-wagging modes of oscillation cause significant stress concentrations at re-entrant corners and can cause structural damage; and
(5) It is prudent to not use buildings with complex plan shapes, or if compelled, ensure that their natural periods are small (outside the range of natural periods with significant earthquake energy).

(b) Plan Aspect Ratio

It is not good to have buildings with large plan aspect ratio, just like it is not good to have buildings with large projections. During earthquake shaking, inertia force is mobilized in the building, usually at the floor levels where the mass is large. The inertia force then is distributed to different lateral load resisting systems (columns and/or structural walls). It is preferred to distribute this lateral inertia force to various lateral load resisting systems in proportion to their lateral load resisting capacities (Figure 6). This is achieved when the floor slabs do not deform too much in their own (horizontal) plane. This condition, when floor slab helps in distributing the inertia force to different lateral load resisting systems in proportion to their stiffness, is known as *rigid diaphragm action*. However, the inertia force is distributed based on tributary area when floor slabs deform in their plane. This leads to overloading of members with less capacity and thus causing undue damage to buildings. Floor slabs in buildings with large plan aspect ratio (>4) may not provide rigid diaphragm action.

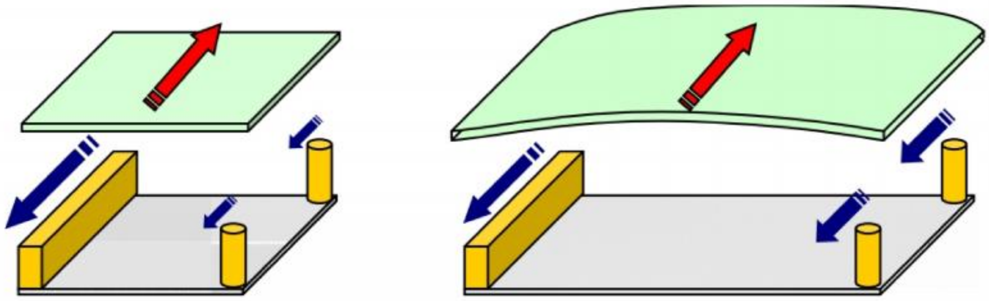


Figure 6: *Rigid diaphragm action*: In-plane flexural bending of floor slabs affects the distribution of mobilized lateral inertia force to different lateral force resisting members

(2) Buildings with regular plan shape, but of large plan size and with cut-outs

It is not desirable to have a building with large plan size, because lateral load resisting systems are required to be distributed throughout the building plan to carry the inertia force through direct load paths with no/little detours. When these lateral load resisting systems undergo inelastic actions, they are likely to loose stiffness and thereby the building generates stiffness eccentricity, which is detrimental to the symmetrical swinging of the building during earthquake shaking. The problem is even more aggravated if building with large plan has large openings or cut-outs at the center or inside the plan of the building. These large cut-outs in the plan of the building push the floor diaphragms of the building to not remain *rigid* in their own plane, which causes the inertia force mobilized at floor levels during earthquake shaking to be unevenly distributed to the different lateral load resisting elements. This is not desirable for good seismic performance of this type of buildings; this irregularity should be avoided or minimised.

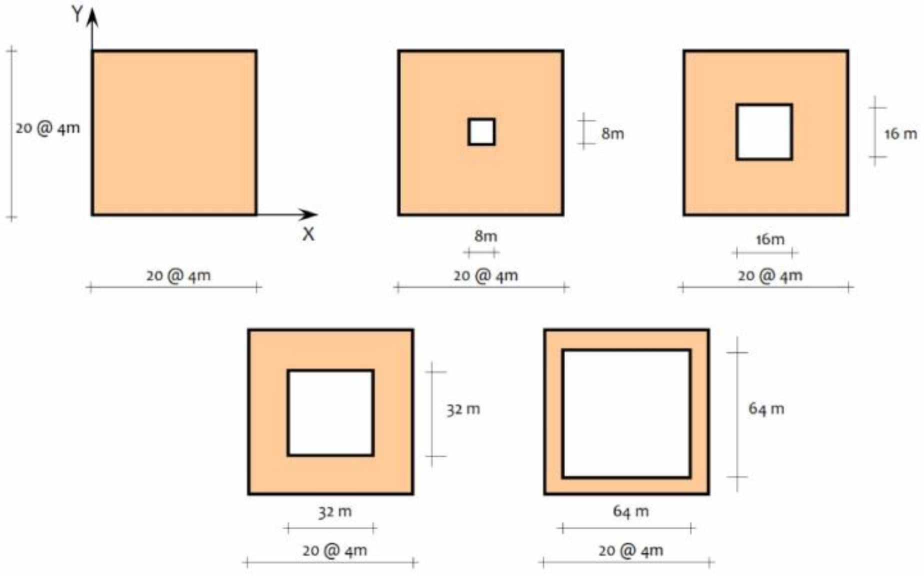


Figure 7: *Effect of cut-out in diaphragm*: different size of openings considered

(c) Slenderness Ratio

It is not desirable to have buildings with large slenderness ratio, just like it is not good to have buildings with large projecting arms and large plan aspect ratio. During earthquake shaking, buildings sway laterally and excessive lateral displacement is not desirable. Large lateral displacements cause significant non-structural damage, structural damage and even second order P-Δ effects that lead to collapse of buildings. Design codes recommend that inter-storey drift under design earthquake forces be restricted to 0.4 percent of storey height.

Structural Systems and Components

Using an appropriate structural system is critical to good seismic performance of buildings. While *moment-frame* is the most commonly used lateral load resisting structural system, other structural systems also are commonly used (Figure 8) like *structural walls*, *frame-wall system*, and *braced-frame system*. Sometimes, even more redundant structural systems are necessary, *e.g.*, *Tube*, *Tube-in-Tube* and *Bundled Tube systems* are required in many buildings to improve their earthquake behaviour. These structural systems are used depending on the size, loading, and other design requirements of the building. One structural system commonly used poses special challenges in ensuring good seismic performance of buildings; this is the *Flat slab-column system*. The system makes the building flexible in the lateral direction and hence the building deforms significantly even under small levels of shaking. Further, it has relatively low lateral strength, and therefore ductility demand during strong earthquake shaking tends to be large; many times, such levels of ductility cannot be incorporated in buildings with flat slab-column system. This structural system should not be used without introducing in the building stiff and strong lateral force resisting elements, like *structural walls* and *braces*.

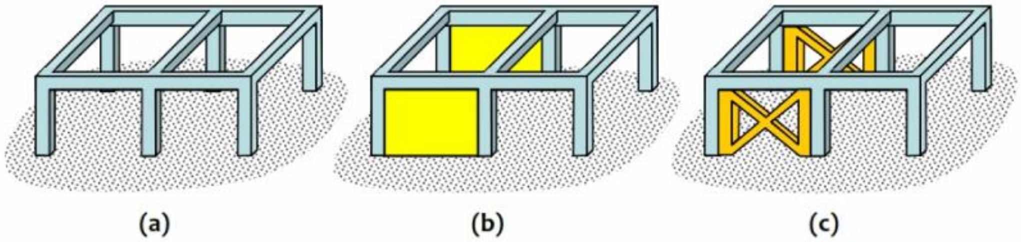


Figure 8: *Common structural systems employed in buildings*: (a) Moment frames, (b) Moment frames with structural walls, and (c) Braced moment frames. *Walls and braces shown are shown only along one direction in plan; but designers can choose to provide them along both directions.*

MASS

Inertia forces are generated in buildings during earthquake shaking at locations where masses are present. For uniform distribution of forces in structural members, it is important to have inertia force mobilized uniformly in the building. For this, there should be uniform distribution of mass, both in plan and along the height of the building.

1. Mass Asymmetry in Plan

It is a common practice to have water tanks at roof top. But usually, water tanks with large mass of water are placed at corners of buildings. This affects the distribution of mass in plan, at least at the roof level. This asymmetry in mass in plan causes twisting of buildings during earthquake shaking due to mismatch of center of mass and center of rigidity (Figure 9).

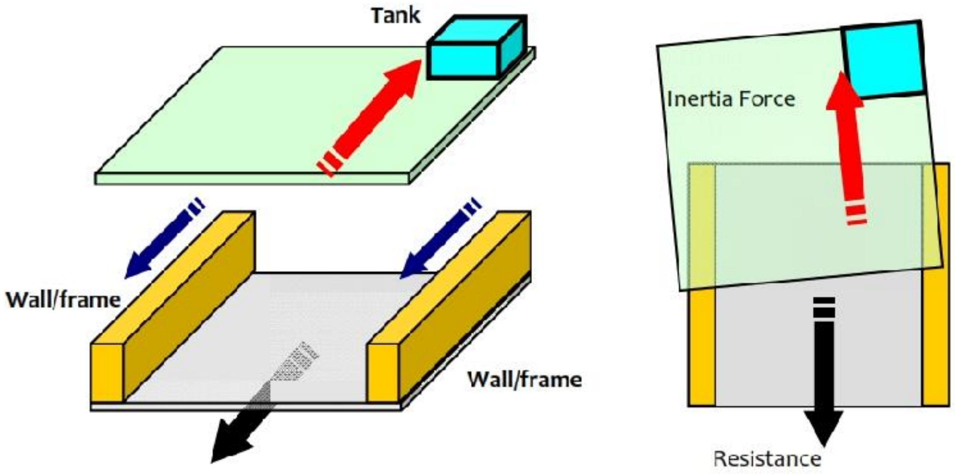


Figure 9: *Asymmetry of mass in plan*: Buildings twist during earthquake shaking due to mismatch in line of action of inertia force and resistance offered by structural members

2. Mass Irregularity in Elevation

Multi-storeyed tall buildings often have service floors with heavy mass compared to regular floors (Figure 10). This causes sudden change or asymmetry in mass along the elevation of buildings. With increase in mass in one storey, there is increase in inertia force generated in that storey. If the percentage difference is small of change in mass in comparison to the total mass of the building, the effect of the mass irregularity is small on the mode shape in regular buildings. The difference becomes pronounced if the difference is large; the difference in response is explicit during nonlinear response of such buildings under strong earthquake shaking.

INITIAL STIFFNESS

Initial lateral stiffness plays an important role in overall response of buildings. The amount of lateral load resisted by individual members in buildings is controlled by their lateral stiffness – stiffer elements attract more force than flexible ones. In addition, adequate overall stiffness is essential in a building to control overall lateral displacement during earthquake shaking. Thus, it is important to have uniform distribution of stiffness in a building to ensure uniform distribution of lateral deformation and lateral forces over the plan and elevation of a building.

1. Stiffness Irregularity in Plan

Irregularity in stiffness in plan occurs due to (a) use of columns of different sizes, (b) presence of structural wall on one side of buildings, or (c) presence of staircase or elevator core at one corner of buildings (Figure 11). Stiffness irregularity in plan causes twisting of buildings under lateral load (Figure 12).

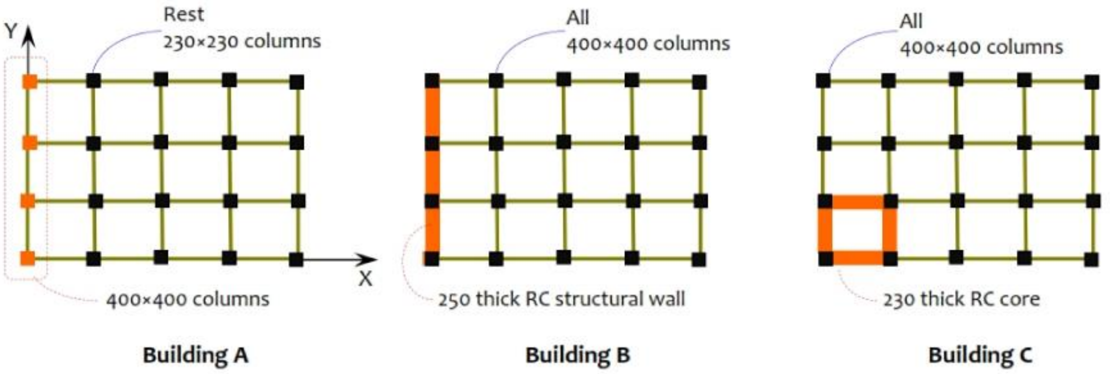


Figure 11: *Stiffness irregularity in plan*: Unequal stiffness of elements and their distribution in plan cause overall stiffness irregularity

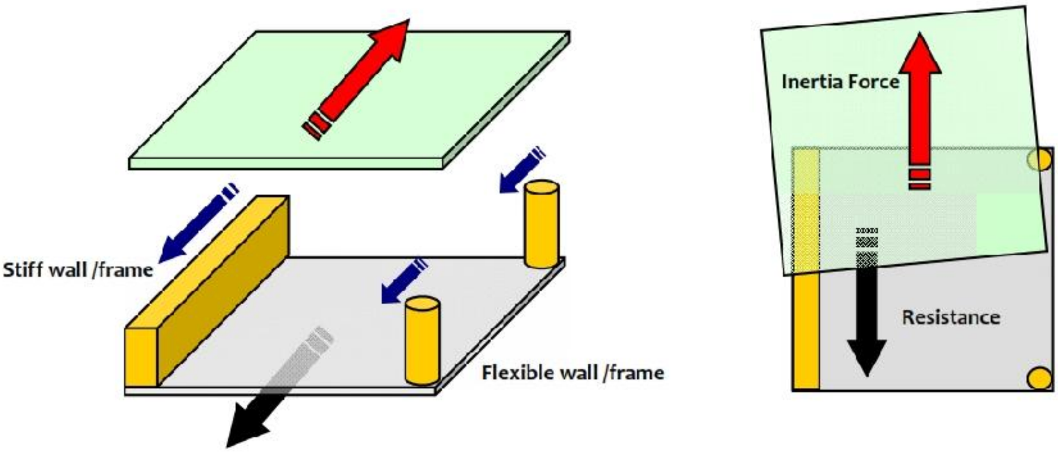


Figure 12: *Stiffness irregularity in plan*: Buildings twist during earthquake shaking due to mismatch in line of action of inertia force and resistance offered by structural members

Stiffness Irregularity in Elevation

Irregularity in stiffness along the height of buildings arises from both architectural and structural choices. Often, the former is a more formidable choice to ensure safety, since it is driven by considerations other than safety. On the other hand, the latter is more a subtle choice made by structural designers, sometime inadvertently. In both cases, the consequence is severe. This section explains some of these choices.

(a) Open or Flexible Storey in Buildings

Lateral stiffness irregularity occurs in elevation when (a) sizes of lateral load resisting elements are varied along the height of buildings, and (b) additional elements are added or existing elements are removed (Figure 13). In building C (in Figure 13), the column sizes are reduced to 230mm×230mm from 400mm×400mm, while buildings A and B have additional masonry infill except at one storey. Buildings A and B represent moment frames with masonry (brick) infill walls. Masonry has good strength in compression. Thus, under lateral loads, the load transfer takes place through compressive strut action in the infilled masonry portion – this action is somewhat similar to that seen when diagonal compression braces are present in frames (Figure 14). Hence, modeling of unreinforced masonry infilled frame buildings for structural analysis should include masonry infills as diagonal *compression-only* strut members.

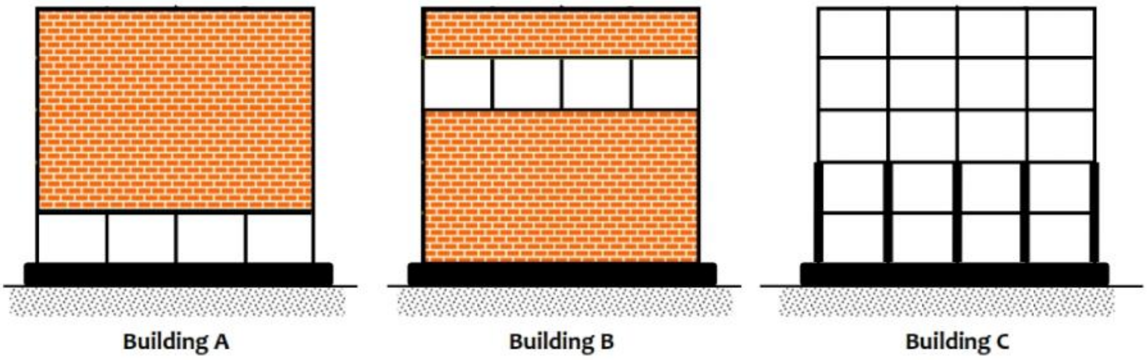


Figure 13: *Stiffness irregularity in elevation*: Variation of element size and presence of additional or absence of elements in elevation cause overall stiffness irregularity

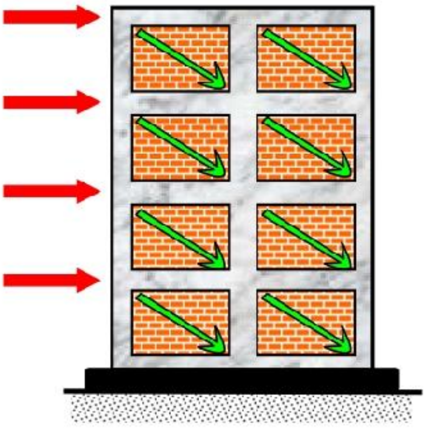


Figure 14: *Masonry infilled frame*: Infill helps transfer lateral loads through diagonal strut action and reduces demand on columns

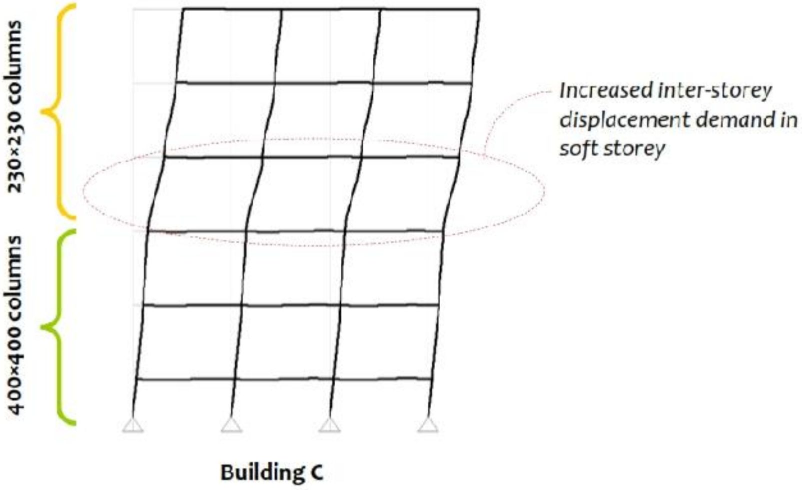


Figure 15: *Stiffness irregularity in elevation*: Stiffness irregularity in elevation increase deformation demand in storeys with less stiffness

(b) Plinth and Lintel Beams (Bands) in Buildings

Bands (e.g., Plinth and Lintel) are primarily associated with load bearing masonry structure. These bands are provided often in reinforced concrete buildings without considering their effect on the behaviour of the buildings. Failure observed during the past earthquake has illustrated the importance of considering these bands during the analysis and design stage. The effect is presented separately of each of these on the behaviour of buildings.

Plinth beams are structural members (beams) and reduce the effective length of ground storey column which are generally longer than those in the upper storeys. As a result, the stiffness of the ground storey columns is altered by the addition of plinth beams. The deformation demand on the building without plinth beam is largely concentrated at the ground storey level because of low lateral stiffness of the longer columns; this is reduced significantly by the addition of plinth beam. But, shear force increases with addition of plinth beam, particularly in the ground storey columns due to the short column effect. A more practical solution is to use larger size ground storey column such that the stiffness of the ground storey is close to the stiffness of the upper storey. In such case, both lateral deformation and shear force demands are well distributed along the building height.

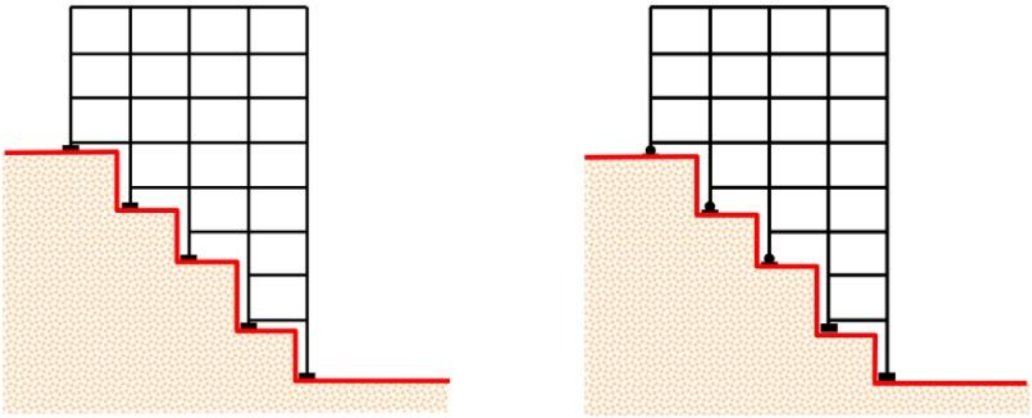
Lintel beams introduce local deformation restraint at locations, when they frame into columns. The level of restraint depends on the relative stiffness of the lintel beam and the column. With increase in lintel size, deformation restraint offered increases, and the column region between the lintel and roof beam exhibits short column effect. Comparison of shear demand imposed, due to same lateral load, on the columns of the benchmark building without and with lintel of various sizes (100, 200 and 300mm). The shear demand imposed on columns increases with increase in size of lintel. Amplification of shear demand on columns due to presence of large lintels may lead to brittle shear failure of columns.

(c) Buildings on Slope

Buildings are constructed on slopes in hill regions. Typical features of these buildings include *columns of unequal lengths along the slope*, and *lack of proper foundation well embedded into the soil underneath* to provide adequate translational fixity under lateral earthquake shaking. Two basic types of fixity conditions are achieved depending on construction type and local soil/rock strata; one that provides full translational and rotational restraints, and the other that do not provide the same. Lack of translational and rotational fixity occurs due to slope subsidence particularly during strong earthquake shaking. Actual degree of fixity (translational and rotational) varies.

Consider two buildings with three storeys above and four storeys below ground level, but with different restraints at base of columns (Figure 16); Building A has fixed column bases, and Building B has roller column base (to capture effects of sliding along the slope during strong earthquake shaking) except underneath the tallest valley-side column. Buildings rested on hard rock strata behave more like *Building A* during low intensity of ground shaking, wherein the lateral frictional resistance under the columns is more than the horizontal shear induced in the building by the lateral shaking. Once the inertia force exceeds the frictional resistance during strong ground shaking, these buildings behave more like *Building B*, wherein except the last column on the valley side, all other column bases start sliding from the ground in the lateral direction.

In comparison of deformed shapes of these two buildings, and axial forces, shear forces and bending moments in members of these two possible building conditions under lateral force. Under small intensity of shaking, the lateral deformation is concentrated only in the portion of the building *ABOVE the uppermost support* (as in Building A), and cause predominantly axial force in the valley-side columns below the ground level. This additional axial force, along with the existing gravity load, may cause compression failure of these columns. Under strong shaking, most column bases loose contact with the soil and cause large axial force, shear force and bending moment in columns, particularly in those *BELOW the uppermost support* (as in Building B), and is likely to cause catastrophic collapse of buildings under combined action of axial force, shear force and bending moment.



Building Condition A

Building Condition B

Figure 16: *Buildings on slope*: Stiffness irregularity in elevation due to unequal length of columns and degree of fixity at column base

(d) Set-back and Step-back Buildings

Irregularity in overall geometry of the building in elevation also is detrimental to good earthquake behaviour of buildings. The common types of overall geometric irregularities include *set-back buildings* and *step-back buildings* (Figure 17). These geometric forms arise largely from architectural extravaganzas, and result in concave geometries that have a number of re-entrant corners at which load paths are disturbed requiring sharp bends.

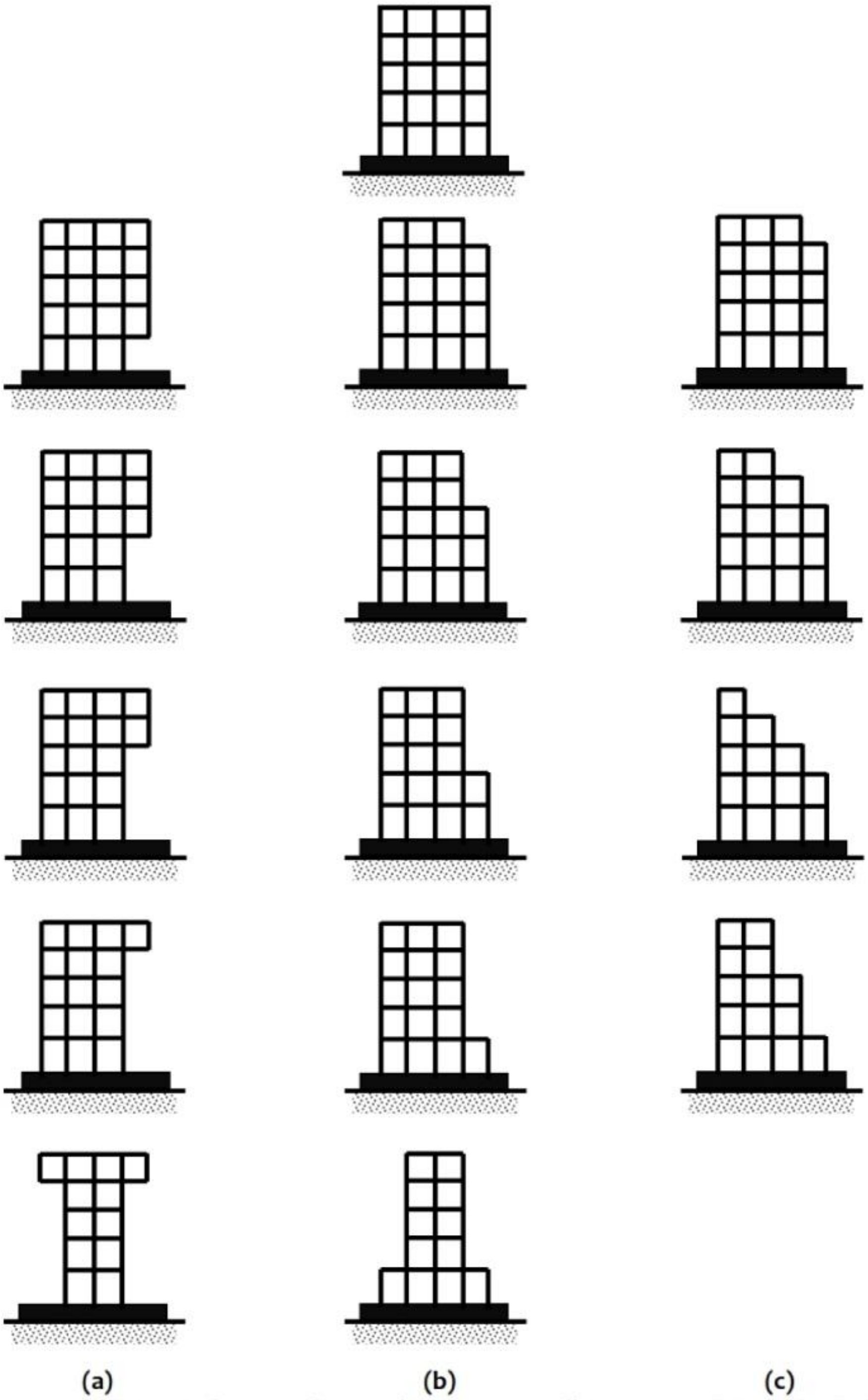


Figure 17: *Buildings with vertical irregularity in overall geometry*: (a) Set-back buildings, and (b) & (c) Step-back buildings

How Architectural Features affect Buildings during Earthquakes?

Importance of Architectural Features

The behaviour of a building during earthquakes depends critically on its overall shape, size and geometry, in addition to how the earthquake forces are carried to the ground. Hence, at the planning stage itself, architects and structural engineers must work together to ensure that the unfavourable features are avoided and a good building configuration is chosen.

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

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

Architectural Features

A desire to create an aesthetic and functionally efficient structure drives architects to conceive wonderful and imaginative structures. Sometimes the *shape* of the building catches the eye of the visitor, sometimes the *structural system* appeals, and in other occasions *both shape and structural system* work together to make the structure a marvel. However, each of these choices of shapes and structure has significant bearing on the performance of the building during strong earthquakes. The wide range of structural damages observed during past earthquakes across the world is very educative in identifying structural configurations that are desirable versus those which must be avoided.

Size of Buildings: In tall buildings with large height-to-base size ratio (Figure 1a), the horizontal movement of the floors during ground shaking is large. In short but very long buildings (Figure 1b), the damaging effects during earthquake shaking are many. And, in buildings with large plan area like warehouses (Figure 1c), the horizontal seismic forces can be excessive to be carried by columns and walls.

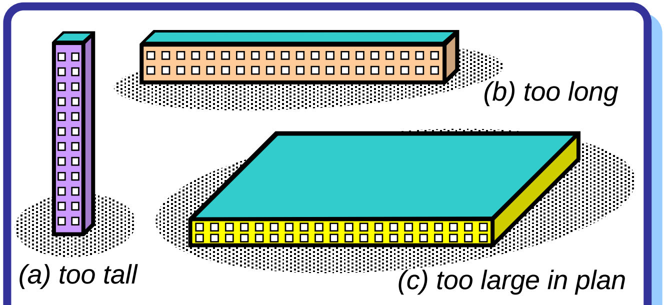


Figure 1: Buildings with one of their overall sizes much larger or much smaller than the other two, do not perform well during earthquakes.

Horizontal Layout of Buildings: In general, buildings with simple geometry in plan (Figure 2a) have performed well during strong earthquakes. Buildings with re-entrant corners, like those U, V, H and + shaped in plan (Figure 2b), have sustained significant damage. Many times, the bad effects of these interior corners in the plan of buildings are avoided by making the buildings in two parts. For example, an L-shaped plan can be broken up into two rectangular plan shapes using a separation joint at the junction (Figure 2c). Often, the plan is simple, but the columns/walls are not equally distributed in plan. Buildings with such features tend to twist during earthquake shaking.

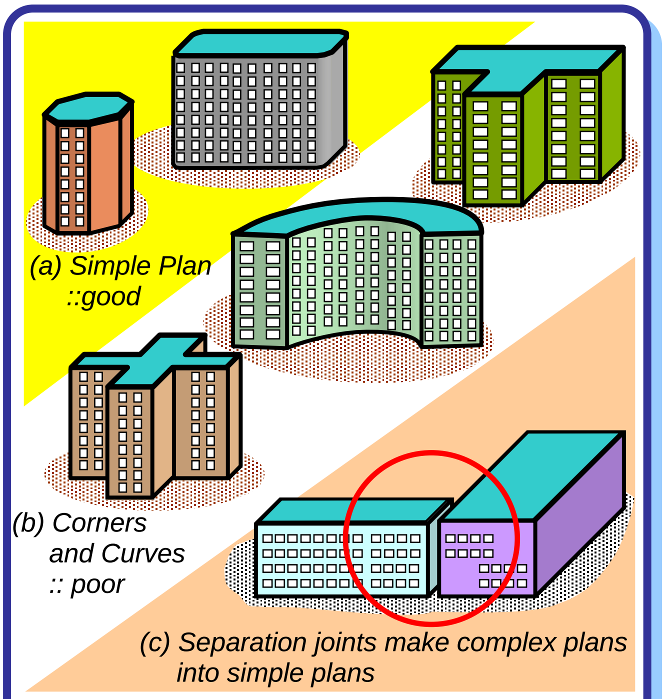
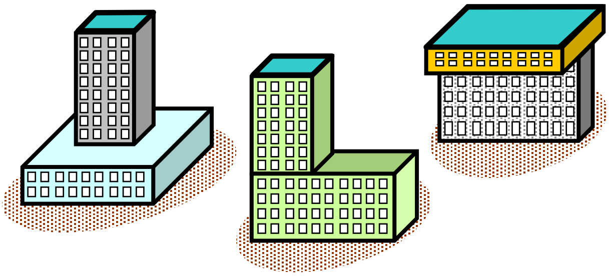


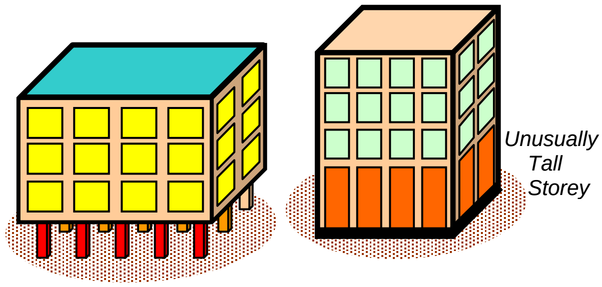
Figure 2: Simple plan shape buildings do well during earthquakes.

Vertical Layout of Buildings: The earthquake forces developed at different floor levels in a building need to be brought down along the height to the ground by the shortest path; any deviation or discontinuity in this load transfer path results in poor performance of the building. Buildings with vertical setbacks (like the hotel buildings with a few storeys wider than the rest) cause a sudden jump in earthquake forces at the level of discontinuity (Figure 3a). Buildings that have fewer columns or walls in a particular storey or with unusually tall storey (Figure 3b), tend to damage or collapse which is initiated in that storey. Many buildings with an open ground storey intended for parking collapsed or were severely damaged in Gujarat during the 2001 Bhuj earthquake.

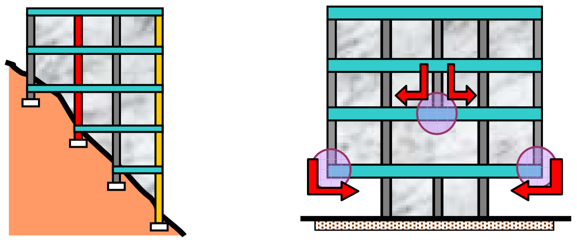
Buildings on slopy ground have unequal height columns along the slope, which causes ill effects like twisting and damage in shorter columns (Figure 3c). Buildings with columns that hang or float on beams at an intermediate storey and do not go all the way to the foundation, have discontinuities in the load transfer path (Figure 3d). Some buildings have reinforced concrete walls to carry the earthquake loads to the foundation. Buildings, in which these walls do not go all the way to the ground but stop at an upper level, are liable to get severely damaged during earthquakes.



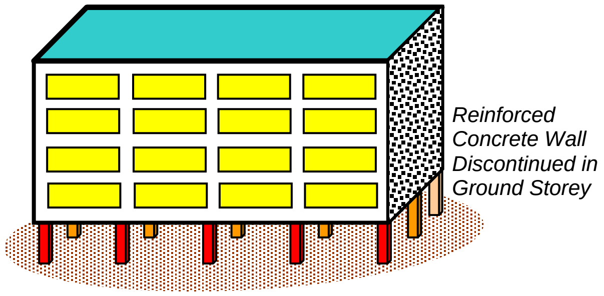
(a) Setbacks



(b) Weak or Flexible Storey



(c) Sloppy Ground *(d) Hanging or Floating Columns*



(e) Discontinuing Structural Members

Figure 3: Sudden deviations in load transfer path along the height lead to poor performance of buildings.

Adjacency of Buildings: When two buildings are too close to each other, they may pound on each other during strong shaking. With increase in building height, this collision can be a greater problem. When building heights do not match (Figure 4), the roof of the shorter building may pound at the mid-height of the column of the taller one; this can be very dangerous.

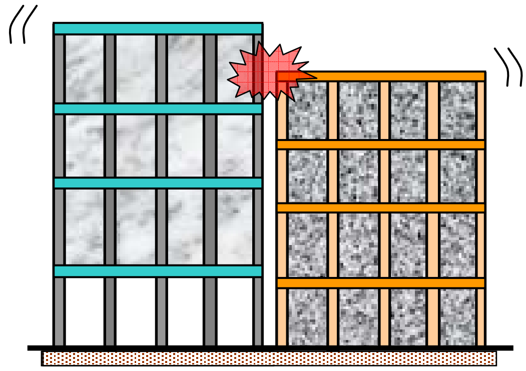


Figure 4: Pounding can occur between adjoining buildings due to horizontal vibrations of the two buildings.

Provisions for earthquake resistant construction

Earthquake-Resistant Buildings

The engineers do not attempt to make *earthquake-proof buildings* that *will not* get damaged even during the rare but strong earthquake; such buildings will be too robust and also too expensive. Instead, the engineering intention is to make buildings *earthquake-resistant*; such buildings resist the effects of ground shaking, although they may get damaged severely but would not collapse during the strong earthquake. Thus, safety of people and contents is assured in earthquake-resistant buildings, and thereby a disaster is avoided. This is a major objective of seismic design codes throughout the world.

Earthquake Design Philosophy

The earthquake design philosophy may be summarized as follows (Figure 1):

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

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

(c) Under strong but rare shaking, the main members may sustain severe (even irreparable) damage, but the building should not collapse.

Thus, after minor shaking, the building will be fully operational within a short time and the repair costs will be small. And, after moderate shaking, the building will be operational once the repair and strengthening of the damaged main members is completed. But, after a strong earthquake, the building may become dysfunctional for further use, but will stand so that people can be evacuated and property recovered.

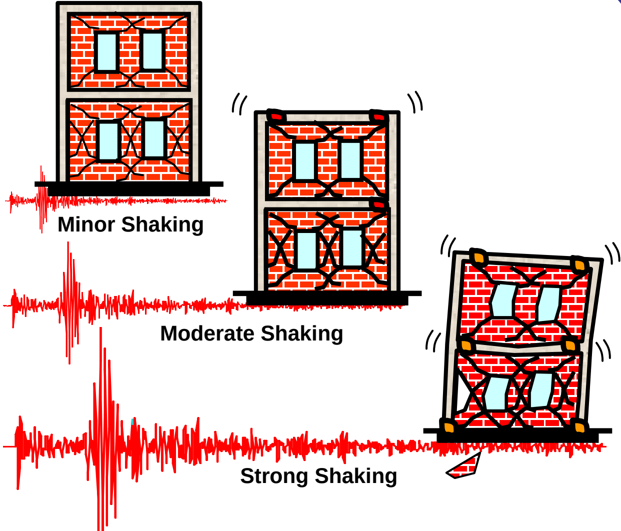


Figure 1: Performance objectives under different intensities of earthquake shaking – *seeking low repairable damage under minor shaking and collapse-prevention under strong shaking.*

The consequences of damage have to be kept in view in the design philosophy. For example, important buildings, like hospitals and fire stations, play a critical role in post-earthquake activities and must remain functional immediately after the earthquake. These structures must sustain very little damage and should be designed for a higher level of earthquake protection. Collapse of dams during earthquakes can cause flooding in the downstream reaches, which itself can be a secondary disaster. Therefore, dams (and similarly, nuclear power plants) should be designed for still higher level of earthquake motion.

Damage in Buildings: Unavoidable

Design of buildings to resist earthquakes involves *controlling the damage to acceptable levels at a reasonable cost*. Contrary to the common thinking that any crack in the building after an earthquake means the building is unsafe for habitation, engineers designing earthquake-resistant buildings recognize that some damage is unavoidable. Different types of damage (mainly visualized through cracks; especially so in concrete and masonry buildings) occur in buildings during earthquakes. Some of these cracks *are* acceptable (in terms of both their *size* and *location*), while others *are not*. For instance, in a reinforced concrete frame building with masonry filler walls between columns, the cracks between vertical columns and masonry filler walls are acceptable, but diagonal cracks running through the columns are not (Figure 2). In general, qualified technical professionals are knowledgeable of the causes and severity of damage in earthquake-resistant buildings.

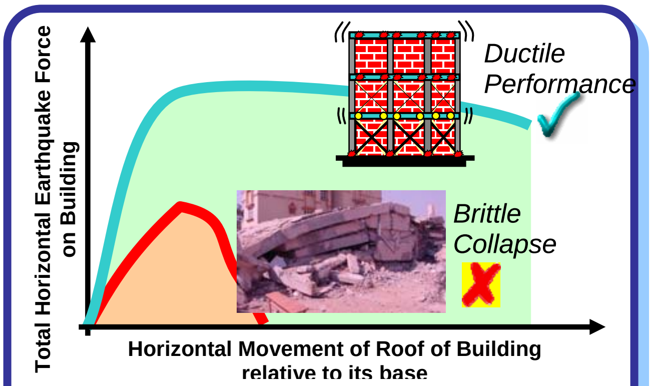
Figure 2: Diagonal cracks in columns jeopardize vertical load carrying capacity of buildings - ***unacceptable damage*****.**

Earthquake-resistant design is therefore concerned about ensuring that the damages in buildings during earthquakes are of the *acceptable* variety, and also that they occur at the right places and in right amounts. This approach of earthquake-resistant design is much like the use of electrical fuses in houses: *to protect the entire electrical wiring and appliances in the house, you sacrifice some small parts of the electrical circuit, called fuses; these fuses are easily replaced after the electrical over-current.* Likewise, to save the building from collapsing, you need to allow some pre-determined parts to undergo the acceptable type and level of damage.

Acceptable Damage: Ductility

So, the task now is to identify acceptable forms of damage and desirable building behaviour during earthquakes. To do this, let us first understand how different materials behave. Consider *white chalk* used to write on blackboards and *steel pins* with solid heads used to hold sheets of paper together. Yes… a chalk *breaks easily*!! On the contrary, a steel pin *allows it to be bent back-and-forth*. Engineers define the property that allows steel pins to bend back-and-forth by large amounts, as *ductility*; chalk is a *brittle* material.

Earthquake-resistant buildings, particularly their main elements, need to be built with ductility in them. Such buildings have the ability to sway back-and-forth during an earthquake, and to withstand earthquake effects with some damage, but without collapse (Figure 3). Ductility is one of the most important factors affecting the building performance. Thus, earthquake-resistant design strives to predetermine the locations where damage takes place and then to provide good detailing at these locations to ensure ductile behaviour of the building.



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

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

(b) Brittle failure of a reinforced concrete column

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

Seismic Strengthening of Masonry Buidlings :

Horizontal Reinforcement (IS 4326 – 1993)

Horizontal reinforcement should be provided in walls to strengthen them against horizontal in-plane bending. This also helps to tie together the perpendicular walls. Provisions of horizontal bands should be made at various levels, in particular at the lintel level. The lintel band ties the walls together and creates a support to the walls loaded in the weak direction. This band also reduces the unsupported height of the walls and improves their stability in the weaker direction. A band at the roof level prevents out-of-plane failure of walls. The longitudinal steel in bands should be provided as given in Table below.

Recommended longitudinal steel in reinforced concrete bands

Span (m)	Building category B		Building category C		Building category D		Building category E	
	No. of bars	Diameter (mm)	No. of bars	Diameter (mm)	No. of bars	Diameter (mm)	No. of bars	Diameter (mm)
≤5	2	8	2	8	2	8	2	10
6	2	8	2	8	2	10	2	12
7	2	8	2	10	2	12	4	10
8	2	10	2	12	4	10	4	12

Notes :

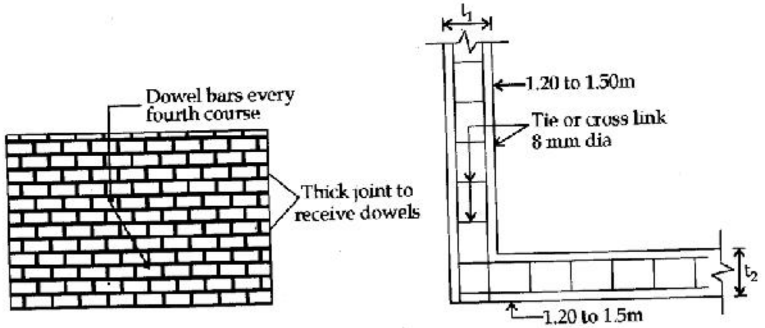
1. Span of wall will be the distance between the centre lines of its cross walls or buttersses. For spans greater than 8m it is desirable to insert pilasters or buttresses to reduce the span or to make special calculations to determine the strength of the wall and the section of the band.
2. The number and diameter of bars given above pertain to high strength deformed bars. If plain mild-steel bars are used keeping the same number, the following diameters may be used :

High strength deformed bars	8	10	12	16	20
mid steel plain bars	10	12	16	20	25

3. Width of the RCC band is assumed to be the same as the thicknes of the wall. Wall thickness shall be 200 mm (minimum). A clear cover of 20 mm from the face of the wall will be maintained.
4. Two vertical thickness of the RCC band should be kept at 75mm (minimum) where two longitudinal bars are specified, with one on each face; it shouldbe 150mm, where for bars are specified.
5. Concrete mix shall be of grade M-15 of IS 456 or 1 : 2 : 4 by volume.
6. The longitudinal steel bars shall be held in position by steel links or stirrups of 6mm diameter speced 150 mm apart.

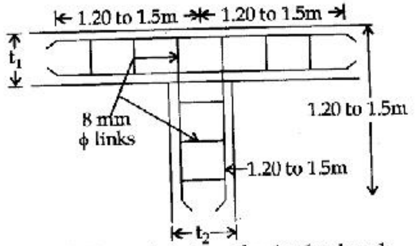
Dowels at Corners and Junction (IS 4326 – 1993)

Steel dowel bars may be used at corners and T junctions as a supplement to bands to create the box action of walls as shown in figure Dowels serve to reinforce the wall in horizontal bending near the junction. Generally dowels are place in every fourth course or at about 50 cm interval and taken into walls to sufficient length so as to provide full bond strength. Alternatively, strengthcing to T junctions and corners wire mesh may be used as shown in figure



(a) Corner strengthening by dowel bars

Figure : 4.23



(b) T-junction strengthening by dowels

Vertical Reinforcement (IS 4326 – 1996)

Tension occurs inthe jambs of openings, at corners, and junction of walls. Therefore, at corners and junctions of walls, vertical reinforcing bars should be provided. The amount of vertical steel will depend upon the number of storeys, storey heights, the effective seismic coefficient, improtance of the building, and soil type. The vertical reinforcement should be properly embedded in the plinth masonry of the foundation and the roof slab or roof band, so as to develop its tensile strength in bond. The reinforcement should pass through the lintel bands and floor slabs or floor level bands in all storeys. For walls up to 350 mm thick, the vertical reinforcement as specified in Table should be provided. For thicker walls, the area of bars should be increased proportionately.

Vertical steel reinforcement in rectangular masonry units

No. of storeys	*Storeys*	*Diameter of HSD single bar in mm at each cirtical section*			
		Category B	Category C	Category D	Category E
One	—	Nil	Nil	10	12
Two	Top	Nil	Nil	10	12
	Bottom	Nil	Nil	12	16
Three	Top	Nil	10	10	12
	Middle	Nil	10	12	16
	Bottom	Nil	12	12	16
Four	Top	10	10	10	Four-storey Building not permitted
	Third	10	10	12	
	Second	10	12	16	
	Bottom	12	12	20	

Other Useful Points for Seismic Strengthening :

The building should neither be slender in plan nor should it have reentrant corners (H, T, etc shapes). Such buildings should be separated into simple rectangular blocks with adequate gaps (minimum 15 mm for box type construction). These blocks can then oscillate independently without pounding each other. Shear reinforcement should be provided in walls to ensure ductile behaviour.

Inclined flights of stairs joining different floor levels will act like a cross brace between various floors. They transfer large horizontal forces at the roof and lower levels and cause damage during earthquakes. To check this, staircase should be completely separated as discussed before stiff, strong, continuous footings should be used for foundation.

To avoid pounding during an earthquake, a gap of a 0.04 × height of the storey or at least 15mm gap per storey should be provided.

Large overhanging projections, cantilevers, floating columns and attachment of heavy mass as water tanks on roof should be avoided.

Workmanship of the construction affects the performance of the building to a great extent there fore good workman ship should be ensured.

Building should be founded on firm and uniform soils and should be away from steep slopes.

Seismic Performance of Reinforced Concrete Buildings

Earthquakes effects on Reinforced Concrete Buildings

Reinforced Concrete Buildings

In recent times, *reinforced concrete* buildings have become common in India, particularly in towns and cities. Reinforced concrete (or simply *RC*) consists of two primary materials, namely *concrete* with *reinforcing steel bars*. Concrete is made of *sand*, *crushed stone (called aggregates)* and *cement*, all mixed with pre-determined amount of water. Concrete can be molded into any desired shape, and steel bars can be bent into many shapes. Thus, structures of complex shapes are possible with RC.

A typical RC building is made of horizontal members (*beams* and *slabs*) and vertical members (*columns* and *walls*), and supported by *foundations* that rest on ground. The system comprising of RC columns and connecting beams is called a *RC Frame*. The RC frame participates in resisting the earthquake forces. Earthquake shaking generates inertia forces in the building, which are proportional to the building mass. Since most of the building mass is present at floor levels, earthquake-induced inertia forces primarily develop at the floor levels. These forces travel downwards - through *slab and beams* to *columns and walls*, and then to the foundations from where they are dispersed to the ground. As inertia forces accumulate downwards from the top of the building, the columns and walls at lower storeys experience higher earthquake-induced forces (Figure 1) and are therefore designed to be stronger than those in storeys above.

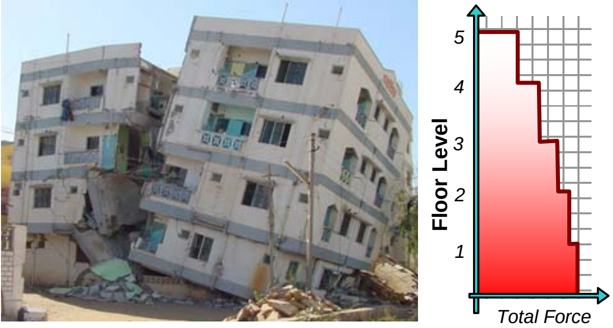
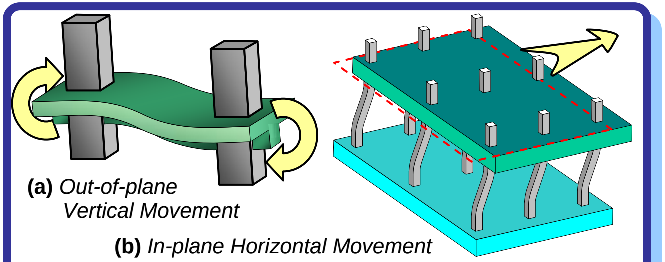


Figure 1: Total horizontal earthquake force in a building increases downwards along its height.

Roles of Floor Slabs and Masonry Walls

Floor slabs are horizontal plate-like elements, which facilitate functional use of buildings. Usually, beams and slabs at one storey level are cast together. In residential multi-storey buildings, thickness of slabs is only about 110-150mm. When beams bend in the vertical direction during earthquakes, these thin slabs bend along with them (Figure 2a). And, when beams move with columns in the horizontal direction, the slab usually forces the beams to move together with it. In most buildings, the geometric distortion of the slab is negligible in the horizontal plane; this behaviour is known as the *rigid diaphragm action* (Figure 2b). Structural engineers must consider this during design.



(a) *Out-of-plane Vertical Movement*

(b) *In-plane Horizontal Movement*

Figure 2: Floor bends with the beam but moves all columns at that level together.

After columns and floors in a RC building are cast and the concrete hardens, vertical spaces between columns and floors are usually filled-in with masonry walls to demarcate a floor area into functional spaces (rooms). Normally, these masonry walls, also called *infill walls*, are not connected to surrounding RC columns and beams. When columns receive horizontal forces at floor levels, they try to move in the horizontal direction, but masonry walls tend to resist this movement. Due to their heavy weight and thickness, these walls attract rather large horizontal forces (Figure 3). However, since masonry is a brittle material, these walls develop cracks once their ability to carry horizontal load is exceeded. Thus, infill walls act like sacrificial fuses in buildings; they develop cracks under severe ground shaking but help share the load of the beams and columns until cracking. Earthquake performance of infill walls is enhanced by mortars of good strength, making proper masonry courses, and proper packing of gaps between RC frame and masonry infill walls. However, an infill wall that is unduly tall or long in comparison to its thickness can fall *out-of-plane* (*i.e.*, along its thin direction), which can be life threatening. Also, placing infills irregularly in the building causes ill effects like *short-column effect* and *torsion*).

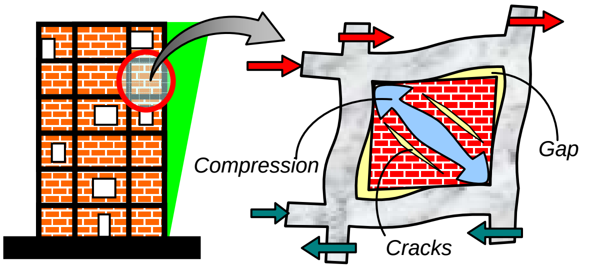


Figure 3: Infill walls move together with the columns under earthquake shaking.

Horizontal Earthquake Effects are Different

Gravity loading (due to self weight and contents) on buildings causes RC frames to bend resulting in *stretching* and *shortening* at various locations. Tension is generated at surfaces that stretch and compression at those that shorten (Figure 4b). Under gravity loads, tension in the beams is at the bottom surface of the beam in the central location and is at the top surface at the ends. On the other hand, *earthquake loading* causes tension on beam and column faces at locations different from those under gravity loading (Figure 4c); the relative levels of this tension (in technical terms, *bending moment*) generated in members are shown in Figure 4d. The level of bending moment due to earthquake loading depends on severity of shaking and can exceed that due to gravity loading. Thus, under strong earthquake shaking, the beam ends can develop tension on either of the top and bottom faces. Since concrete cannot carry this tension, steel bars are required on both faces of beams to resist *reversals* of bending moment. Similarly, steel bars are required on all faces of columns too.

Strength Hierarchy

For a building to remain safe during earthquake shaking, columns (which receive forces from beams) should be stronger than beams, and foundations (which receive forces from columns) should be stronger than columns. Further, connections between beams & columns and columns & foundations should not fail so that beams can safely transfer forces to columns and columns to foundations.

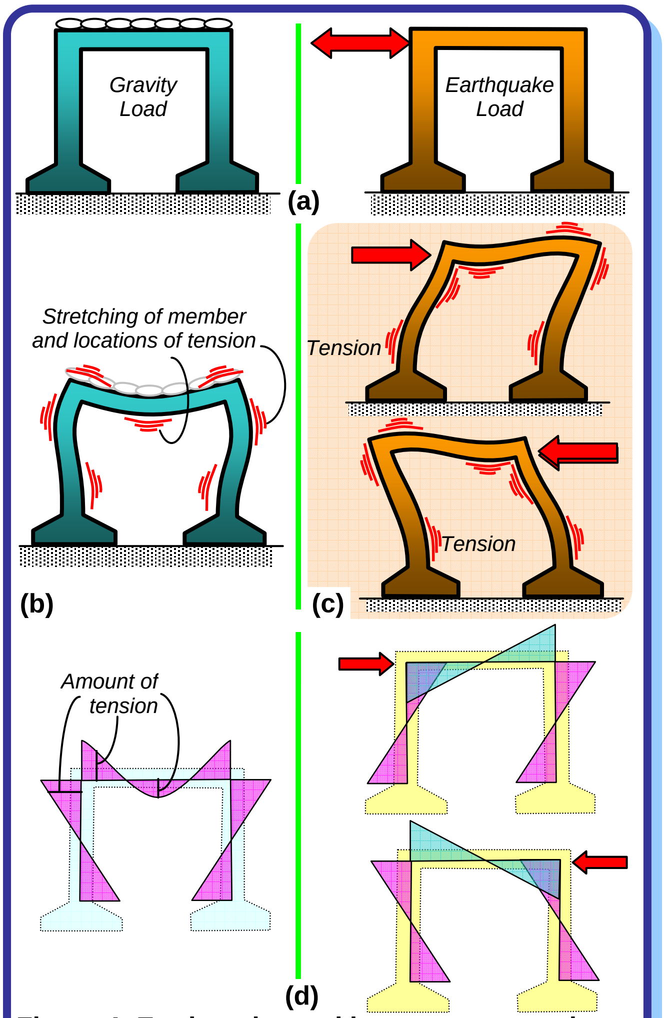
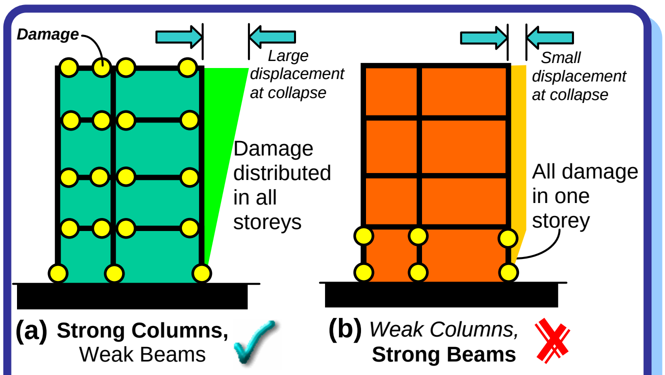


Figure 4: Earthquake shaking reverses tension and compression in members – *reinforcement is required on both faces of members.*

When this strategy is adopted in design, damage is likely to occur *first* in beams (Figure 5a). When beams are detailed properly to have large ductility, the building as a whole can deform by large amounts despite progressive damage caused due to consequent yielding of beams. In contrast, if columns are made weaker, they suffer severe local damage, at the top and bottom of a particular storey (Figure 5b). This localized damage can lead to collapse of a building, although columns at storeys above remain almost undamaged.



(a) **Strong Columns,** Weak Beams ✓ (b) *Weak Columns,* **Strong Beams** ✗

Figure 5: Two distinct designs of buildings that result in different earthquake performances – *columns should be stronger than beams.*

a single cause of damage to buildings is not possible. There are combined reasons, which are responsible for multiple damages. It is difficult to classify the damage, and even more difficult to relate it in quantitative manner. This is because of the dynamic character of the seismic action and the inelastic response of the structures. The principal causes of damage to buildings are soft stories, floating columns, mass irregularities, poor quality of material, faulty construction practices, inconsistent seismic performance, soil and foundation effect, pounding of adjacent structures and inadequate ductile detailing in structural components, which have been described in detail subsequently.

Soft Storey Failure

In general, multi-storeyed buildings in metropolitan cities require open taller first storey for parking of vehicles and/or for retail shopping, large space for meeting room or a banking hall owing to lack of horizontal space and high cost. Due to this functional requirement, the first storey has lesser strength and stiffness as compared to upper stories, which are stiffened by masonry infill walls. This characteristic of building construction creates "weak" or "soft" storey problems in multi-storey buildings. Increased flexibility of first storey results in extreme deflections, which in turn, leads to concentration of forces at the second storey connections accompanied by large plastic deformations. In addition, most of the energy developed during the earthquake is dissipated by the columns of the soft stories. In this process the plastic hinges are formed at the ends of columns, which transform the soft storey into a mechanism. In such cases the collapse is unavoidable. Therefore, the soft stories deserve a special consideration in analysis and design.

It has been observed from the survey that the damage is due to collapse and buckling of columns especially where parking places are not covered appropriately. On the contrary, the damage is reduced considerably where the parking places are covered adequately. It is recognised that this type of failure results from the combination of several other unfavourable reasons, such as torsion, excessive mass on upper floors, P–Δ effects and lack of ductility in the bottom storey.

Floating Columns

Most of the buildings in Ahmedabad and Gandhidham, are covering the maximum possible area on a plot within the available bylaws. Since balconies are not counted in Floor Space Index (FSI), buildings have balconies overhanging in the upper stories beyond the column footprint area at the ground storey, overhangs upto 1.2 m to 1.5 m in plan are usually provided on each side of the building. In the upper stories, the perimeter columns of the ground storey are discontinued, and floating columns are provided along the overhanging perimeter of the building. These floating columns rest at the tip of the taper overhanging beams without considering the increased vulnerability of lateral load resisting system due to vertical discontinuity. This type of construction does not create any problem under vertical loading conditions. But during an earthquake a clear load path is not available for transferring the lateral forces to the foundation. Lateral forces accumulated in upper floors during the earthquake have to be transmitted by the projected cantilever beams. Overturning forces thus developed overwhelm the columns of the ground floor. Under this situation the columns begin to deform and buckle, resulting in total collapse. This is because of primary deficiency in the strength of ground floor columns, projected cantilever beam and ductile detailing of beam-column joints. Ductile connection at the exterior beam-column joint is indispensable for transferring these forces.

Plan and Mass Irregularity

Refer IS code 1893 (Part-1):2002, page no. 18 to 22. (Different types of irregularities with figures).

Poor Quality of Construction Material and Corrosion of Reinforcement

There are numerous instances in which faulty construction practices and lack of quality control contributed to the damage. In the cement-sand ratio, the ratio of sand was dangerously high. It also appeared that recycled steel was used as reinforcement. Many buildings are damaged due to spalling of concrete by the corrosion of embedded reinforcing bars. The corrosion is related to insufficient concrete cover, poor concrete placement and porous concrete. Several buildings constructed about 5 to 10 years ago were damaged due to lack of quality control. It is reported that the water supply in the outer part of the city is through ground water, which is salty in taste and the same water is used in preparing the concrete mix for construction. The presence of salts may also have affected the quality of concrete

Pounding of Buildings

Although the number of buildings damaged by pounding is small, yet there are few examples in which the primary cause of damage in buildings is due to hammering of adjacent buildings.

Pounding is the result of irregular response of adjacent buildings of different heights and of different dynamic characteristics. When the floors of adjacent buildings are at different elevations, the floor of each building acts like rams, battering the columns of the other building. When one of the buildings is higher than the other, the building of lower height acts as a base for the upper part of the adjacent taller building. The low height building receives an unexpected load while the taller building suffers from a major stiffness discontinuity at the level of the top of the lower building. Pounding may also occur because of non-compliance of codal provisions particularly for lateral and torsional stiffness and cumulative tilting due to foundation movement.

Inconsistent Seismic Performance of Buildings

It is evident that the earthquake did not affect all the structures uniformly. The dynamic characteristics of buildings are one of the predominant factors. The severity of damage varied dramatically, with total collapse of buildings in some cases to minor damage in nearby buildings.

DAMAGE TO STRUCTURAL ELEMENTS

Oblong cross section, a space left at the top of column called *'topi'* during casting and relatively slender column sections compared with beam sections are the main structural defects in columns. These columns are neither designed nor detailed for ductility. Lack of confinement due to large tie spacing, insufficient development length, inadequate splicing of all column bars at the same section, hook configurations of reinforcement do not comply with ductile detailing practices.

Crushing of the compression zone is manifested first by spalling of the concrete cover to the reinforcement; subsequently the concrete core expands and crushes. This phenomenon is usually accompanied by buckling of bars in compression and by hoop fracture. The opening of the ties and the disintegration of concrete lead to shortening of the column under the action of axial force. This type of damage is serious as the column not only loses its stiffness but also loses its ability to carry vertical loads

DAMAGE TO NON-STRUCTURAL PANEL ELEMENTS

Damage to Infill Walls

Masonry infill walls are used as interior partitions and as exterior walls to form a part of the building envelope in multi-storeyed buildings. In general design practices in India, the strength and stiffness of infill walls are ignored with the assumption of conservative design. In actual, infill walls add considerably to the strength and rigidity of the structures and their negligence will cause failure of many of multi-storeyed buildings. The failure is basically due to stiffening effect of infill panels which is cause of (i) unequal distribution of lateral forces in the different frames and overstressing of some of the building frames; (ii) soft storey or weak storey; (iii) short column or captive column effect; (iv) torsional forces; (v) cracking of the infill walls.

During the excitation of the structure, the reinforced concrete frame begins to deform, and initially the first cracks appear on the plaster along the line of contact of the masonry infill with the frame. As the deformation of the frame becomes larger, the cracks penetrate into the masonry, and are manifested by the detachment of the masonry infill from the frame. Subsequently, diagonal cracks (X shaped) appear because of the strut action of the infill.

Damage to Exterior Walls

exterior walls that are poorly connected with the RC frame. These walls are subjected to out-of-plane vibrations. This form of construction of large exterior walls creates a weak plane around the perimeter. When subjected to intense shaking, these large un-reinforced masonry panels confined by stiff frame members have a tendency to resist large out-of-plane vibrations with little sign of distress. When the flexure strength of these panels becomes insufficient to resist these forces, the entire infill panels fail. The magnitude of damage is found to be dependent on the quality of materials and method of construction.

Open-Ground Storey Buildings (Soft Storey effects)

Basic Features

Reinforced concrete (RC) frame buildings are becoming increasingly common in urban India. Many such buildings constructed in recent times have a special feature – the ground storey is left *open* for the purpose of parking (Figure 1), *i.e.,* columns in the ground storey do not have any partition walls (of either masonry or RC) between them. Such buildings are often called *open ground storey buildings* or *buildings on stilts*.

Figure 1: Ground storeys of reinforced concrete buildings are left open to facilitate parking – *this is common in urban areas in India.*

An open ground storey building, having *only columns* in the ground storey and *both partition walls and columns* in the upper storeys, have two distinct characteristics, namely:

(a) It is relatively *flexible* in the ground storey, *i.e.,* the relative horizontal displacement it undergoes in the ground storey is much larger than what each of the storeys above it does. This flexible ground storey is also called *soft storey*.

(b) It is relatively *weak* in ground storey, *i.e.,* the total horizontal earthquake force it can carry in the ground storey is significantly smaller than what each of the storeys above it can carry. Thus, the open ground storey may also be a *weak storey*.

Often, open ground storey buildings are called *soft storey buildings*, even though their ground storey may be *soft and weak*. Generally, the soft or weak storey usually exists at the ground storey level, but it could be at any other storey level too.

Earthquake Behaviour

Open ground storey buildings have consistently shown poor performance during past earthquakes across the world (for example during *1999 Turkey*, *1999 Taiwan* and *2003 Algeria* earthquakes); a significant number of them have collapsed. A large number of buildings with open ground storey have been built in India in recent years. For instance, the city of Ahmedabad alone has about 25,000 *five-storey* buildings and about 1,500 *eleven-storey* buildings; majority of them have open ground storeys. Further, a huge number of similarly designed and constructed buildings exist in the various towns and cities situated in moderate to severe seismic zones (namely III, IV and V) of the country. The collapse of more than a hundred RC frame buildings with open ground storeys at Ahmedabad (~225km away from epicenter) during the 2001 Bhuj earthquake has emphasised that such buildings are *extremely* vulnerable under earthquake shaking.

The presence of walls in upper storeys makes them much stiffer than the open ground storey. Thus, the upper storeys move almost together as a single block, and most of the horizontal displacement of the building occurs in the soft ground storey itself. In common language, this type of buildings can be explained as a building on chopsticks. Thus, such buildings swing *back-and-forth* like *inverted pendulums* during earthquake shaking (Figure 2a), and the columns in the open ground storey are severely stressed (Figure 2b). If the columns are weak (do not have the required strength to resist these high stresses) or if they do not have adequate ductility , they may be severely damaged (Figure 3a) which may even lead to collapse of the building (Figure 3b).

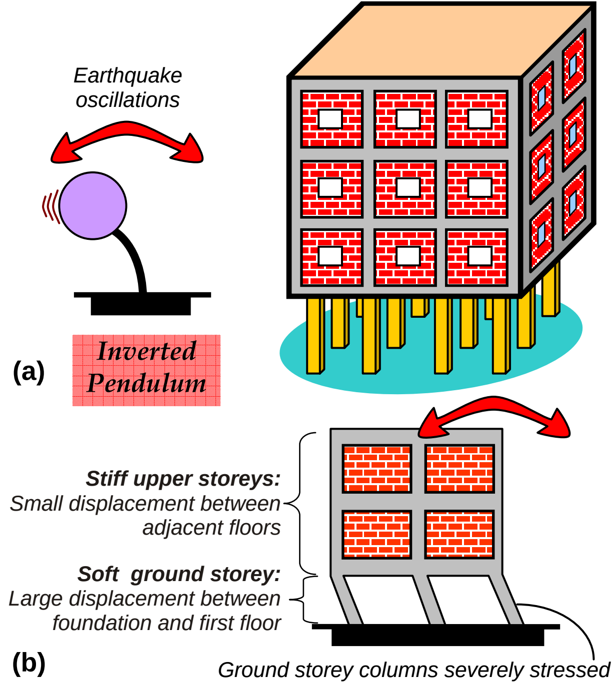


Figure 2: Upper storeys of open ground storey buildings move together as a single block – *such buildings are like inverted pendulums.*

Photo Courtesy: The EERI Annotated Slide Set CD, Earthquake Engineering Research Institute, Oakland (CA), USA, 1998.

(a) 1971 San Fernando Earthquake

(b) 2001 Bhuj Earthquake

Figure 3: Consequences of open ground storeys in RC frame buildings – *severe damage to ground storey columns and building collapses.*

The Problem

Open ground storey buildings are *inherently poor* systems with sudden drop in stiffness and strength in the ground storey. In the current practice, *stiff* masonry walls (Figure 4a) are neglected and only *bare frames* are considered in design calculations (Figure 4b). Thus, the inverted pendulum effect is not captured in design.

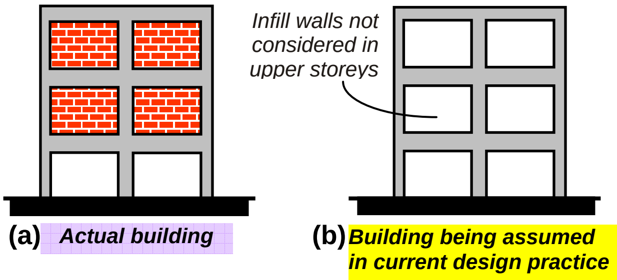


Figure 4: Open ground storey building – *assumptions made in current design practice are not consistent with the actual structure.*

Improved design strategies

After the collapses of RC buildings in 2001 Bhuj earthquake, the Indian Seismic Code IS:1893 (Part 1) - 2002 has included special design provisions related to soft storey buildings. Firstly, it specifies when a building should be considered as a *soft* and a *weak storey building*. Secondly, it specifies higher design forces for the soft storey as compared to the rest of the structure. The Code suggests that the forces in the columns, beams and shear walls (if any) under the action of seismic loads specified in the code, may be obtained by considering the *bare frame* building (without any infills) (Figure 4b). However, beams and columns *in the open ground storey* are required to be designed for 2.5 times the forces obtained from this bare frame analysis.

For all *new RC frame buildings*, the best option is to avoid such sudden and large decrease in stiffness and/or strength in any storey; it would be ideal to build walls (either masonry or RC walls) in the ground storey also (Figure 5). Designers can avoid dangerous effects of flexible and weak ground storeys by ensuring that too many walls are not discontinued in the ground storey, *i.e.,* the drop in stiffness and strength in the ground storey level is not abrupt due to the absence of infill walls.

The *existing open ground storey buildings* need to be strengthened suitably so as to prevent them from collapsing during strong earthquake shaking. The owners should seek the services of qualified structural engineers who are able to suggest appropriate solutions to increase seismic safety of these buildings.

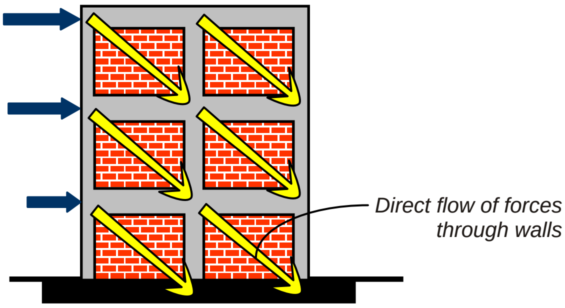
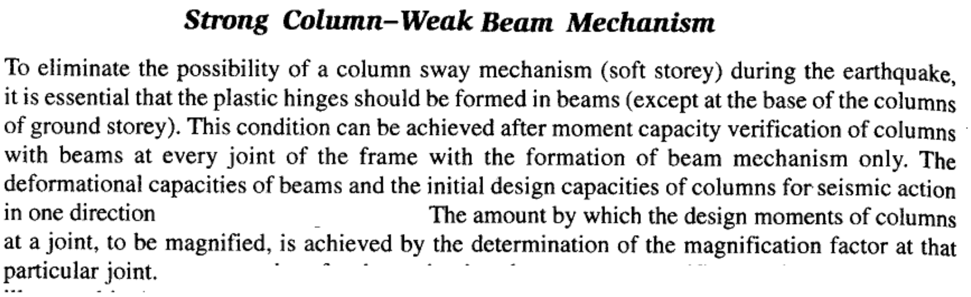


Figure 5: Avoiding open ground storey problem – *continuity of walls in ground storey is preferred.*



Strong Column–Weak Beam Mechanism

To eliminate the possibility of a column sway mechanism (soft storey) during the earthquake, it is essential that the plastic hinges should be formed in beams (except at the base of the columns of ground storey). This condition can be achieved after moment capacity verification of columns with beams at every joint of the frame with the formation of beam mechanism only. The deformational capacities of beams and the initial design capacities of columns for seismic action in one direction The amount by which the design moments of columns at a joint, to be magnified, is achieved by the determination of the magnification factor at that particular joint.

Beam-Column Joints theory in RC Buildings to resist Earthquakes

Why Beam-Column Joints are Special

In RC buildings, portions of *columns* that are common to *beams* at their intersections are called *beam-column joints* (Figure 1). Since their constituent materials have limited strengths, the joints have *limited force carrying capacity*. When forces larger than these are applied during earthquakes, joints are severely damaged. Repairing damaged joints is difficult, and so damage must be avoided. Thus, beam-column joints must be designed to resist earthquake effects.

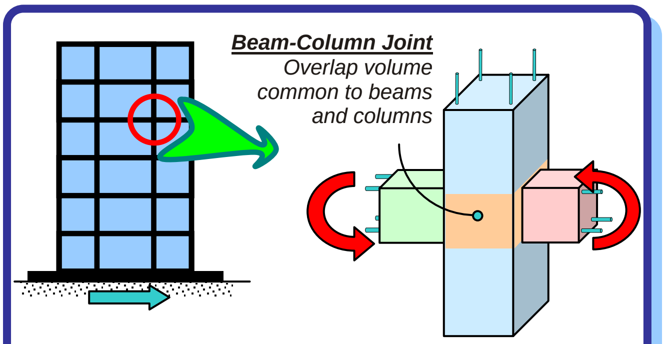
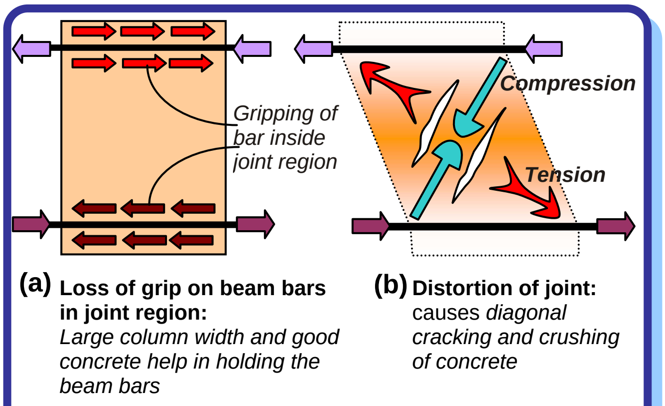


Figure 1: Beam-Column Joints are critical parts of a building – *they need to be designed*.

Earthquake Behaviour of Joints

Under earthquake shaking, the beams adjoining a joint are subjected to moments in the same (clockwise or counter-clockwise) direction (Figure 1). Under these moments, the top bars in the beam-column joint are pulled in one direction and the bottom ones in the opposite direction (Figure 2a). These forces are balanced by bond stress developed between concrete and steel in the joint region. If the column is not wide enough or if the strength of concrete in the joint is low, there is insufficient grip of concrete on the steel bars. In such circumstances, the bar slips inside the joint region, and beams loose their capacity to carry load.



(a) Loss of grip on beam bars in joint region: *Large column width and good concrete help in holding the beam bars*

(b) Distortion of joint: *causes diagonal cracking and crushing of concrete*

Figure 2: Pull-push forces on joints cause two problems – these result in irreparable *damage in joints under strong seismic shaking*.

Further, under the action of the above pull-push forces at top and bottom ends, joints undergo geometric distortion; one diagonal length of the joint elongates and the other compresses (Figure 2b). If the column cross-sectional size is insufficient, the concrete in the joint develops diagonal cracks.

Reinforcing the Beam-Column Joint

Diagonal cracking & crushing of concrete in joint region should be prevented to ensure good earthquake performance of RC frame buildings. Using *large column sizes* is the most effective way of achieving this. In addition, *closely spaced closed-loop steel ties* are required around column bars (Figure 3) to hold together concrete in joint region and to resist shear forces. *Intermediate column bars* also are effective in confining the joint concrete and resisting horizontal shear forces.

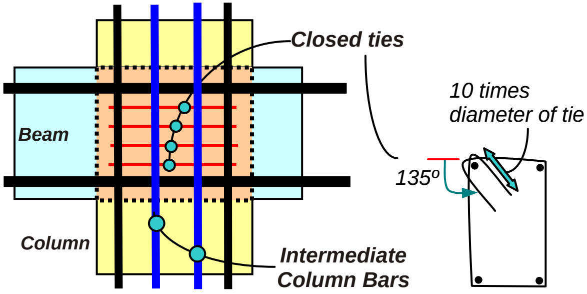


Figure 3: Closed loop steel ties in beam-column joints – *such ties with 135° hooks resist the ill effects of distortion of joints*.

Providing closed-loop ties in the joint requires some extra effort. Indian Standard IS:13920-1993 recommends continuing the transverse loops around the column bars through the joint region. In practice, this is achieved by preparing the cage of the reinforcement (both *longitudinal bars* and *stirrups*) of all beams at a floor level to be prepared on top of the beam formwork of that level and lowered into the cage (Figures 4a and 4b). However, this may not always be possible particularly when the beams are long and the entire reinforcement cage becomes heavy.

Anchoring Beam Bars

The gripping of beam bars in the joint region is improved *first* by using columns of reasonably large cross-sectional size. Indian Standard IS:13920-1993 requires building columns in seismic zones III, IV and V to be at least *300mm* wide in each direction of the cross-section when they support beams that are longer than *5m* or when these columns are taller than *4m* between floors (or beams). The American Concrete Institute recommends a column width of at least *20 times the diameter of largest longitudinal bar used in adjoining beam*.

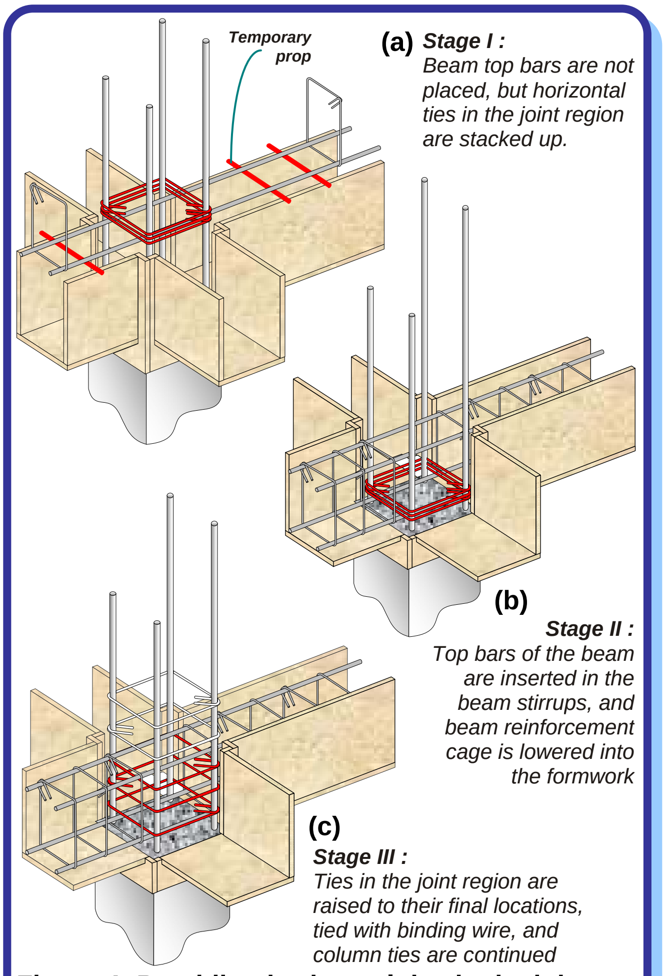


Figure 4: Providing horizontal ties in the joints – *three-stage procedure is required*.

In exterior joints where beams terminate at columns (Figure 5), longitudinal beam bars need to be anchored into the column to ensure proper gripping of bar in joint. The length of anchorage for a bar of grade Fe415 (characteristic tensile strength of 415MPa) is about *50* times its diameter. This length is measured from the face of the column to the end of the bar anchored in the column. In columns of small widths and when beam bars are of large diameter (Figure 5a), a portion of beam top bar is embedded in the column that is cast up to the soffit of the beam, and a part of it overhangs. It is difficult to hold such an overhanging beam top bar in position while casting the column up to the soffit of the beam. Moreover, the vertical distance beyond the *90°* bend in beam bars is not very effective in providing anchorage. On the other hand, if column width is large, beam bars may not extend below soffit of the beam (Figure 5b). Thus, it is preferable to have columns with sufficient width. Such an approach is used in many codes [*e.g.*, ACI318, 2005].

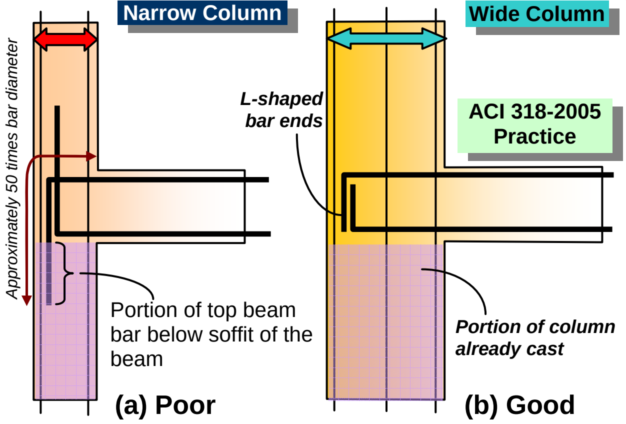


Figure 5: Anchorage of beam bars in exterior joints – *diagrams show elevation of joint region*.

In interior joints, the beam bars (both top and bottom) need to go through the joint without any cut in the joint region. Also, these bars must be placed within the column bars and with no bends (Figure 6).

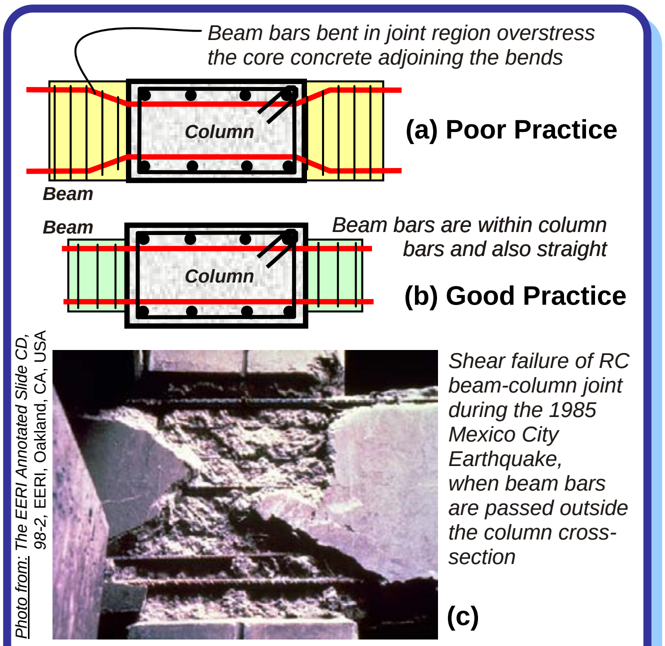


Figure 6: Anchorage of beam bars in interior joints – *diagrams (a) and (b) show cross-sectional views in plan of joint region*.

Buildings with Shear Walls

What is a Shear Wall Building

Reinforced concrete (RC) buildings often have *vertical plate-like* RC walls called *Shear Walls* (Figure 1) in addition to slabs, beams and columns. These walls generally start at foundation level and are continuous throughout the building height. Their thickness can be as low as 150mm, or as high as 400mm in high rise buildings. Shear walls are usually provided along *both* length and width of buildings (Figure 1). Shear walls are like *vertically-oriented* wide *beams* that carry earthquake loads downwards to the foundation.

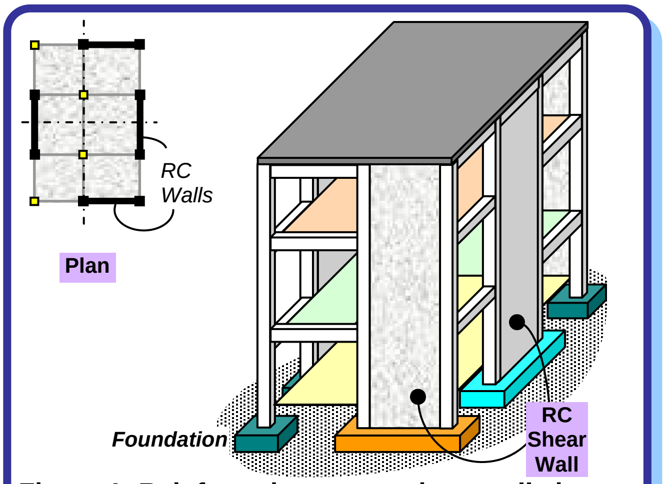


Figure 1: Reinforced concrete shear walls in buildings – *an excellent structural system for earthquake resistance.*

Advantages of Shear Walls in RC Buildings

Properly designed and detailed buildings with shear walls have shown *very good* performance in past earthquakes. The overwhelming success of buildings with shear walls in resisting strong earthquakes is summarised in the quote:

> *"We cannot afford to build concrete buildings meant to resist severe earthquakes without shear walls."*
>
> :: Mark Fintel, a noted consulting engineer in USA

Shear walls in high seismic regions require special detailing. However, in past earthquakes, even buildings with sufficient amount of walls that were not specially detailed for seismic performance (but had enough well-distributed reinforcement) were saved from collapse. Shear wall buildings are a popular choice in many earthquake prone countries, like Chile, New Zealand and USA. Shear walls are easy to construct, because reinforcement detailing of walls is relatively straight-forward and therefore easily implemented at site. Shear walls are efficient, both in terms of construction cost and effectiveness in minimizing earthquake damage in structural and non-structural elements (like glass windows and building contents).

Architectural Aspects of Shear Walls

Most RC buildings with shear walls also have columns; these columns primarily carry *gravity* loads (*i.e.,* those due to self-weight and contents of building). Shear walls provide large strength and stiffness to buildings in the direction of their orientation, which significantly reduces lateral sway of the building and thereby reduces damage to structure and its contents. Since shear walls carry *large* horizontal earthquake forces, the overturning effects on them are large. Thus, design of their foundations requires special attention. Shear walls should be provided along preferably *both* length and width. However, if they are provided along only one direction, a proper grid of beams and columns in the vertical plane (called a *moment-resistant frame*) must be provided along the other direction to resist strong earthquake effects.

Door or window openings can be provided in shear walls, but their size must be small to ensure least interruption to force flow through walls. Moreover, openings should be symmetrically located. Special design checks are required to ensure that the net cross-sectional area of a wall at an opening is sufficient to carry the horizontal earthquake force.

Shear walls in buildings must be symmetrically located in plan to reduce ill-effects of twist in buildings (Figure 2). They could be placed symmetrically along one or both directions in plan. Shear walls are more effective when located along exterior perimeter of the building – such a layout increases resistance of the building to twisting.

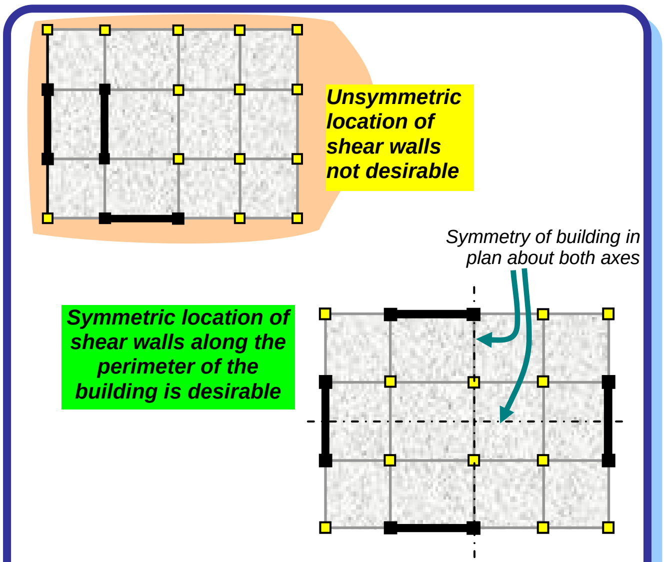


Figure 2: Shear walls must be symmetric in plan layout – *twist in buildings can be avoided***.**

Ductile Design of Shear Walls

Just like reinforced concrete (RC) beams and columns, RC shear walls also perform much better if designed to be ductile. Overall geometric proportions of the wall, types and amount of reinforcement, and connection with remaining elements in the building help in improving the ductility of walls. The Indian Standard *Ductile Detailing Code* for RC members (IS:13920-1993) provides special design guidelines for ductile detailing of shear walls.

Overall Geometry of Walls: Shear walls are oblong in cross-section, *i.e.,* one dimension of the cross-section is much larger than the other. While rectangular cross-section is common, L- and U-shaped sections are also used (Figure 3). Thin-walled hollow RC shafts around the elevator core of buildings also act as shear walls, and should be taken advantage of to resist earthquake forces.

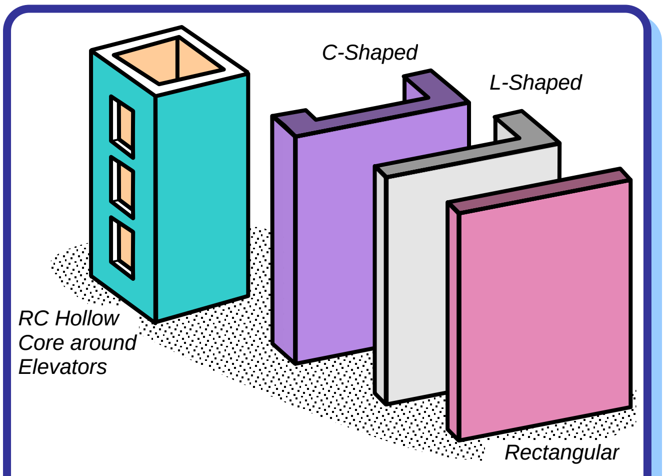


Figure 3: Shear walls in RC Buildings – *different geometries are possible*.

Reinforcement Bars in RC Walls: Steel reinforcing bars are to be provided in walls in regularly spaced *vertical* and *horizontal* grids (Figure 4a). The vertical and horizontal reinforcement in the wall can be placed in one or two parallel layers called *curtains*. Horizontal reinforcement needs to be anchored at the ends of walls. The minimum area of reinforcing steel to be provided is *0.0025* times the cross-sectional area, along *each* of the horizontal and vertical directions. This vertical reinforcement should be distributed uniformly across the wall cross-section.

Boundary Elements: Under the large overturning effects caused by horizontal earthquake forces, edges of shear walls experience high compressive and tensile stresses. To ensure that shear walls behave in a ductile way, concrete in the wall end regions must be reinforced in a special manner to sustain these load reversals without loosing strength (Figure 4b). End regions of a wall with increased confinement are called *boundary elements*. This special confining transverse reinforcement in boundary elements is similar to that provided in columns of RC frames. Sometimes, the thickness of the shear wall in these boundary elements is also increased. RC walls *with boundary elements* have substantially higher bending strength and horizontal shear force carrying capacity, and are therefore less susceptible to earthquake damage than walls *without boundary elements*.

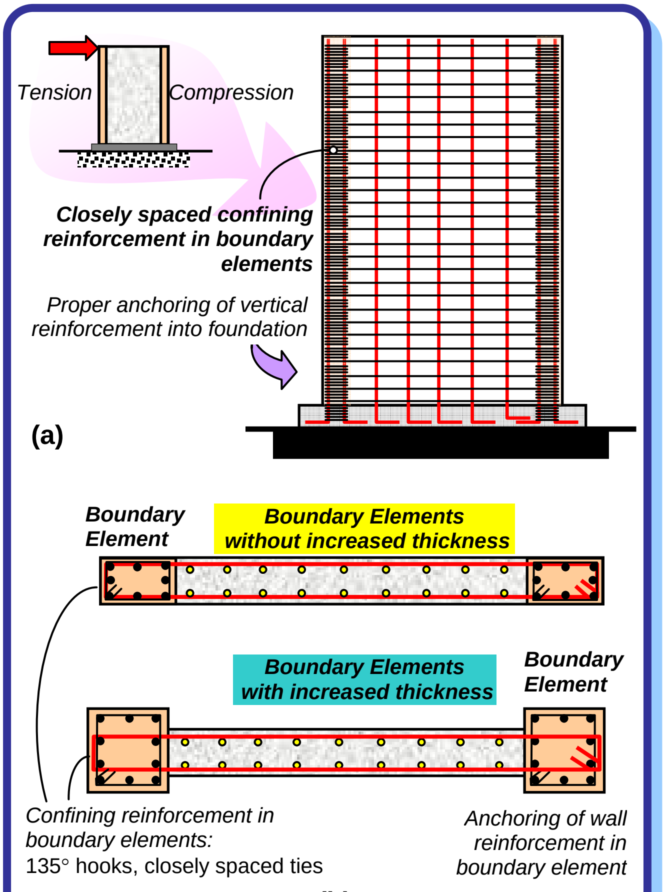


Figure 4: Layout of main reinforcement in shear walls as per IS:13920-1993 – *detailing is the key to good seismic performance*.

DUCTILE DETAILING CONSIDERATIONS AS PER IS 13920:1993

Provision for ductile detailing in the members of reinforced concrete buildings are given in IS 13920: 1993. These provisions are for the anchorage and splices of longitudinal reinforcement, spacing, anchorage and splices of lateral reinforcement, and joint of member. It is often observed in past earthquakes that the problems in structural detailing may also be a significant cause of damage. The discussions herein focus on the provision of ductile detailing provision for RC buildings and its possible reasons for providing structure (Madhekar and Jain, 1993, NZS 3101, 1995, ACI 318, 1999, Euro code 8, 2002), which will be helpful to understand the importance of the ductile detailing for earthquake resistant design of structure.

General Specifications

1 ***The design and construction of reinforced concrete buildings shall be governed by the provision of IS 456: 1978 (now IS: 456: 2000), except as modified by the provisions of this code.***

2 ***For all buildings which are more than 3 stories in height, the minimum grade of concrete shall be M 20 (f_{ck} = 20 MPa)***

Possible Explanations:

- The concrete strength below M 20 may not have the requisite strength in bond or shear to take full advantage of the design provisions
- Bending strength of a reinforced concrete member is relatively insensitive to concrete compressive, tensile and shear strength and durability, which are adversely affected by weak concrete

3 ***Steel reinforcements of grade Fe 415 or less shall be used***

Possible Explanations:

- For reinforcement, the provisions, firstly, of adequate ductility and secondly, of an upper limit on the yield stress or characteristic strength, are essential. It is a general practice to limit the yield stress of reinforcement to 415 MPa
- Strong steel is not preferable to low strength steel in earthquake prone region because typical stress strain curve of low steel shows the following advantages: (a) a long yield plateau; (b) a greater breaking strain; and (c) less strength gain after first yield
- Mild steel is more ductile and its reduced post yield strength gain is advantageous. Provided that the yield strength is confined to specified limits, design can determine section maximum flexure strengths in order to design other areas of the structure to prevent premature brittle shear failure (capacity design approach)
- Mild steel should be used, as primarily reinforcement in areas where earthquake damage is expected, such as beam in moment resisting frames Higher strength steel (with a yield strength > 300 MPa) is appropriate for other structural elements where flexural yielding can't occur under earthquake load

Flexural Members

.1 *General*

These requirements apply to frame members resisting earthquake-induced forces and designed to resist flexure. These members shall satisfy the following requirements.

.1.1 The factored axial stress on the member under earthquake loading shall not exceed $0.1f_{ck}$.

Possible Explanation:

- Generally, axial force in the flexural member is relatively very less but if factored axial compressive stress in the frame member exceeds to $0.1f_{ck}$, axial force will also be considered besides bending and member will be designed as per clause 7.0

.1.2 The member shall preferably have a width to depth ratio of more than 0.3.

Possible Explanations:

- To provide more uniform design approach
- To minimize the risk of lateral instability
- Experience gained from past

.1.3 The width of the member shall not be less than 200 mm.

Possible Explanations:

- To decrease the sensitivity to geometric error
- Experience gained from practice with RC frames resisting earthquake induced forces

.1.4 The depth D of the member shall preferably be not more than one-fourth of the clear span.

Possible Explanations:

- To take into account the non-linearity of strain distribution and lateral buckling
- Experimental evidence indicates that under load reversals or displacement into nonlinear range, the behaviour of continuous members having length to depth ratios of less than four is significantly different from the behaviour of relatively slender members

.2 *Longitudinal Reinforcement*

.2.1 (a) The top as well as bottom reinforcement shall consist of at least two bars throughout the member length.

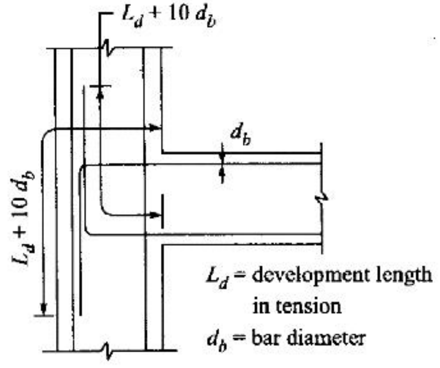
Possible Explanations:

- To ensure integrity of the member under reversed loading
- It is a construction requirement rather than behavioral requirement

In an external joint, both the top and the bottom bars of the beam shall be provided with anchorage length, beyond the inner face of the column, equal to the development length in tension plus 10 times the bar diameter minus the allowance for 90 degrees bend(s). In an internal joint, both face bars of the beam shall be taken continuously through the column.

Possible Explanations:

- Such arrangement will make a ductile junction and provide adequate anchorage of beam reinforcement into columns
- The capacity of the beam is developed by embedment in the column and within the compression zone of the beam on the far side of the connection
- The length available for the development of the strength of a beam bars is gradually reduced during cyclic reversals of earthquake actions because of the yield penetration from the face of a column

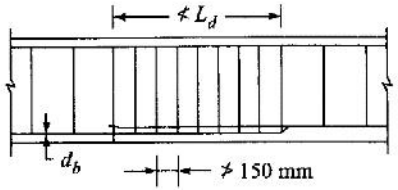


Anchorage of beam bars in an external joint.

The longitudinal bars shall be spliced, only if hoops are provided over the entire splice length, at spacing not exceeding 150 mm. The lap length shall not be less than the bar development length in tension. Lap splices shall not be provided (a) within a joint, (b) within a quarter length of the member where flexural yielding may generally occur under the effect of earthquake forces. Not more than 50 per cent of the bars shall be spliced at one section.

Possible Explanations:

- Lap splices of reinforcement are prohibited at regions where flexural yielding is anticipated because such splices are not reliable under conditions of cyclic loading into the inelastic range
- Transverse reinforcement for lap splices at any location is mandatory because of the possibility of loss of concrete cover



L_d = development length in tension
d_b = bar diameter

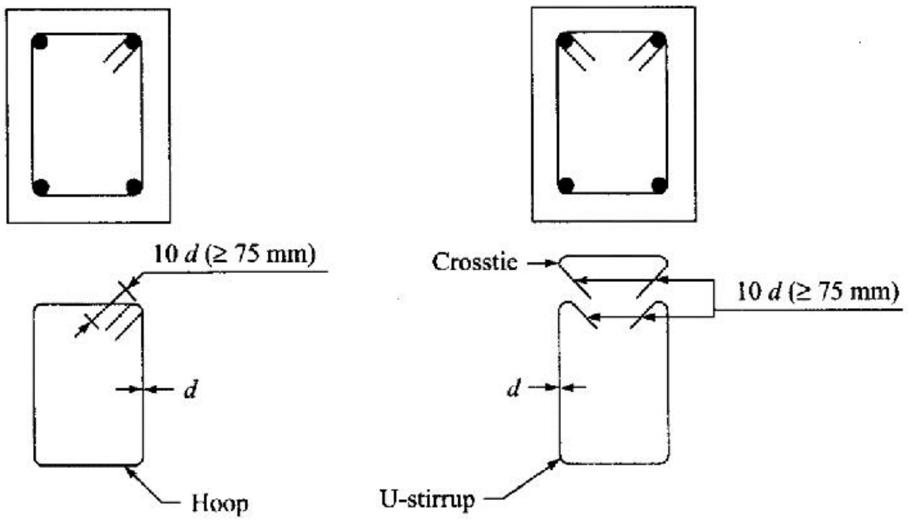
Lap splice in beams.

3 *Web Reinforcement*

3.1 *Web reinforcement shall consist of vertical hoops. A vertical hoop is a closed stirrup having a 135° hook with a 10-diameter extension (but not < 75 mm) at each end that is embedded in the confined core. In compelling circumstances, it may also be made up of two pieces of reinforcement: A U stirrup with a 135° hook and a 10-diameter extension (but not < 75 mm) at each end, embedded in the confined core and cross tie. A crosstie is a bar having à 135° hook with a 10 diameter extension (but not < 75 mm) at each end. The hooks shall engage peripheral longitudinal bars.*

Possible Explanations:

- Stirrups are required to prevent the compression bar from buckling
- Transverse reinforcement is required to confine the concrete in the regions where yielding is expected so as to minimize strength degradation
- To provide shear strength for full flexural capacity of the member



Beam web reinforcement.

3.2 *The minimum diameter of the bar forming a hoop shall be 6 mm. However, in beams with clear span exceeding 5 m, the minimum bar diameter shall be 8 mm.*

Possible Explanation:

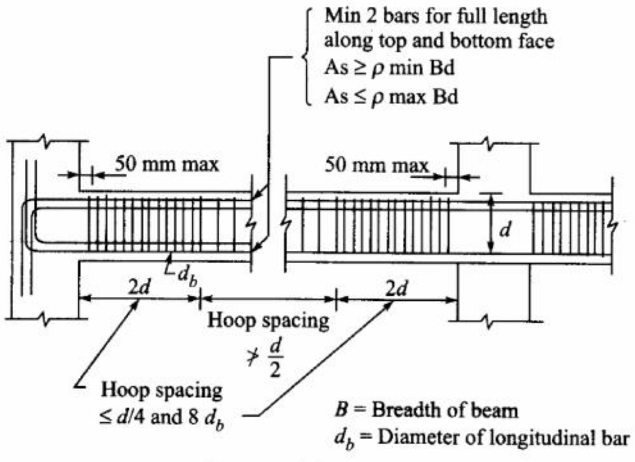
- This refers to construction and durability (corrosion of reinforcement) rather than behavioral requirements

3.3 *The shear force to be resisted by the vertical hoops shall be the maximum of: (a) calculated factored shear force as per analysis, and (b) shear force due to formation of plastic hinges at both ends of the beams plus the factored gravity load on the span.*

The spacing of hoops over a length of 2 d at either end of a beam shall not exceed (a) d/4, and (b) 8 times the diameter of the smallest longitudinal bar; however it need not be less than 100 mm. The first hoop shall be at a distance not exceeding 50 mm from the joint face. Vertical hoops at the same spacing as above shall also be provided over a length equal to 2 d on either side of a section where flexural yielding may occur under the effect of earthquake forces. Elsewhere the beam shall have vertical hoops at a spacing not exceeding d/2.

Possible Explanations:

- Potential plastic hinge regions in beams require special detailing where a plastic hinge develops. It serves three main purposes (i) prevents buckling of longitudinal bars in compression; (ii) provides some confinement of the concrete; and (iii) acts as shear reinforcement
- In the case of members with varying strength along the span or member for which the permanent load represents a large proportion of the total design load, concentration of inelastic rotation may occur within the span. If such a condition is anticipated, transverse reinforcement should also be provided in regions where yielding is expected



Beam reinforcement.

Columns and Frame Members subjected to Bending and Axial load

General

These requirements apply to frame members, which have a factored axial stress in excess of 0.1 f_{ck} under the effect of earthquake forces.

Possible Explanation:

- the member subjected to axial forces greater than a specified limit shall take both the load bending and axial

The minimum dimension of the member shall not be less than 200 mm. However, in frames, which have beams with center-to-center span exceeding 5 m or columns of unsupported length exceeding 4 m, the shortest dimension of the column shall not be less than 300 mm.

Possible Explanations:

- to avoid very slender columns
- to avoid column failure before beams (strong column weak beam concept)
- experience from practice with reinforced concrete frames resisting earthquake-induced forces

The ratio of the shortest cross sectional dimension to the perpendicular dimension shall preferably be not less than 0.4.

Possible Explanation:

- Experience from practice with reinforced concrete frames resisting earthquake-induced forces

Transverse Reinforcement

Transverse reinforcement for circular columns shall consist of spiral or circular hoops. In rectangular columns rectangular hoops may be used. A rectangular hoop is a closed stirrup, having a 135° hook with 10-diameter extension (but not < 75 mm) at each end that is embedded in the confined core.

Possible Explanation:

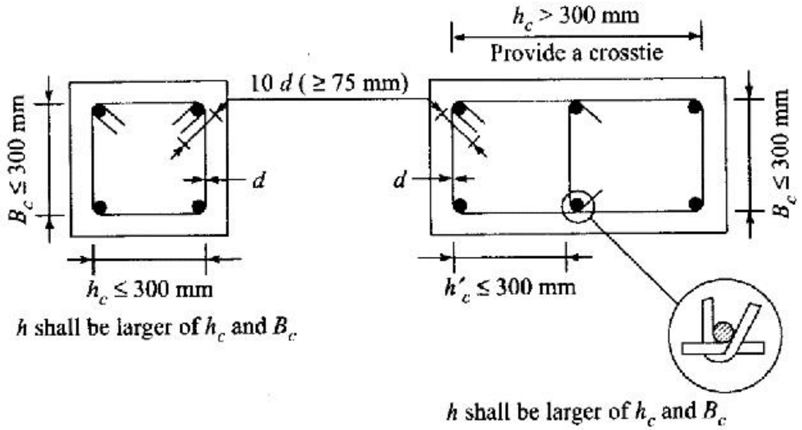
- Columns of building subjected to seismic loading often carry large flexure and shear load, when diagonal tension cracks are possible, shear reinforcement will be required. Therefore, the anchorage and the shape of tie must be such that tensile forces resulting from truss action can be transversed from one face of the column to the other

The parallel legs of rectangular hoop shall be spaced not more than 300 mm centre-to-centre. If the length of any side of the hoop exceeds 300 mm, a crosstie shall be provided. Alternatively, a pair of overlapping hoops may be provided within the column. The hooks shall engage peripheral longitudinal bars.

The spacing of hoops shall not exceed half the least lateral dimension of the column, except where special confining reinforcement is provided as 7.4.

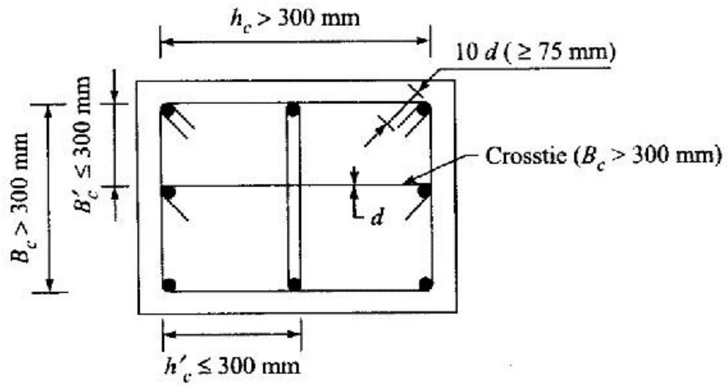
Possible Explanations:

- The maximum centre-to-centre spacing of the transverse reinforcement is considered necessary to restrain buckling of longitudinal steel and for adequate confinement of the concrete. Too much spacing would not provide adequate lateral restraint or confinement; too small a spacing would not allow aggregate particles to pass between the transverse bars when concrete is being placed
- Observations after earthquakes have shown significant damage to columns in the non-confined region, and the minimum ties or spirals required should provide more uniform toughness of the column along its length
- Column bars carrying compression are liable to buckle under large strain. When yielding takes place in steel approach, the lateral restrain provided the cover cannot rely upon concrete. Therefore, transverse ties must provide lateral support to each column bar to prevent stability due to outward buckling



single hoop

single hoop with a crosstie



h shall be larger of h'_c and B_c

overlapping hoops with a crosstie

Transverse reinforcement in columns.

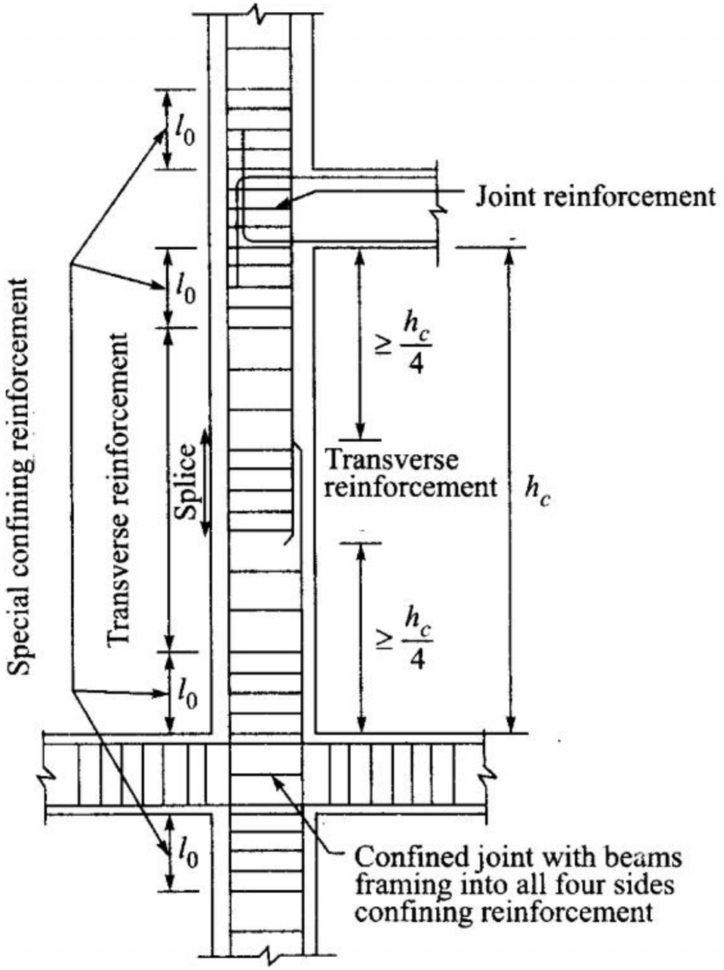
Special Confining Reinforcement

This requirement shall be met with, unless a larger amount of transverse reinforcement is required from shear strength considerations.

Special confining reinforcement shall be provided over a length l_0 from each joint face, towards midspan, and on either side of any section, where flexural yielding may occur under the effect of earthquake forces. The length 'l_0' shall not be less than (a) larger lateral dimension of the member at the section where yielding occurs, (b) 1/6 of clear span of the member, and (c) 450 mm.

Possible Explanations:

- Potential plastic hinge regions in columns shall considered to be end regions adjacent to moment resisting connections over a minimum length from the connection
- This stipulates a minimum length which provides closely spaced transverse reinforcement at the member ends, where flexural yielding normally occurs
- This is provided to confine the concrete core, to support the longitudinal compressive reinforcement against inelastic buckling and for resistance in conjunction with the confined concrete, against shear



Column and joint detailing.