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1.INTRODUCTION

Site Planning and building form are very important from the point of view of seismic performance of the structure. Also it is very important to have proper compatibility of elements resisting seismic forces. Site planning and selection of building forms is the first step in designing of any structure and the decisions taken are very crucial for the behavior of those structures during any earthquake. Based on examples taken from various past earthquakes and theories, this project gives guidelines for site planning, selection of building form and formulation of architectural design concepts for earthquake resistant structures in the earthquake prone zones.

2.HISTORICAL EXPERIENCES

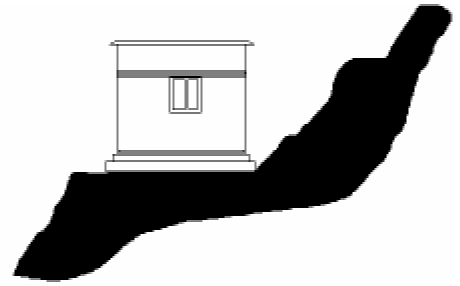
Compliance to site regulations is very important and has a historical basis. Even Napoleon had imposed regulations for compliance as for loss of serviceability in a construction project within 10 years of construction; say foundation failure or poor workmanship; the contractor and the architect were to be sent to prison. Whether such and other rules from ancient times stopped all failures is not known, but they certainly were a deterrent to shoddy construction practices and eliminated the possibility of repetitive malpractices. Present day law and order demands accountability for professional performance**.** One must be well aware @ past experience regarding architectural design concepts, from past earthquakes.

3.SITE SELECTION

The selection of suitable site is a crucial step in the design of a building or planning a settlement in an earthquake prone zone. There are a number of earthquake related hazards which should always be considered when choosing a site, together with the influence of the ground conditions at the site on the ground motion which the building may experience in a future earthquake. An assessment of the extent of the earthquake hazard should always form a part of the overall site assessment and of the specification for the design of any structures to be built there. No site can be expected to be ideal in all respects, so the choice of site will often involve a judgment about relative risks and the costs of designing to protect from them. But there can be some sites which could be so hazardous that they should be avoided if at all possible, since the cost of building is likely to be prohibitive. A few important considerations for site selection are given below:

3.1 Steep Slopes

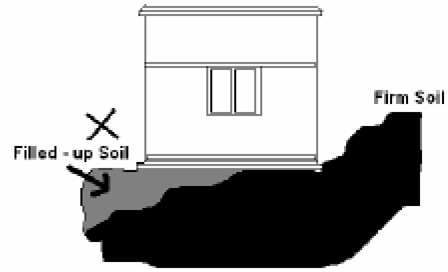
Buildings should be sufficiently away from steep slopes. Sites located on or very close to steep slopes are always prone to landslides, especially in the earthquake prone regions. Even if the building has good earthquake resistant construction, they are prone to damages or total destructions on such sites. Frequent landslides in Uttar kashi region after the October 1991 earthquake caused massive devastations in the region. The periodic landslides are triggered by other aspects like excess rains, seepage etc. The Himalayan regions are particularly prone to landslides. Such landslides often prove to be more disastrous than the actual earthquake event.



Buildings located near steep slopes

3.2 Filled Up Soil

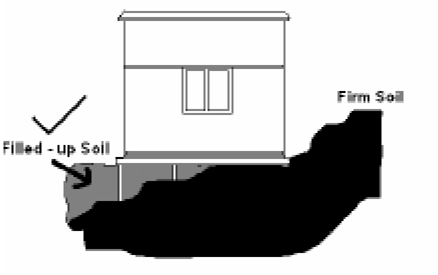
Foundation should rest only on firm soil and not on filled up soil. Such constructions on filled up soils have witnessed extensive damages in the January2001 Gujarat earthquake.



Buildings located on filled – up soil should be avoided

Raft on Pile Foundations

Many times it is unavoidable to construct the structure on filled up soil, as in most cases choice of site is not the option we have. In such situations raft on pile foundations have to be provided



Buildings located on filled – up soil should be provided with raft on pile foundations

4.BUILDING FORMS

Building form has to be decided initially in the design process. Different aspects of building forms viz. scale, height, horizontal size, proportion and symmetry are discussed below:

4.1 Scale

A large masonry building is always in contrast with a small wood frame building which can be made a seismically safe structure with the inclusion of relatively inexpensive and unobtrusive provisions. This is because a small wood structure is lightweight and the internal forces will be low. In addition the spans are relatively small and there would be large number of walls to distribute the loads. On the other hand, for a larger building, the violation of basic layout and proportion principles result in an increasingly high cost as the forces become greater and the good performance becomes difficult as compared to an equivalent building. As the absolute size of a building increase, the number of options for its structure design decreases. A bridge span of 100 meters may be designed as a beam, arch, truss or suspension system, but if this span increases to 1000 meters the structural discipline becomes more rigorous and the design options become limited. The architectural solutions that are perfectly acceptable at the size of a simple structural system like house become physically impossible at the scale of large spans like suspension bridge. It is not possible to alter the size of a structure and its components and still retain the same structural behavior. Every building has to be considered differently with increase in size, as the size of the building influences its seismic performance.

4.2 Height

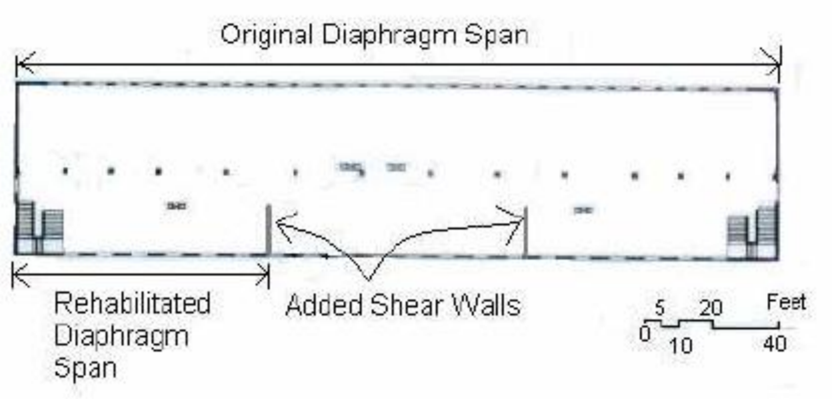
Increasing the height of a building may be similar to increasing the span of a cantilever beam. As the building grows taller there is a change in the level of response to the seismic forces. The effect of the building period therefore, must be considered in relation with the period of ground motion and its amplification. The effect of an increase in height may be quiet disproportionate to the increase in seismic forces itself. Thus the doubling of the building height from 5 to 10 storeys may, if amplification occurs, result in four or five fold increase in seismic forces. These concepts are already explained in section 3.5 and 3.6.

4.3 Horizontal size

It is easy to visualize the overturning forces associated with height as a seismic problem, but large plan areas can also be detrimental. When the plan becomes extremely large, even if it is symmetrical, simple shape, the building can have trouble responding as one unit to earth vibrations.

Increase in length of a building increases the stresses in a floor working as a horizontal distribution diaphragm in a transverse direction. The rigidity of thefloor may not be sufficient to redistribute the horizontal load during an earthquake from weaker or damaged supporting elements of the building to stronger elements or those with minor damage.

Unless there are numerous interior lateral force resisting elements, large plan buildings impose unusually severe requirements on their diaphragms, which have large lateral spans and can build up large forces to be resisted by shear walls or frames. The solution is to add walls or frames that will reduce the span of the diaphragm, though it will reduce flexibility in the use of the building

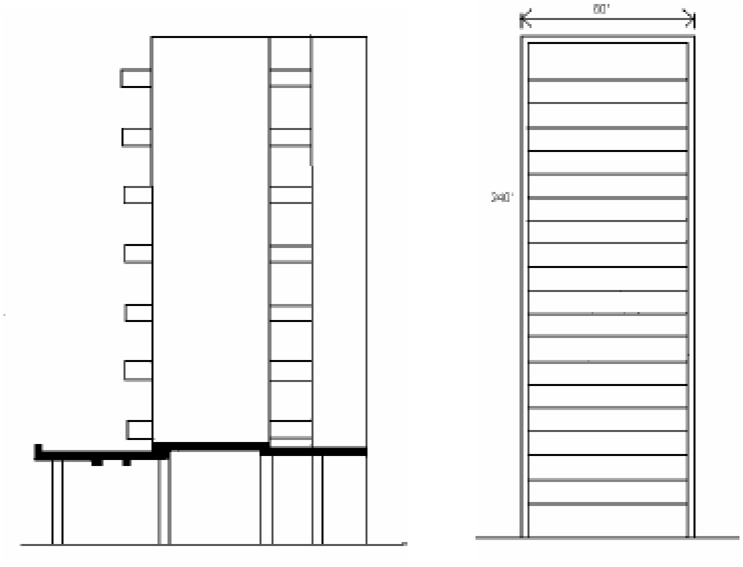


Addition of shear walls to decrease span of diaphragm

4.4 Proportion

In seismic design, the proportions of a building may be more important than its absolute size. For tall buildings the slenderness ratio of a building is one of the important considerations than just the height alone. The more slender the building is worse are the overturning effects of an earthquake and greater are the earthquake stresses in the outer columns, particularly the overturning compressive forces, which can be very difficult to deal with. Some experts suggest limiting the height / depth ratio to 3 or 4, to safeguard the building against overturning.

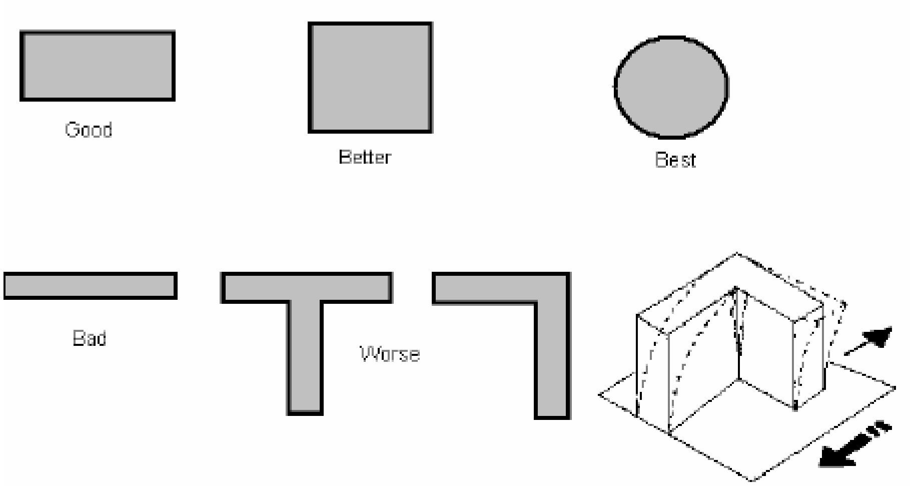
As the urban land is becoming more scarce and expensive, there is a trend to design slender buildings, which although not necessarily very high, may have a large height / depth ratio. This trend is clearly apparent in downtown Tokyo, where multistoried buildings were built on sites that are only 5 to 6 meters wide. At the same time the economic forces often dictate the distance between the two buildings which were very close and at times they tend to respond as one unit rather than as individual freestanding buildings.



Unusually High Building

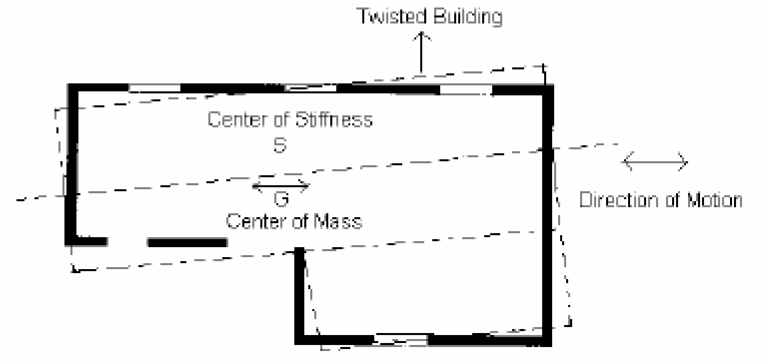
4.5 Symmetry

The plan shape of a building should be as simple as possible. A theoretical optimum shape is a round tower, where as long buildings, L-shaped or zigzag shape or buildings with attached wings are undesirable in the high risk areas and therefore should be avoided.



Shape of Buildings

The term symmetry denotes a geometrical property of the plan configuration, whereas the structural symmetry means that the center of mass and the center of resistance are located at the same point. In asymmetrical configuration / structural system the eccentricity between the center of mass and resistance will produce torsion and stress concentration and therefore the symmetrical forms are preferred to the asymmetrical ones



Torsion of Unsymmetrical Building Plan

Thus it is amply clear that as the building becomes more symmetrical its tendency to suffer torsion and the stress concentration will reduce and performance under seismic loads tends to considerably improve. This suggests that when good seismic performance has to be achieved along with maximum economy of design and construction, the simple, regular and symmetrical shapes are much preferred. However these tendencies must not be mistaken for an axiom that the symmetrical building does not suffer torsion.

5. SEISMIC EFFECTS RELATED TO BUILDING CONFIGURATION

Building configuration refers to the size, shape and proportions of the building form. From seismic point of view configuration may also include the location, shape and approximate size of structural elements as these elements are often determined based on the architectural design decisions. This extended definition of configuration is necessary because of the intricate relationship of seismic performance between these elements. In general the architectural configuration depends on:

1. Architectural design

2. Functional requirements

3. Urban design parameters

4. Planning considerations

5. Aesthetic appearance

6. Identity (distinctiveness)

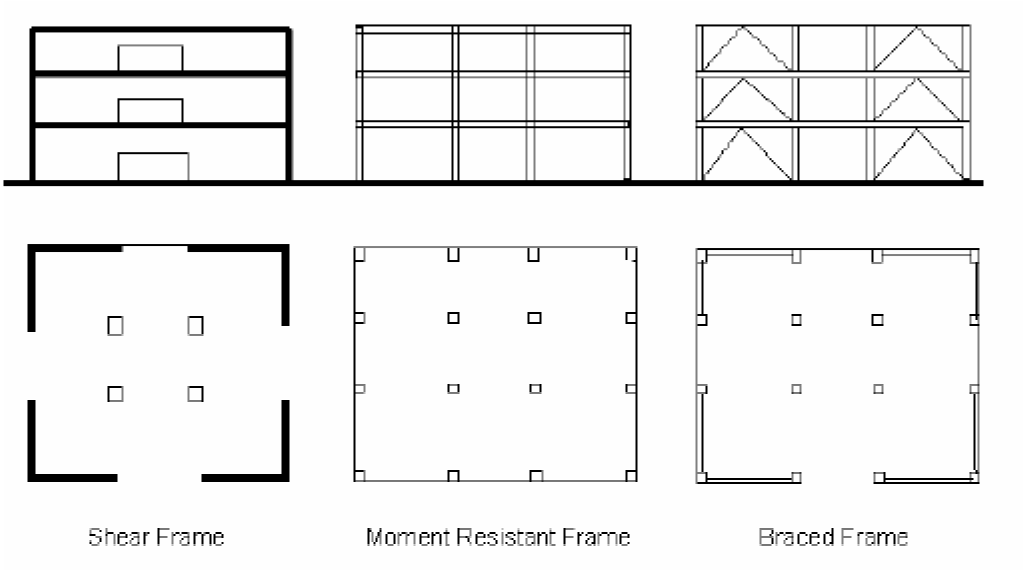
The earthquake forces depend on mass and stiffness distribution, the material size and shape of the building establish it's mass. Stiffness is directly related with the type of configuration. For the same overall size and shape of the building various configuration can provide a solution.

The coda provisions for earthquake resistant buildings are based on simple, symmetrical and uniform building configurations. Their application to unusual / irregular building configurations, therefore may lead to unrealistic evaluation. It is important to understand about regular and irregular configurations, before taking the architectural design decisions.

Any configuration, whether regular or irregular, will have some resistant system, to take the lateral forces, which acts in horizontal and vertical planes. In vertical plane there are shear walls, braced frames and moment resisting frames whereas in horizontal plane the lateral forces are resisted by diaphragms formed by floor and roof slabs of the building. The presence of these resistant systems is the result of schematic architectural design.

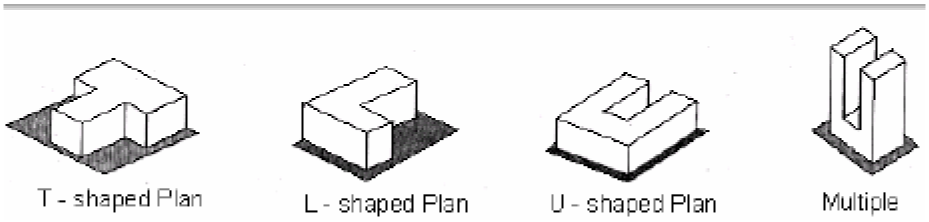
5.1 Regular Configuration

Regular configuration shown in is seismically ideal. These configurations have low heights to base ratio, symmetrical plane, uniform section and elevation and thus have balanced resistance. These configurations would have maximum tensional resistance due to location of shear walls and bracings. Uniform floor heights, short spans and direct load path play a significant role in seismic resistance, of the building. The optimal (regular) seismic configuration

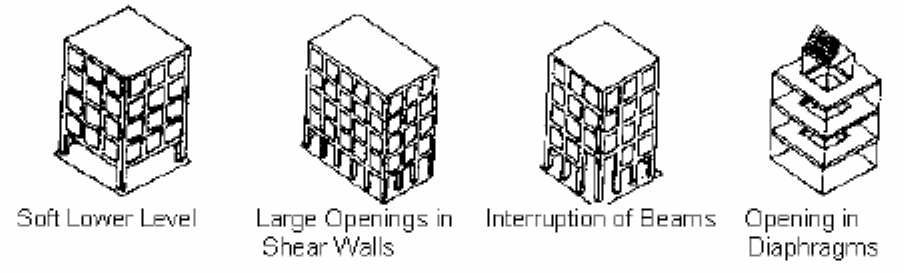


The Irregular Configuration

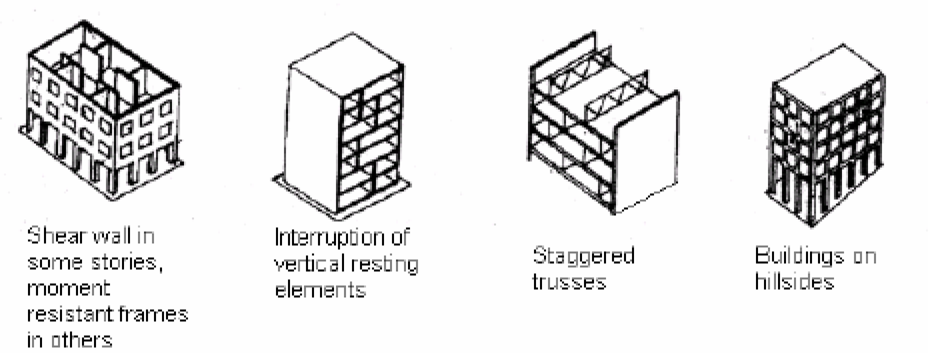
Some of the common irregular building configurations as defined by some American Codes are as shown in these codes permit the use of equivalent static force method in these irregular buildings with some zonal constraints as the height and stiffness changes between two stories. Optimal (regular) seismic configuration is the graphical representation of irregular structures or framingssystems.



Buildings with irregular configuration



Buildings with abrupt changes in lateral resistance

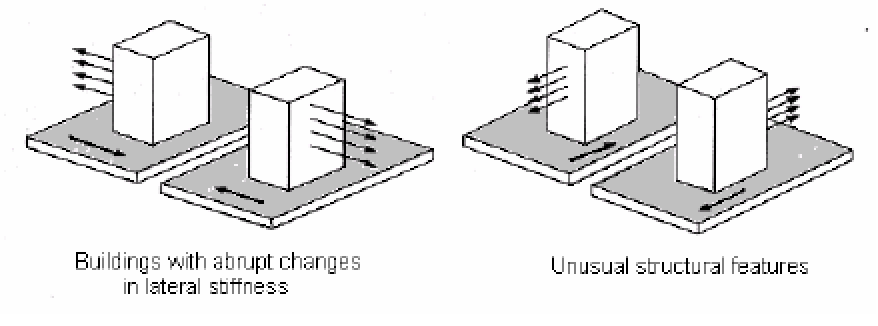


Buildings with abrupt changes in lateral stiffness

5.2 Influence of Configuration on Seismic Performance

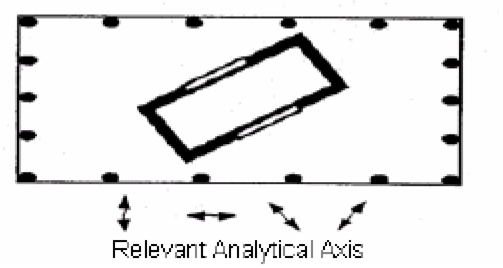
To understand the influence of configuration on seismic performance one should understand the ways in which the building responds to the dynamic forces due to motion of the ground. Static vertical loads are directly transferred down to the round through foundation. The earthquake exerts fluctuation dynamic loads; it is difficult to determine the seismic forces without knowing and understanding the dynamic characteristic of the building along with the sequence of events and the behavior of different elements of the building structure under dynamic loads.

The forces that are exerted on the building elements and the exact nature of their resultant behavior are quiet complex and should be taken into account while taking the decision regarding the building configuration. These forces are below.



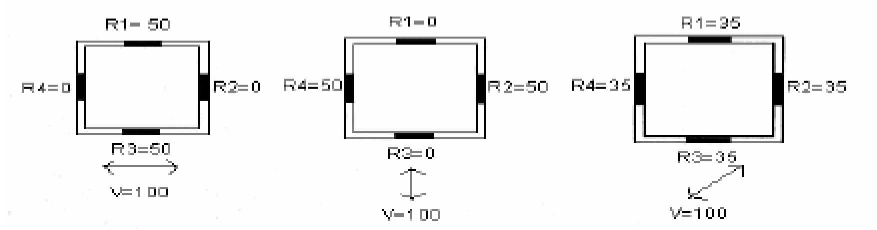
Typical analytical diagram of earthquake forces

The above diagram originates in the form of typical seismic design analysis in which earthquake forces are separately applied to each of the main axis for a rectangular shape and for a circle there would be more axis which are similar, (more stable) however for irregular shape which is complicated we may have to look at along several axis.



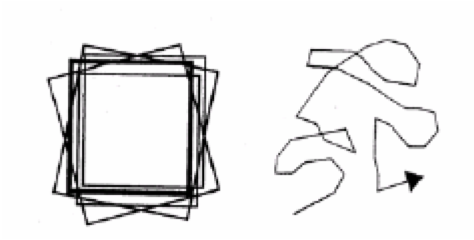
For complicated configuration more than two axes may be used for analysis

In fact the earthquake forces may come from any direction, however, the forces perpendicular to the major axes of walls or frames usually simulates the worst direction. If the ground motion and its resulting forces occur diagonally then the walls or frames along both X axes and Y axes can participate in negating the resistance and the forces in each of the wall or frame will be considerably reduced.



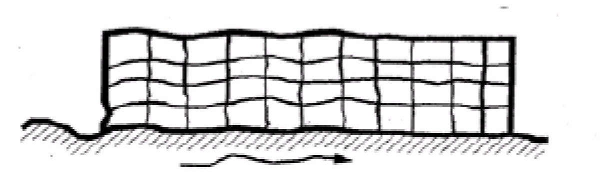
Earthquake forces on buildings

It is important to note that in reality the earthquake forces are much more complex than our diagrams would indicate. This is because the ground motion is random and the main direction of emphasis will only be axial by chance. In any event, the total ground motion will always include non axial components also. Thus a better diagram for visualizing building configuration related to reaction to the ground motion will be.



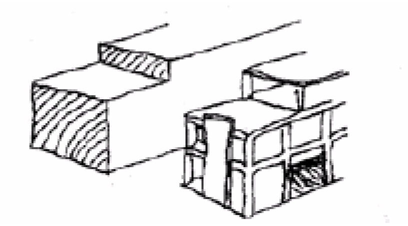
Earthquake forces: The reality

A building is not a homogeneous block but an assembly of parts, and each part is subjected to earthquake forces horizontally and vertically and from adjoining parts through joints. In a large building the ground motion affects different parts of the building differently. These forces induce torsion or incompatible movement, even in a geometrically symmetrical building.



Localized strength and stiffness

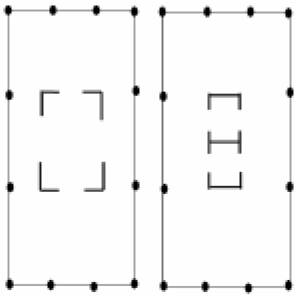
The building being made of parts which are joined together by means of different connections will have different localized strengths and stiffness, some calculated and some inadvertently caused by interaction of non structural elements or configuration influence. This further differentiates its behavior from that of a homogeneous building block.

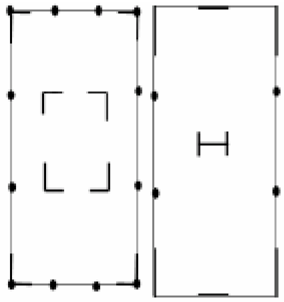


Localized strength and stiffness

6. PLAN AND VERTICAL IRREGULARITIES, REDUNDANCY AND SETBACKS

Many times it has been seen that geometrically building may appear to be regular and symmetrical, but it may have irregularity due to distribution of mass and stiffness. It is always better to distribute the lateral load resisting elements near the perimeter of the building rather than concentrate these, near centre of the building. As a general rule, buildings with irregular configuration perform poorly in earthquakes even when good engineering has been carried out.





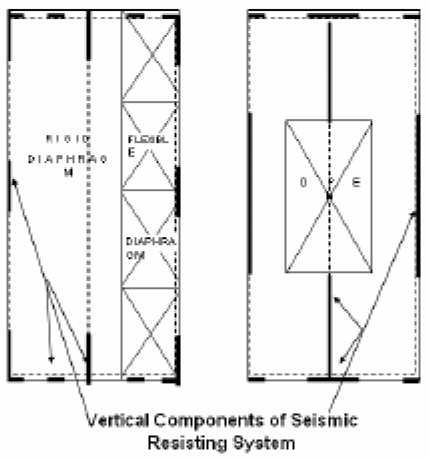
Note that the heavy lines indicate shear walls and/or braced frames

Arrangement of shear walls and braced frames not recommended.

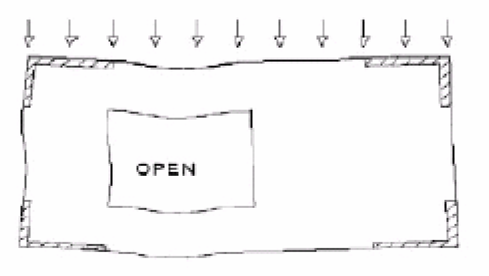
Arrangement of shear walls and braced frames recommended

6.1 Plan Irregularity

Plan irregularities are already discussed in section 5.6.2 of this chapter. An example of discontinuity in diaphragm stiffness leading to plan irregularity



Discontinuity in Diaphragm Stiffness



Diaphragm openings

6.2 Vertical Geometric Irregularity

All buildings with vertical offsets fall in this category. Also, a building may have no apparent offset, but its lateral load carrying elements may have irregularity. For instance, shear wall length may be suddenly reduced. When building is such that larger dimension is above the smaller dimension, it acts as an inverted pyramid and is undesirable. Dynamic analysis is required in buildings with vertical irregularity where load distribution with building height is different. In buildings with plan irregularity, load distribution to different vertical elements becomes complex. In such cases floor diaphragm plays an important role and needs to be modeled carefully. For such buildings a good 3-D analysis is needed. In irregular building, there may be concentration of ductility demand in a few locations. In such buildings just dynamic analysis may not solve the problem and special care is needed in detailing.

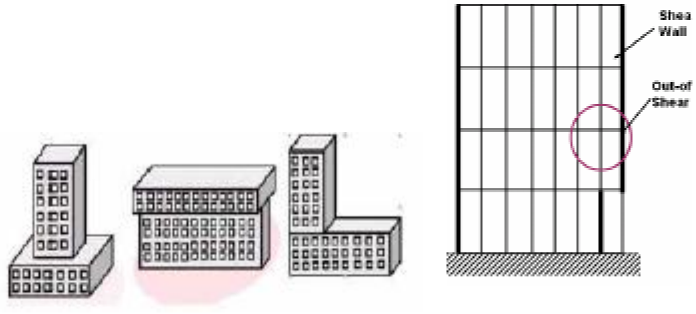
Dynamic analysis is not always sufficient for irregular buildings and dynamic analysis is not always needed for irregularities.

6.3 Projections

All projections (vertical and horizontal) are most vulnerable to damage during earthquakes. As they are cantilevers, there is no redundancy, and hardly any ductility. Design of such projections has to be five times the seismic coefficient. This is same as in the international practice11.

6.4 Out of Plane Offsets

This is a very serious irregularity wherein there is an out-of-plane offset of the vertical element that carries the lateral loads. Such an offset imposes vertical and lateral load effects on horizontal elements, which are difficult to design for adequately. Shear walls are not obvious.

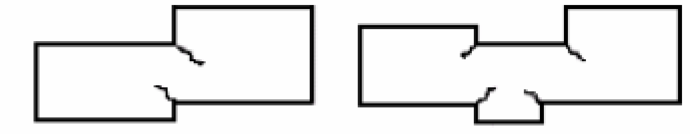


Buildings with offsets

Damage to buildings with offsets

6.7Re-entrant Corner

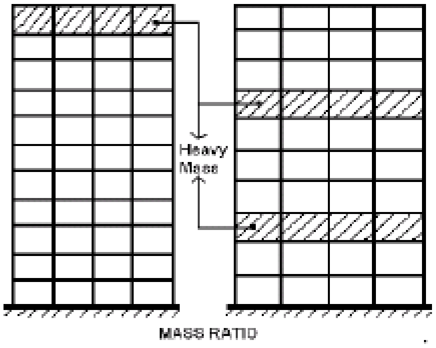
When an otherwise regular building has a large re-entrant corner, wings of the building tend to vibrate in a manner different from that of the entire building. Hence, building is treated as irregular when offset dimensions exceed.



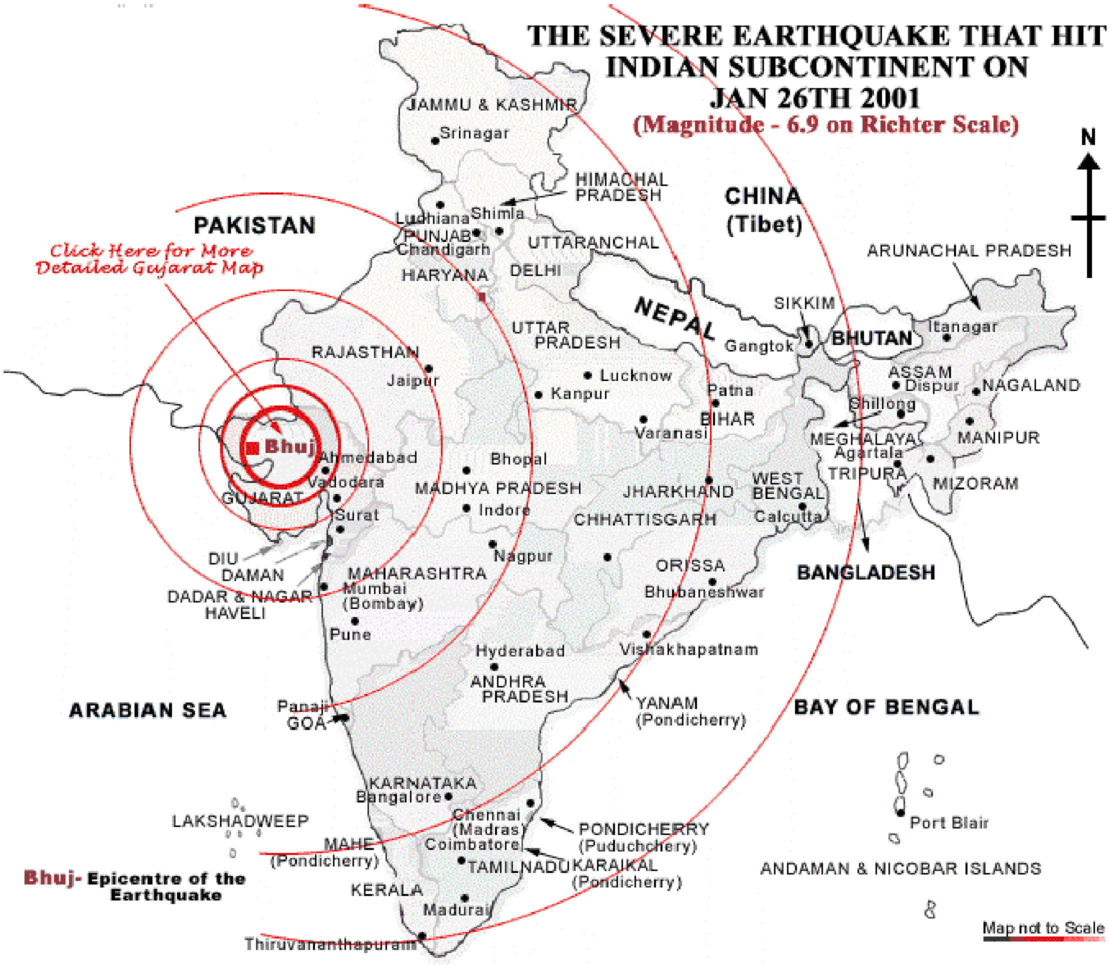
Re-entrant Corner

6.8 Mass Irregularity

Mass irregularity is induced by the presence of a heavy mass on a floor, say a swimming pool. In IS1893 the mass irregularity has been defined as a situation when weight of a floor exceeds twice the weight of the adjacent floor.NEHRP defines it when the weight exceeds 150% of that of the adjacent floor.



Irregularity in masses



6.7 Seismic Zones of India

The varying geology at different locations in the country implies that the likelihood of damaging earthquakes taking place at different locations is different. Thus, a seismic zone map is required to identify these regions. Based on the levels of intensities sustained during damaging past earthquakes, the 1970 version of the zone map subdivided India into five zones – I, II, III, IV and V. The maximum Modified Mercalli (MM) intensity of seismic shaking expected in these zones were *V or less*, *VI*, *VII*, *VIII*, and *IX and higher*, respectively. Parts of Himalayan boundary in the north and northeast, and the Ketch area in the west were classified as zone V.

The seismic zone maps are revised from time to time as more understanding is gained on the geology, the seism tectonics and the seismic activity in the country. The Indian Standards provided the first seismic zone map in 1962, which was later revised in 1967 and again in 1970. The map has been revised again in 2002 and it now has only four seismic zones – II, III, IV and V. The areas falling in seismic zone I in the 1970 version of the map are merged with those of seismic zone II. Also, the seismic zone map in the peninsular region has been modified. Madras now comes in seismic zone III as against in zone II in the 1970 version of the map. This 2002 seismic zone map is not the final word on the seismic hazard of the country, and hence there can be no sense of complacency in this regard.

The national Seismic Zone Map presents a largescale view of the seismic zones in the country. Local variations in soil type and geology cannot be represented at that scale. Therefore, for important projects, such as a major dam or a nuclear power plant, the seismic hazard is evaluated specifically for that site. Also, for the purposes of urban planning, metropolitan areas are microzoned. Seismic microzonation accounts for local variations in geology, local soil profile, *etc,*.

7. Old masonry building built with thick cut-stones

An old government building (predating 1900's) made with solid cut stone masonry walls .This building received slight to moderate damage although it is in the centre of Bhuj and all around, rubble buildings have totally collapsed. The floors and roof are of timber and an adjacent similar building had cut-stone walls which were at least 0.5m thick. The upper storey wall is seen to be damaged at the edges by bending cracks caused by out-of-plane shear forces. Untied architectural stonework has also fallen off at roof level, as might be expected from severe shaking. The heavy wall units and regular stone blocks prevented collapse of these old buildings.

7.1 Cut-stone building in Bhuj

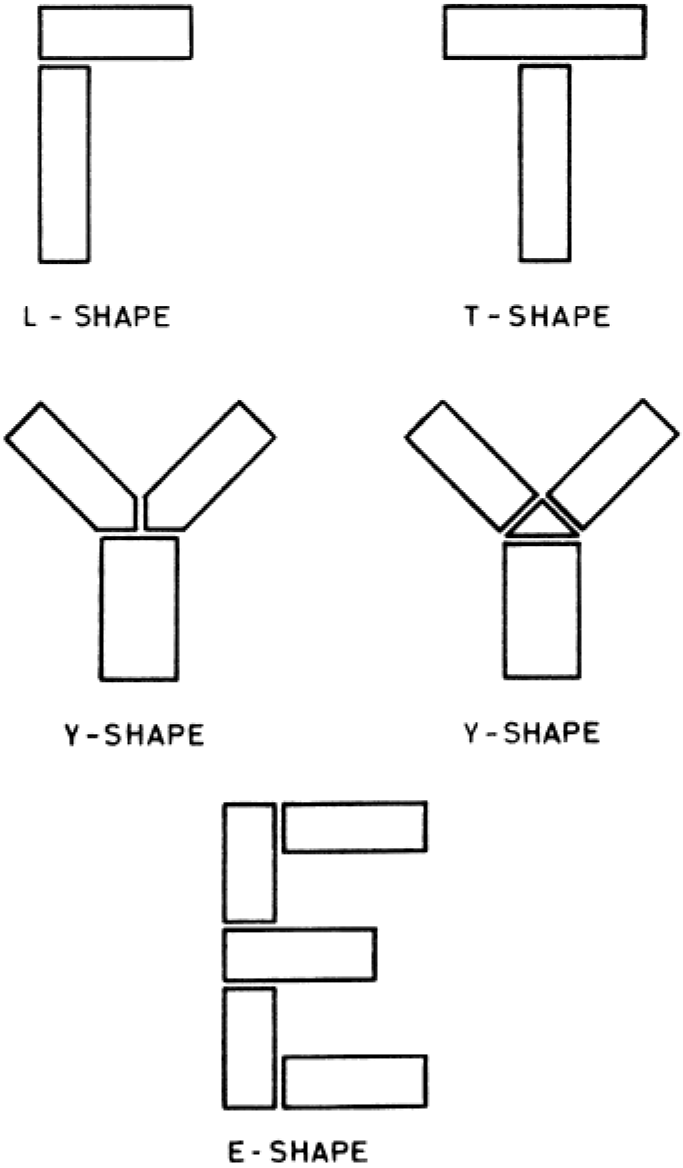
Modern cut-stone masonry building in Mirzapur

Foundations

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

*Loose fine sand, soft silt and expansive clays should be avoided. If unavoidable,
-the building shall rest either on a rigid raft foundation or on piles taken to a firm stratum.
-However, for light constructions the following measures may be taken to improve the soil on which the foundation of the building may rest:
a) Sand piling, and
b) Soil stabilization

*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



L - SHAPE

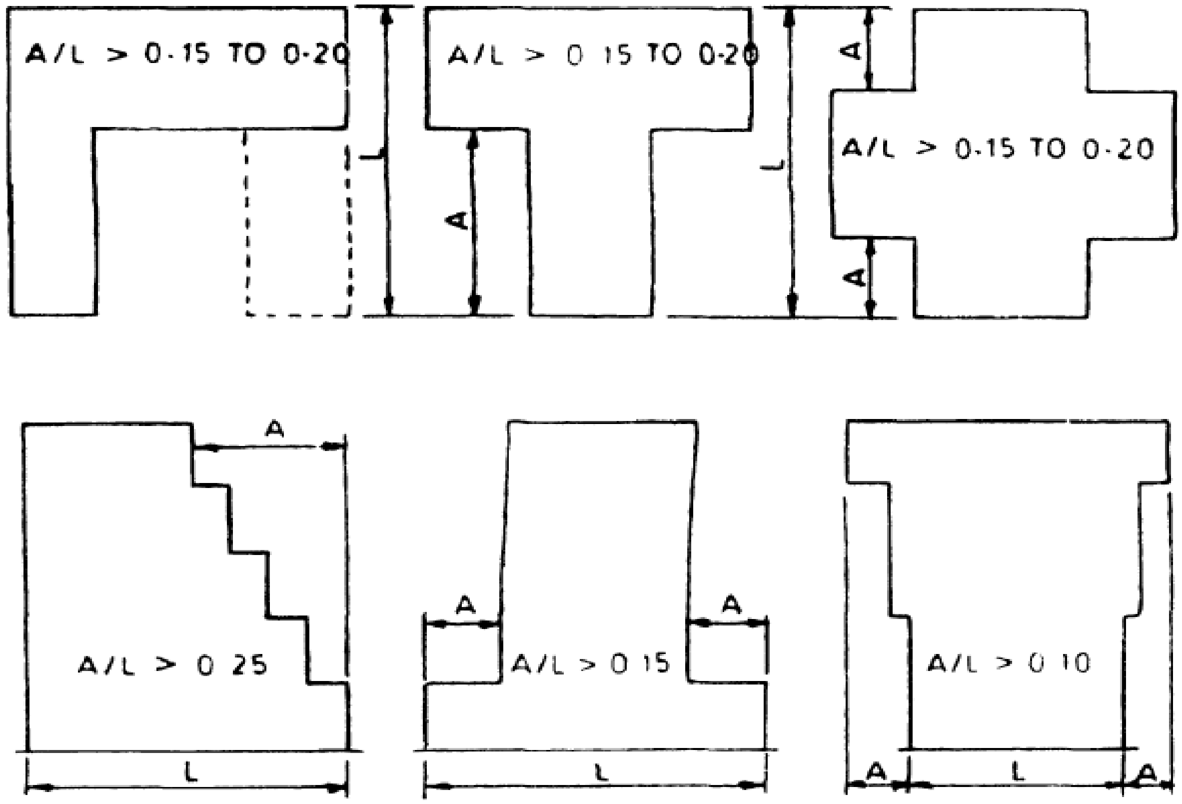
T - SHAPE

Y - SHAPE

Y - SHAPE

E - SHAPE

TYPICAL SHAPES OF BUILDING WITH SEPARATION SECTIONS



PLAN AND VERTICAL IRREGULARITIES

SPECIAL CONSTRUCTION FEATURES

Separation of Adjoining Structures

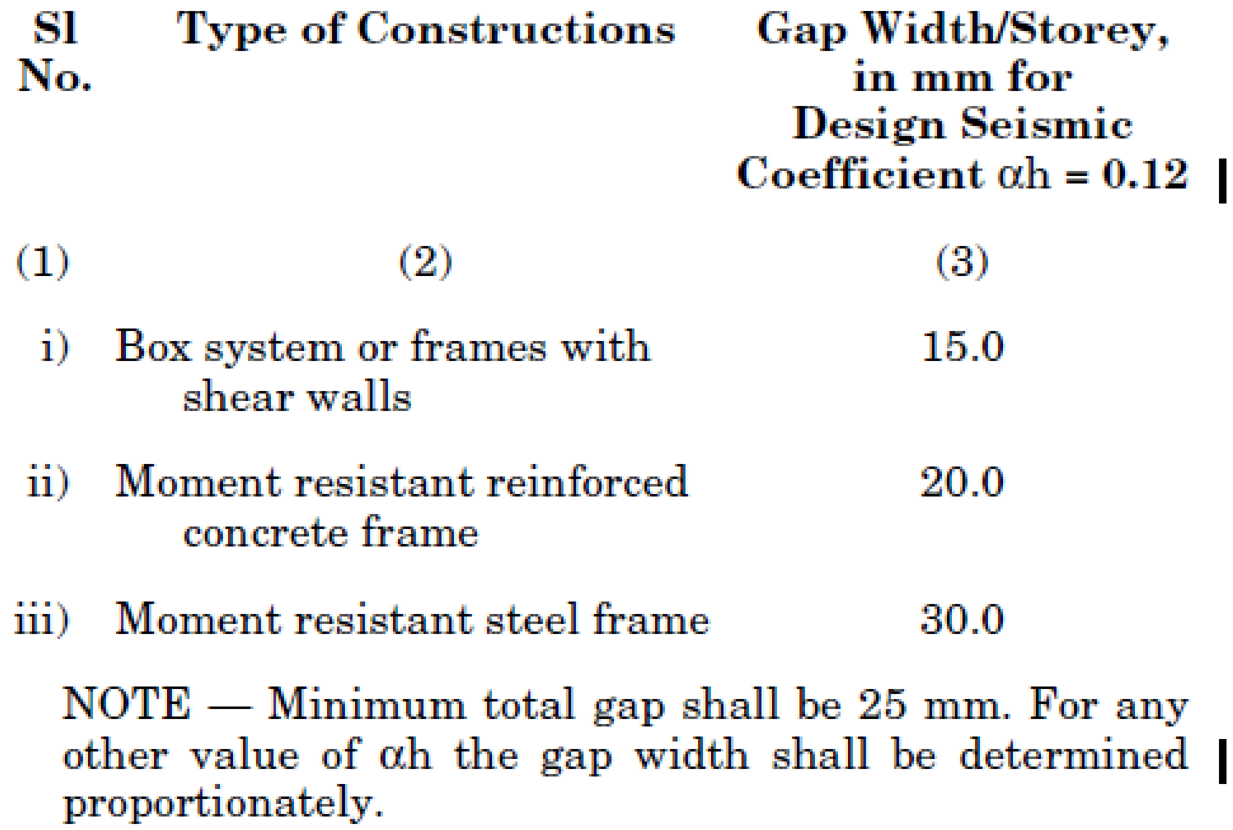
*Separation of adjoining structures or parts of the same structure is required for

-structures having different total heights or storey heights

- different dynamic characteristics.

-THIS IS TO AVOID COLLISION DURING AN EARTHQUAKE

Gap Width for Adjoining Structures



Sl No.	Type of Constructions	Gap Width/Storey, in mm for Design Seismic Coefficient αh = 0.12
(1)	(2)	(3)
i)	Box system or frames with shear walls	15.0
ii)	Moment resistant reinforced concrete frame	20.0
iii)	Moment resistant steel frame	30.0

NOTE — Minimum total gap shall be 25 mm. For any other value of αh the gap width shall be determined proportionately.

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9. STAIRCASES OF EARTHQUAKE

THE INTERCONNECTION OF THE STAIRS WITH THE ADJACENT FLOORS

- appropriately treated by providing sliding joints at the stairs to eliminate their bracing effect on the floors

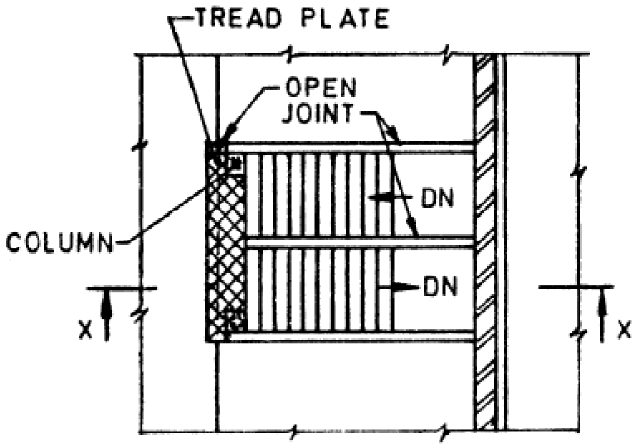
*IN CASE OF LARGE STAIR HALLS

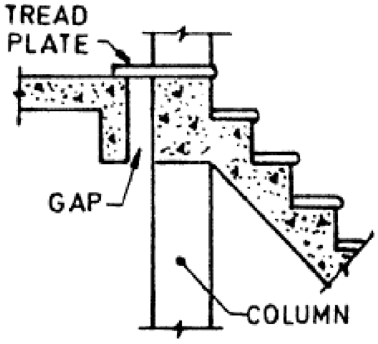
- IT SHOULD BE separated from the rest of the building by means of separation or crumple sections.

*Three types of stair construction may be adopted as described below

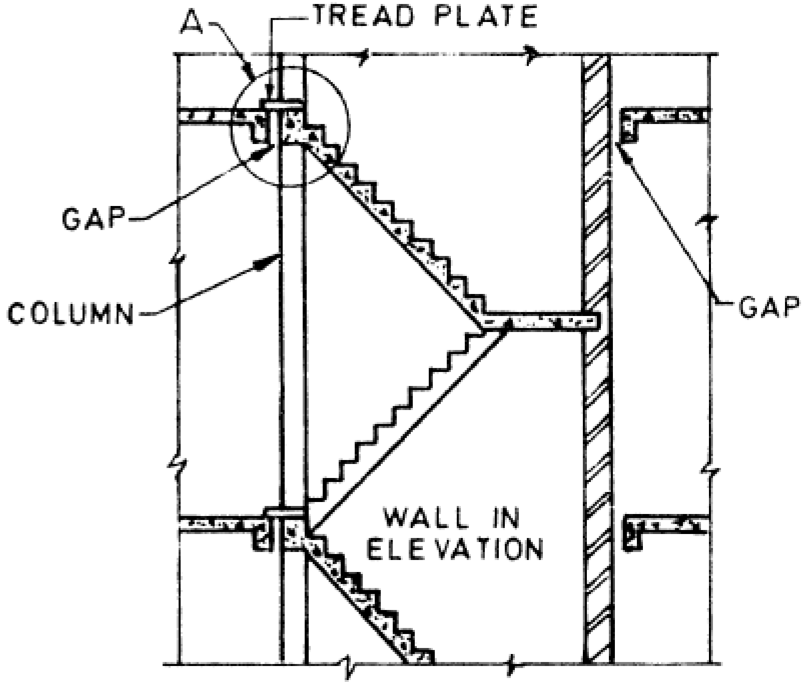
i) *Separated Staircases*

One end of the staircase rests on a wall and the other end is carried by columns and beams which have no connection with the floors.





DETAIL AT A

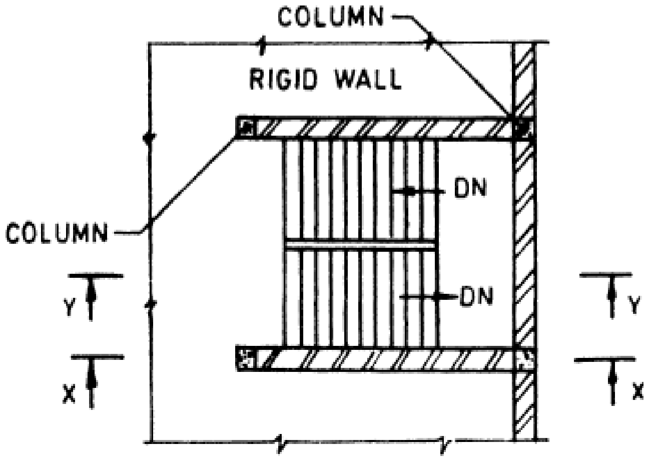


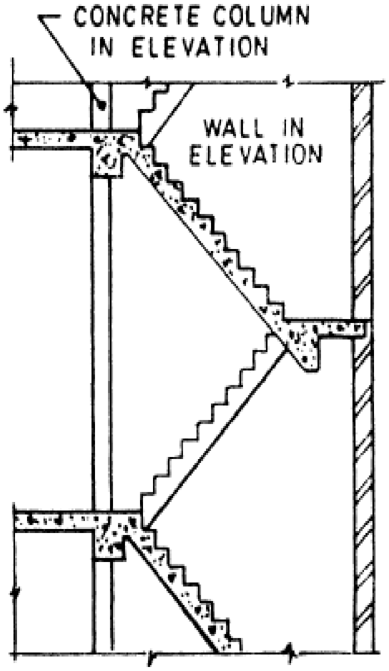
SECTION XX

ii) Built-in Staircase - When stairs are built monolithically with floors,

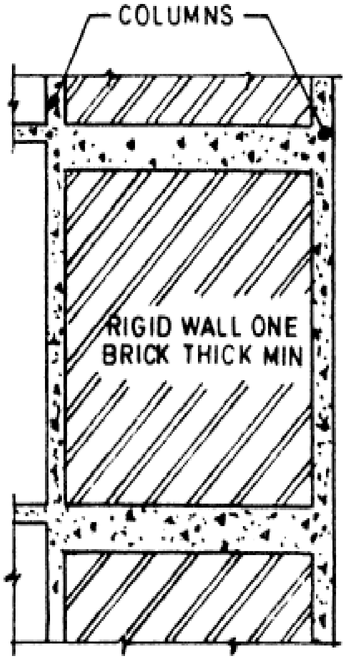
-they can be protected against damage
-by providing rigid walls at the stair opening.

-An arrangement, in which the staircase is enclosed by two walls, is given in Fig.
-In such cases, the joints, as mentioned respect of separated staircases, will not be necessary.
-The two walls mentioned in enclosing
the staircase,
-shall extend through the entire height of the stairs and to the building foundations.





SECTION YY



SECTION XX

10. TYPES OF CONSTRUCTION

a) Framed construction

This type of construction consists of frames with flexible (hinged) joints and bracing
members. Steel multistoried building or industrial frames and timber construction

b) Box type construction

This type of construction consists of prefabricated or in situ masonry, concrete or reinforced concrete wall along both the axes of the building. The walls support vertical loads and also act as shear walls for horizontal loads acting in any direction. All traditional masonry construction falls under this category.

10.1 CATEGORIES OF BUILDINGS

For the purpose of specifying the earthquake resisting features in masonry and wooden buildings, the buildings have beencategorised in five categories A to E based on the value of αh given by:

$$\alpha h = \alpha o \, I.\beta$$

αh = design seismic coefficient for the building,

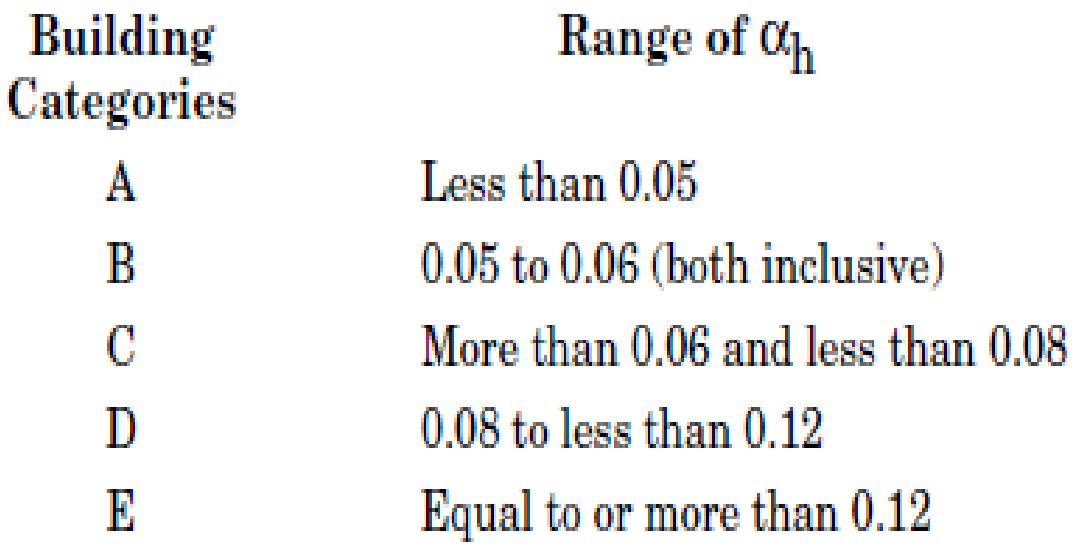
αo = basic seismic coefficient for the seismiczone in which the building is located

I = importance factor applicable to the building

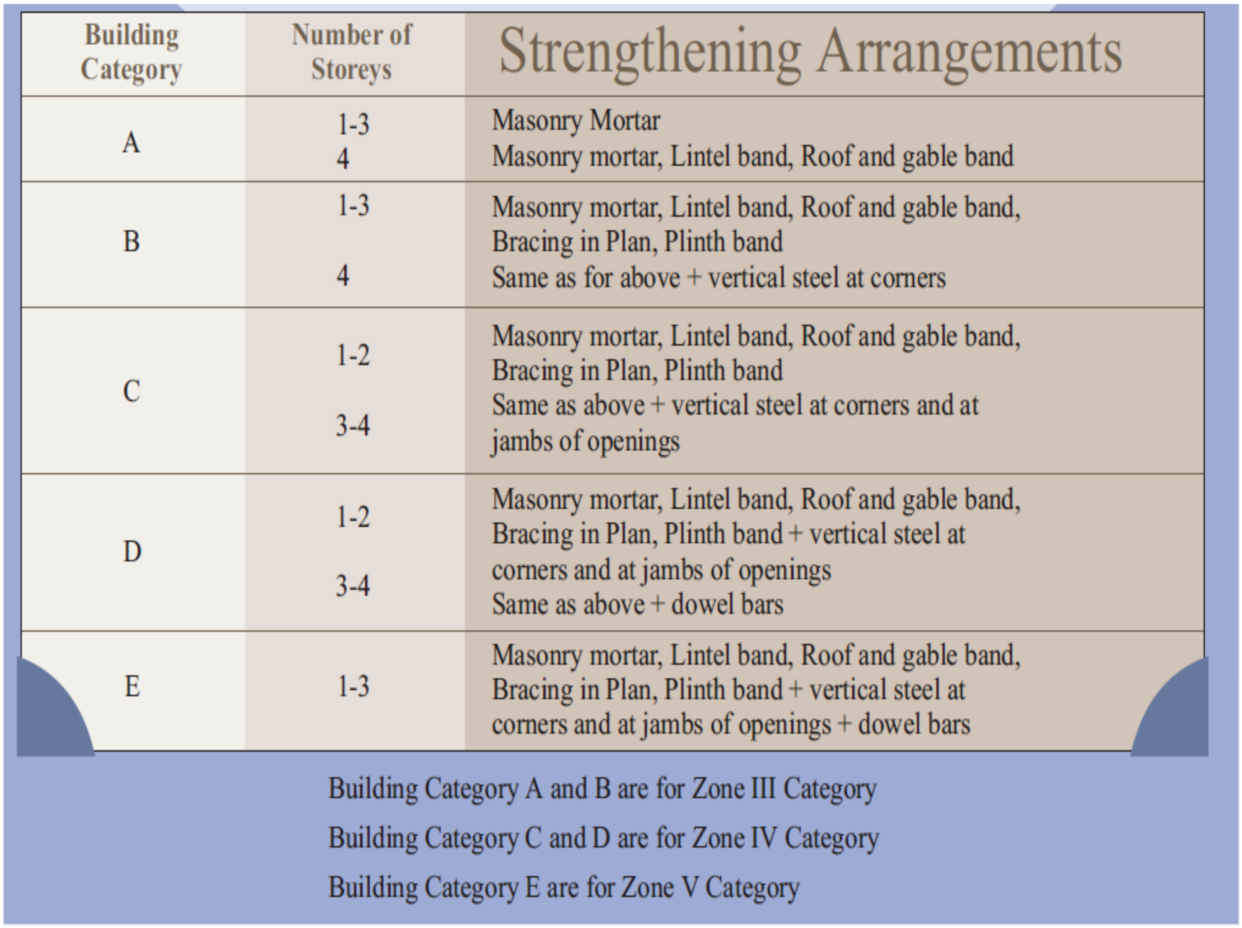
β = soil foundation factor

IS 1893 : 1984).

Building Categories for Earthquake Resisting



Building Categories	Range of α_h
A	Less than 0.05
B	0.05 to 0.06 (both inclusive)
C	More than 0.06 and less than 0.08
D	0.08 to less than 0.12
E	Equal to or more than 0.12



Building Category	Number of Storeys	Strengthening Arrangements
A	1-3 4	Masonry Mortar Masonry mortar, Lintel band, Roof and gable band
B	1-3 4	Masonry mortar, Lintel band, Roof and gable band, Bracing in Plan, Plinth band Same as for above + vertical steel at corners
C	1-2 3-4	Masonry mortar, Lintel band, Roof and gable band, Bracing in Plan, Plinth band Same as above + vertical steel at corners and at jambs of openings
D	1-2 3-4	Masonry mortar, Lintel band, Roof and gable band, Bracing in Plan, Plinth band + vertical steel at corners and at jambs of openings Same as above + dowel bars
E	1-3	Masonry mortar, Lintel band, Roof and gable band, Bracing in Plan, Plinth band + vertical steel at corners and at jambs of openings + dowel bars

Building Category A and B are for Zone III Category

Building Category C and D are for Zone IV Category

Building Category E are for Zone V Category

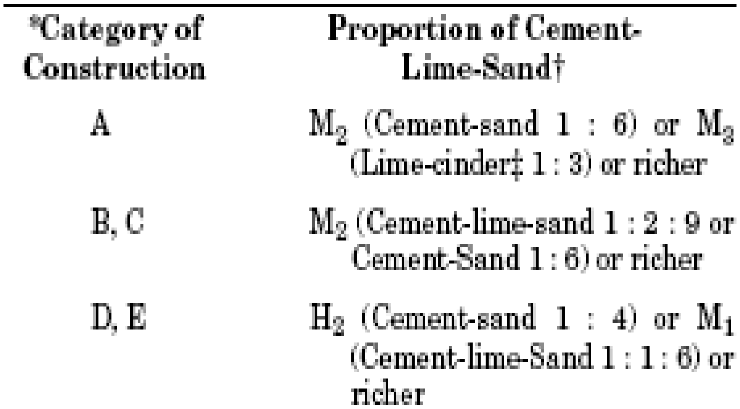
11 Masonry Units

Well burnt bricks conforming to IS 1077: 1992 or solid concrete blocks conformingTo IS 2185 (Part 1) : 1979 and having a crushing strength not less than 3.5 MPa shallbe used. The strength of masonry unit required shall depend on the number of storeys andthickness of walls

Squared stone masonry, stone block masonry or hollow concrete block masonry, as specified in IS 1597 (Part 2) : 1992 of adequate strength, may also be used

11.1 Mortar

Mortars, such as those of equivalent specification, shall preferably be used for masonry construction for various categories of buildings



*Category of Construction	Proportion of Cement-Lime-Sand†
A	M_2 (Cement-sand 1 : 6) or M_3 (Lime-cinder‡ 1 : 3) or richer
B, C	M_2 (Cement-lime-sand 1 : 2 : 9 or Cement-Sand 1 : 6) or richer
D, E	H_2 (Cement-sand 1 : 4) or M_1 (Cement-lime-Sand 1 : 1 : 6) or richer

Where steel reinforcing bars are provided in masonry the bars shall be embedded with adequate cover in cement sand mortar not leaner than 1 : 3 (minimum clear cover 10 mm) or in cement concrete of grade M15 (minimum clear cover 15 mm or bardiameter whichever more), so as to achieve good bond and corrosion resistance.

11.2 Walls

Masonry bearing walls built in mortar, as specified inunless rationally designedas reinforced masonry shall not be built ofgreater height than 15 m subject to a maximumof four storeys when measured from the meanground level to the roof slab or ridge level. Themasonry bearing walls shall be reinforced. The bearing walls in both directions shallbe straight and symmetrical in plan as far aspossible.The wall panels formed between crosswalls and floors or roof shall be checked fortheir strength in bending as a plate or as avertical strip subjected to the earthquake forceacting on its own mass.

11.3 Masonry Bond

For achieving full strength of masonry, the usual bonds specified for masonry should be followed so that the vertical joints are broken properly from course to course. To obtain full bond between perpendicular walls, it is necessary to make a slopping (stepped) joint by making the corners first to a height of 600 mm and then building the wall in between them. Otherwise, the toothed joint should be made in both the walls alternatively in lifts of about 450 mm.

Ignoring tensile strength, free standing walls shall be checked against overturning under the action of design seismic coefficient ⟨h allowing for a factor safety of 1.5.

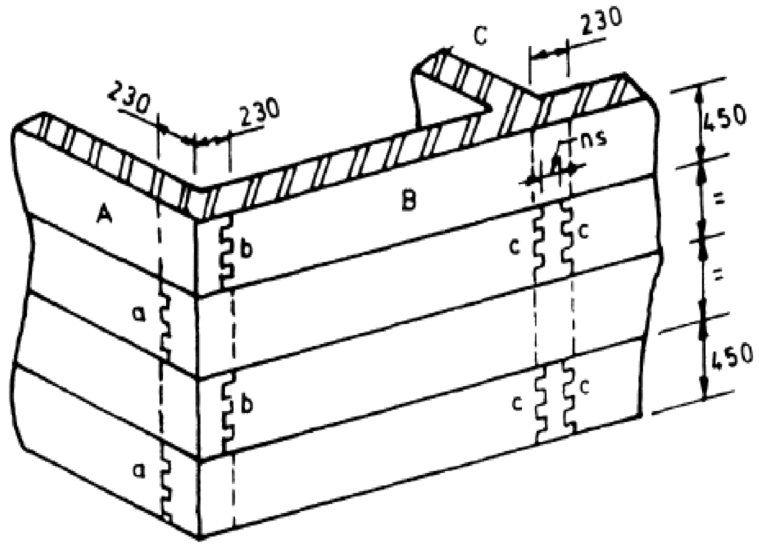
Panel or filler walls in framed buildings shall be properly bonded to surrounding framing members by means of suitable morta or connected through dowels. If the walls are so bonded they shall be checked

Openings in Bearing Walls

Door and window openings in walls reduce their lateral load resistance and hence, should preferably be small and more centrally located. The guidelines on the size and position
Of opening.

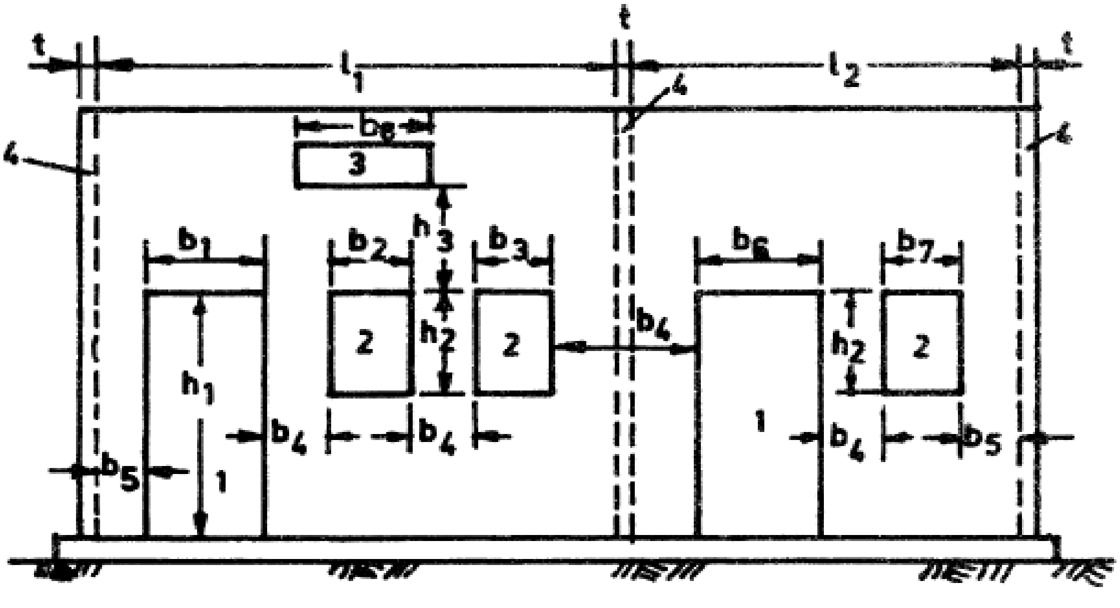
Openings in any storey shall preferably have their top at the same level so that a continuous band could be provided over them, including the lintels throughout the building.

Where openings do not comply with the guidelines of they should be strengthened by providing reinforced concrete or reinforcing the brickwork, with highstrength deformed (H.S.D.) bars of 8 mm dia butthe quantity of steel shall be increased at thejambs to comply with, if so required.If a window or ventilator is to be projectedout, the projection shall be in reinforcedmasonry or concrete and well anchored.If an opening is tall from bottom to almosttop of a storey, thus dividing the wall into twoportions, these portions shall be reinforced withhorizontal reinforcement of 6 mm diameterbars at not more than 450 mm intervals, one oninner and one on outer face, properly tied tovertical steel at jambs, corners or junction ofwalls, where used. The use of arches to span over the openingsis a source of weakness and shall be avoided.Otherwise, steel ties should be provided.



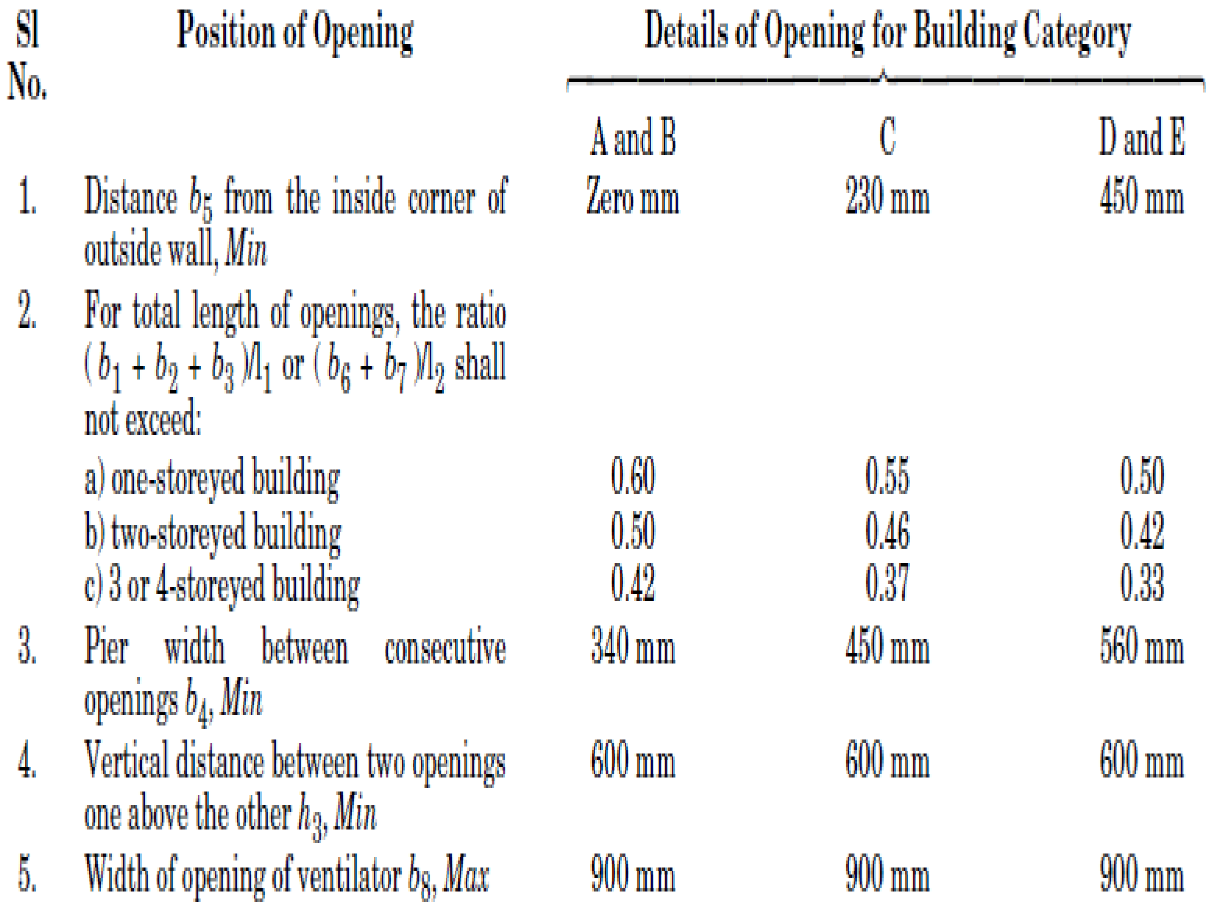
a, *b*, *c* = Toothed ioints in wall and *A*, *B*, *C*

ALTERNATING TOOTHED JOINTS IN WALLS AT CORNER AND T-JUNCTION



1. Door 2. Ventilator 3. Window 4. Cross wall

12. OPENINGS IN BEARING WALLS



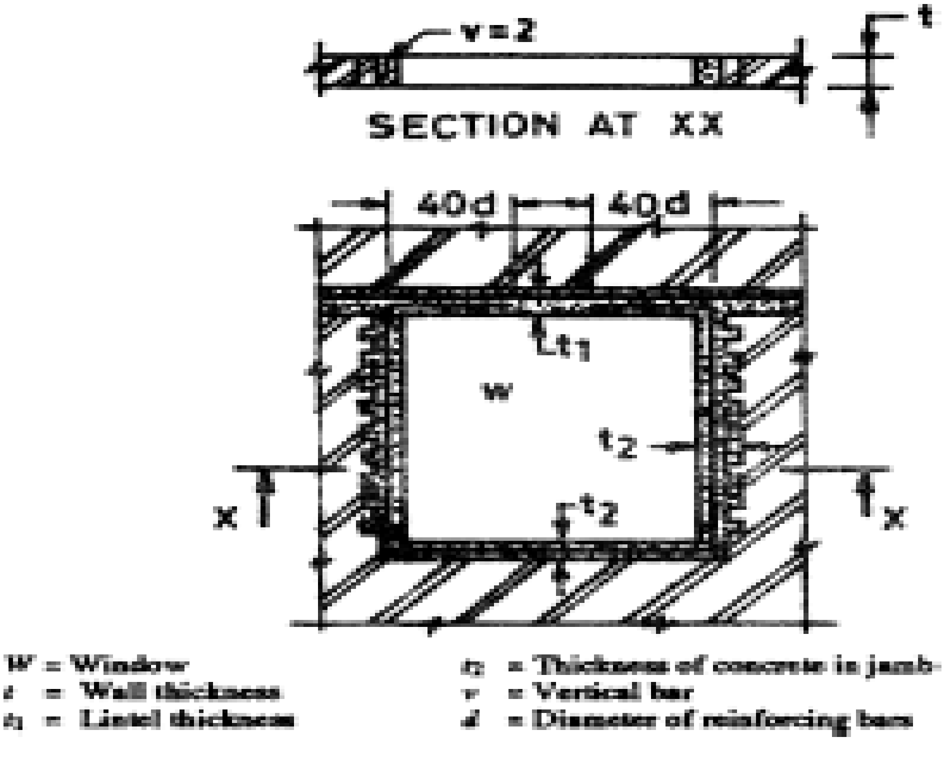
Sl No.	Position of Opening	Details of Opening for Building Category		
		A and B	C	D and E
1.	Distance b_5 from the inside corner of outside wall, *Min*	Zero mm	230 mm	450 mm
2.	For total length of openings, the ratio $(b_1 + b_2 + b_3)/l_1$ or $(b_6 + b_7)/l_2$ shall not exceed:			
	a) one-storeyed building	0.60	0.55	0.50
	b) two-storeyed building	0.50	0.46	0.42
	c) 3 or 4-storeyed building	0.42	0.37	0.33
3.	Pier width between consecutive openings b_4, *Min*	340 mm	450 mm	560 mm
4.	Vertical distance between two openings one above the other h_3, *Min*	600 mm	600 mm	600 mm
5.	Width of opening of ventilator b_8, *Max*	900 mm	900 mm	900 mm

12.1 Window openings

a two-storey modern cut-stone wall building near Bhuj, in town called Mirzapur. The building has cut-stone walls about 0.225 to 0.3m thick and has a 1st level concrete floor and a pitched timber roof. The window openings are not close to the edge and are also sensibly spaced. This is probably one of the main reasons why it survived with so little damage. Even so some vertical bending cracking has happened near to the corners, again due to out of plane shear forces. Many buildings which did not collapse suffered from severe diagonal cracking at their corners, some with partial collapse at corners, primarily because of window openings being too close to thecorner and because of lack of toothing between returns.

12.2 Window openings in infill panels

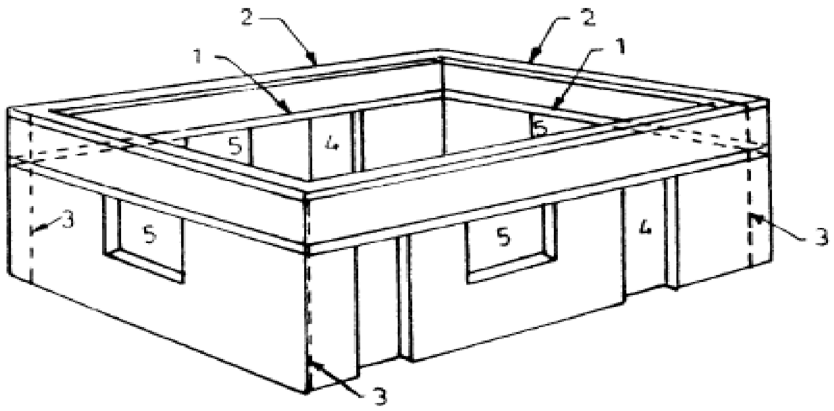
Large window and door openings severely undermined the ability of infill panels to act as nonstructural shear walls. These openings were placed too close to the corner columns of the building. Lintels were placed over the openings but did not extend over the length of the wall as isrecommended for seismic design. Consequently, wall panels experienced diagonal shear crackingwhich extended from the openings to the top and bottom of the solid walls, sometimes causing diagonal cracking of columns when no resistance was afforded by the wall, see Annex 2.Generally, the greatest damage occurred at ground floor level. Upper storeys survived withsurprising little damage (slight). Sometimes older RC buildings, modernized by adding an extra floor, suffered greater damage as columns were not properly connected to the original concrete frame and the structural mass wasaltered by adding this floor.



STRENGTHENING MASONRY AROUNDOPENING

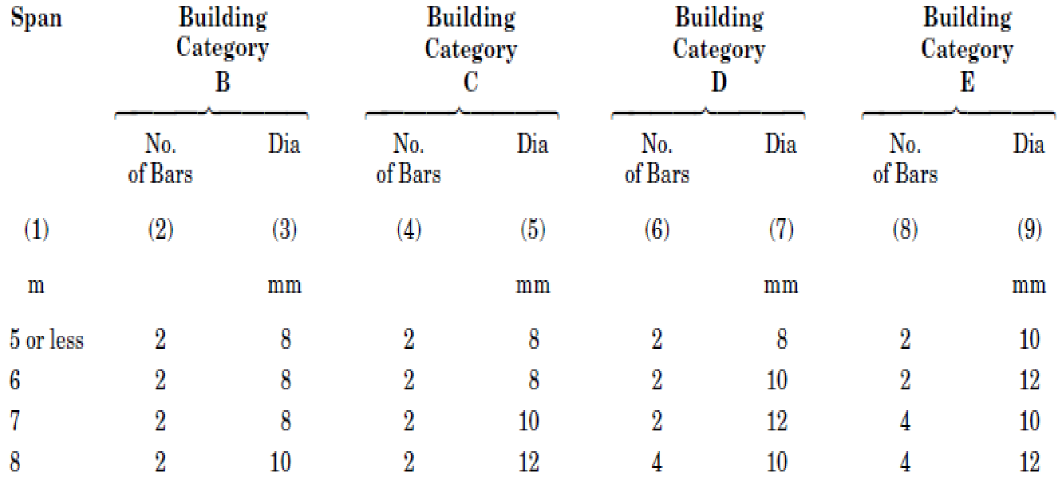
12.3 Section and Reinforcement of Band

The band shall be made of reinforced concrete of grade not leaner than M15 or reinforced brick-work in cement mortar not leaner than 1: 3. The bands shall be of the full width of the wall, not less than 75 mm in depth and reinforced with steel.



1. **Lintel band**
2. **Roof/Floor Band**
3. **Vertical bar**
4. **Door**
5. **Window**

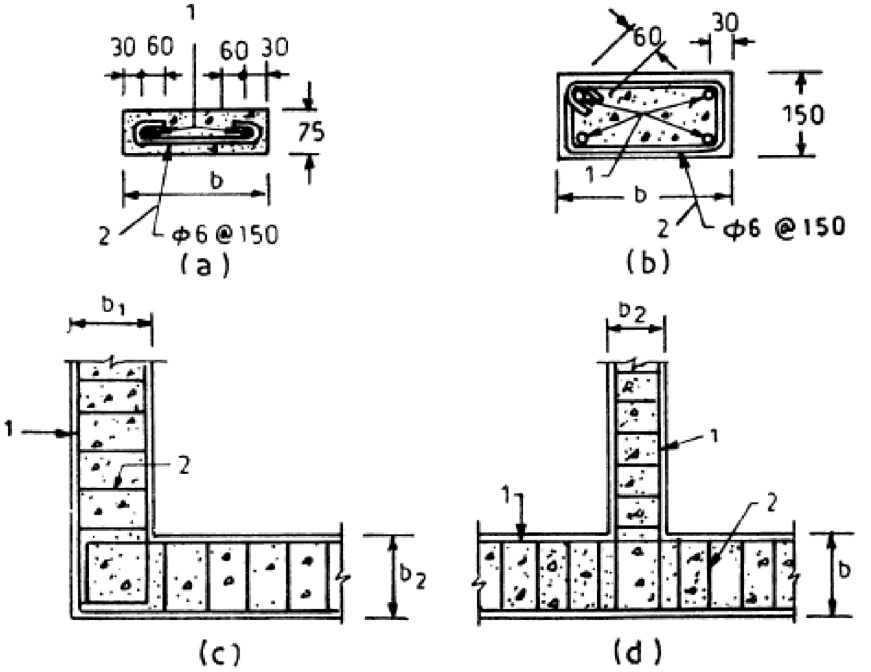
Recommended Longitudinal Steel in Reinforced Concrete Bands



Span	Building Category B		Building Category C		Building Category D		Building Category E	
	No. of Bars	Dia	No. of Bars	Dia	No. of Bars	Dia	No. of Bars	Dia
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
m		mm		mm		mm		mm
5 or less	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

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 Def. Bar dia	8	10	12	16	20
Mild Steel Plain bar dia	10	12	16	20	25



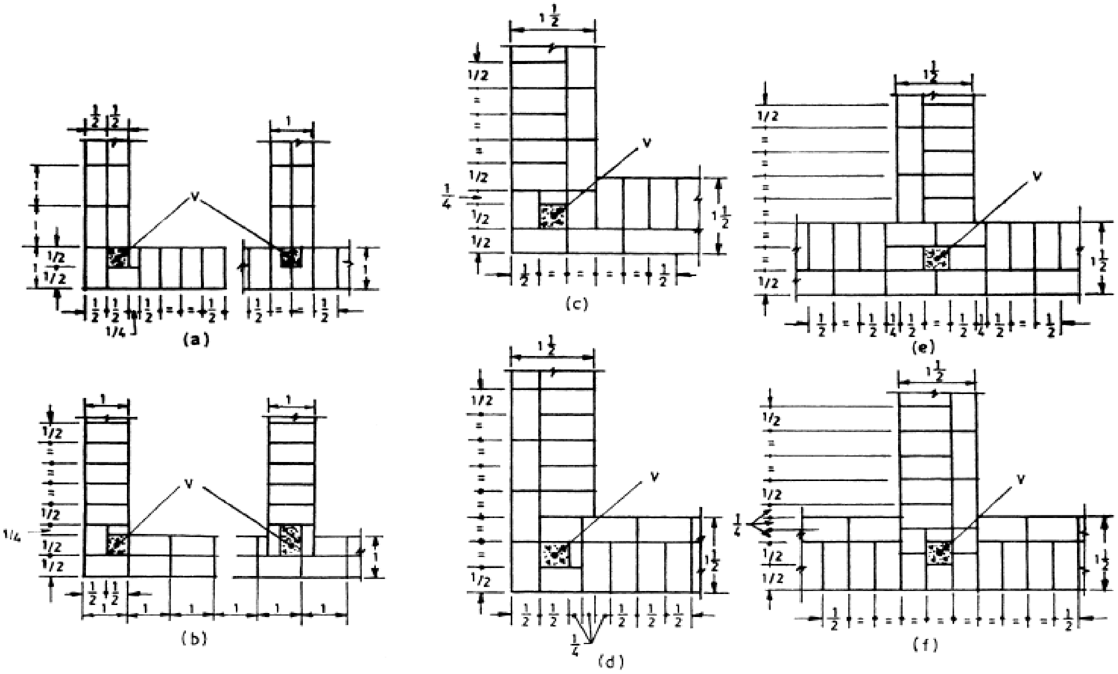
1. **Longitudinal bars**
2. **Lateral ties**

b_1, b_2 — Wall thickness

a) **Section of band with two bars**
b) **Section of band with four bars**
c) **Structural plan at corner junction**
d) **Section plan at T-junction of walls**

All dimensions in millimetres.

REINFORCEMENT AND BENDING DETAIL IN R. C. BAND



1 — One-brick length, ½ — Half-brick length, V — Vertical steel bar with mortar/concrete filling in pocket.
(a) and (b) — Alternate courses in one brick wall.
(c) and (d) Alternate courses at corner junction of 1½-brick wall.
(e) and (f) Alternate courses at T-junction of 1½-brick wall.

TYPICAL DETAILS OF PROVIDING VERTICAL STEEL BARS IN BRICK MASONRY

13 How Architectural Features Affect Buildings During Earthquakes?

13.1 Importance of Architectural Features

The behavior 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 unfavorable features are avoided and a good building configuration is chosen. The importance of the configuration of a building was aptly summarized 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."*

13.2 Architectural Features

A desire to create an aesthetic and functionally efficient structure drives architects to conceivewonderful 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.

13.3 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 likewarehouses

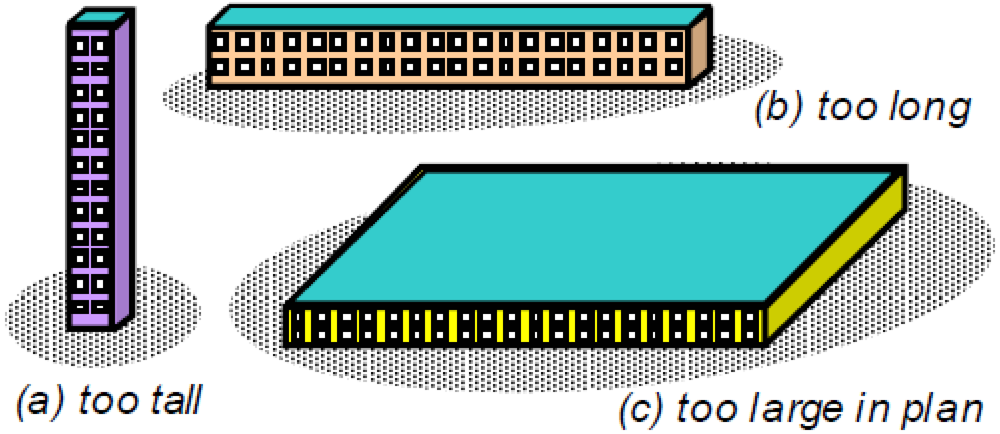


Figure 1: Buildings with one of their overall sizes much larger or much smaller than the other two, do not perform well during earthquakes.

13.4 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, Hand + shaped in plan (Figure 2b), have sustained significant damage. Many times, the bad effects ofthese interior corners in the plan of buildings are avoided by making the buildings in two parts. Forexample, 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. A discussion in this aspect will be presented in the upcoming *IITK-BMTPC Earthquake Tip7* on *How Buildings Twist during Earthquakes?*

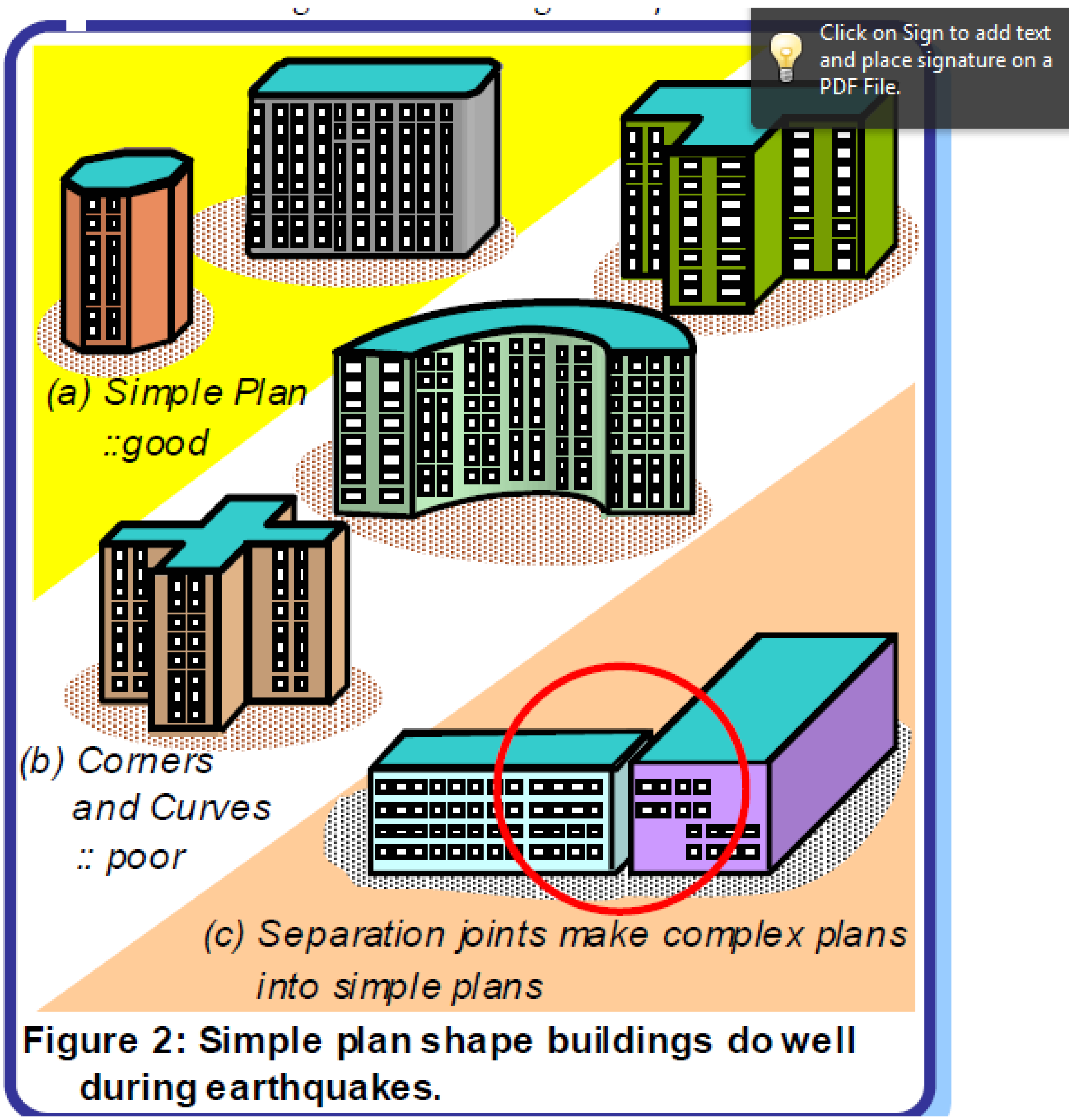


Figure 2: Simple plan shape buildings do well during earthquakes.

13.5 Vertical Layout of Buildings:

The earthquake forces developed at different floor levels in a buildingneed 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 story's wider than the rest) cause a sudden jump inearthquake forces at the level of discontinuity (Figure 3a). Buildings that have fewer columns or walls in aparticularstorey or with unusually tall storey (Figure 3b), tend to damage or collapse which is initiated ingure 1c), theThat story. Many buildings with an open ground storey intended for parking collapsed or were severelydamaged in Gujarat during the 2001 Bhuj earthquake. Buildings on sloppy ground have unequal heightcolumns 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.

13.6 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.

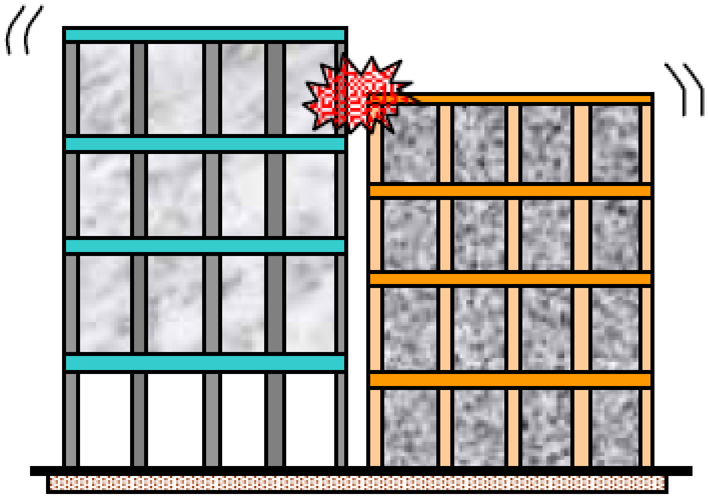


Figure 4: Pounding can occur between adjoining buildings due to horizontal vibrations of the two buildings.

Building Design and Codes…

Looking ahead, of course, one will continue tomake buildings interesting rather than monotonous. However, this need not be done at the cost of poorbehavior and earthquake safety of buildings.Architectural features that are detrimental toearthquake response of buildings should be avoided. Ifnot, they must be minimized. When irregular features are included in buildings, a considerably higher leveler engineering effort is required in the structuraldesign and yet the building may not be as good as onewith simple architectural features.Decisions made at the have made greater difference, than accurate determination of code specified design forces.

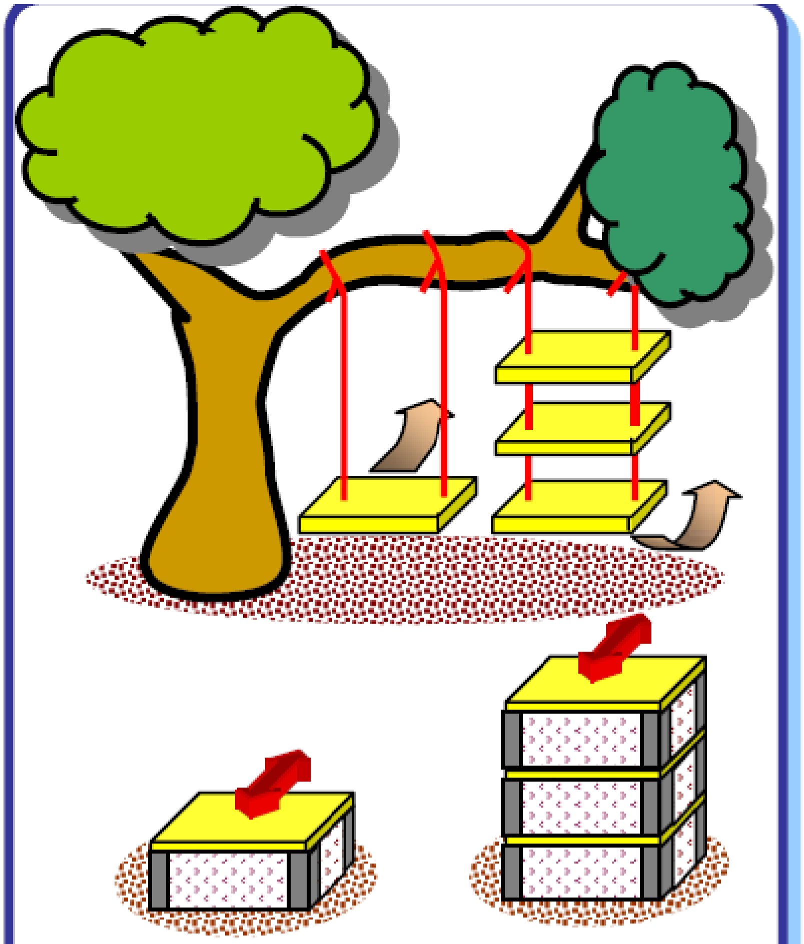
Resource Material:-

Arnold,C., and Reitherman,R., (1982), *Building Configuration andSeismic Design*, John Wiley, USA.Lagorio,H,J, (1990), *EARTHQUAKES An Architect's Guide to Non- Structural Seismic Hazard*, John Wiley & Sons, Inc., USA.

14 How Buildings Twist During Earthquakes?

14.1VWhy a Building Twists:-

In your childhood, you must have sat on a rope swing - a wooden cradle tied with coir ropes to thesturdy branch of an old tree. The more modern versions of these swings can be seen today in the children's parks in urban areas; they have a plastic cradle tied with steel chains to a steel framework.Consider a rope swing that is tied identically with two equal ropes. It swings equally, when you sit in themiddle of the cradle. Buildings too are like these rope swings; just that they are inverted swings (Figure 1). The vertical walls and columns are like the ropes, and the floor is like the



(a) Single-storey building *(b) Three-storey building*

Figure 1: Rope swings and buildings, both swing back-and-forth when shaken horizontally. The former are hung from the top, while the latter are raised from the ground.

cradle. Buildings vibrate back and forth during earthquakes. Buildings with more than one storey are like rope swings with more than one cradle. Thus, if you see from sky, a building with identical vertical members and that are uniformly placed in the two horizontal directions, when shaken at its base in a certain direction, swings back and forth such that all points on the floor movehorizontally by the same amount in the direction in which it is shaken (Figure 2).

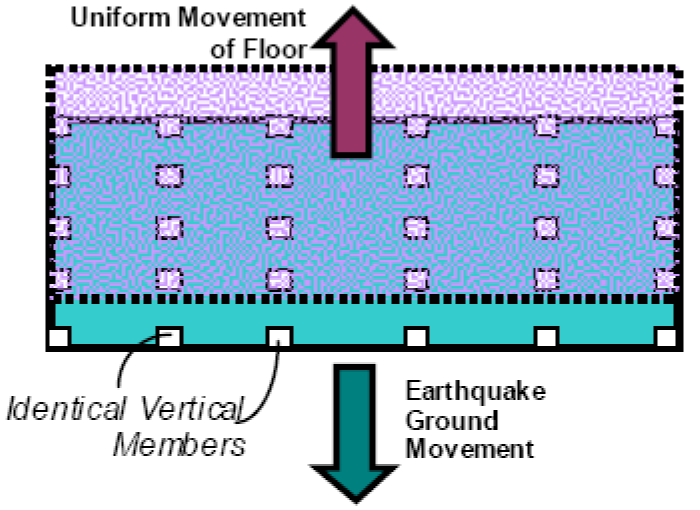


Figure 2: Identical vertical members placed uniformly in plan of building cause all points on the floor to move by same amount.

Again, let us go back to the rope swings on the tree: if you sit at one end of the cradle, it *twists* (*i.e.*, moves more on the side you are sitting). This also happens sometimes when more of your friends bunch together and sit on one side of the swing. Likewise, if the mass on the floor of a building is more on one side (for instance, one side of a building may have a storage or a library), then that side of the building moves more underground movement (Figure 3). This building moves such that its floors displace horizontally as well as rots

15 How Buildings Twist During Earthquakes?

Once more, let us consider the rope swing on the tree. This time let the two ropes with which the cradle is tied to the branch of the tree be different in length. Such a swing also twists even if you sit in the middle (Figure 4a). Similarly, in buildings with unequal vertical members (i.e., columns and/or walls) also the floors twist about a vertical axis (Figure 4b) and displace horizontally. Likewise, buildings, which havewalls only on two sides (or one side) and thin columns along the other, twist when shaken at the ground level (Figure 4c). Buildings that are irregular shapes in plan tend to twist under earthquake shaking. For example, in a propped overhanging building (Figure 5), the overhanging portion swings on the relatively slender columns under it. The floors twist and displace horizontally.

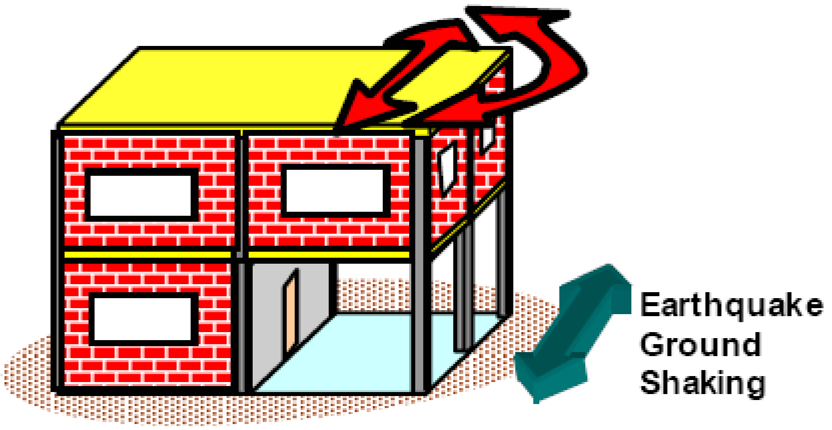


Figure 5: One-side open ground storey building twists during earthquake shaking.

15.1 What Twist does to Building Members?

Twist in buildings, called torsion by engineers, makes different portions at the same floor level to move horizontally by different amounts. This induces more damage in the columns and walls on the side that moves more (Figure 6). Many buildings have been severely affected by this excessive torsignal behavior during past earthquakes. It is best to minimize (if not completely avoid) this twist by ensuring that buildings have symmetry in plan (i.e., uniformly distributed mass and uniformly placed vertical members). If this twist cannot be avoided, special calculations need to be done to account for this additional shear forces in the design of buildings; the Indian seismic code (IS 1893, 2002) has provisions for such calculations. But, for sure, buildings with twist will perform poorly during strong earthquake shaking. Resource

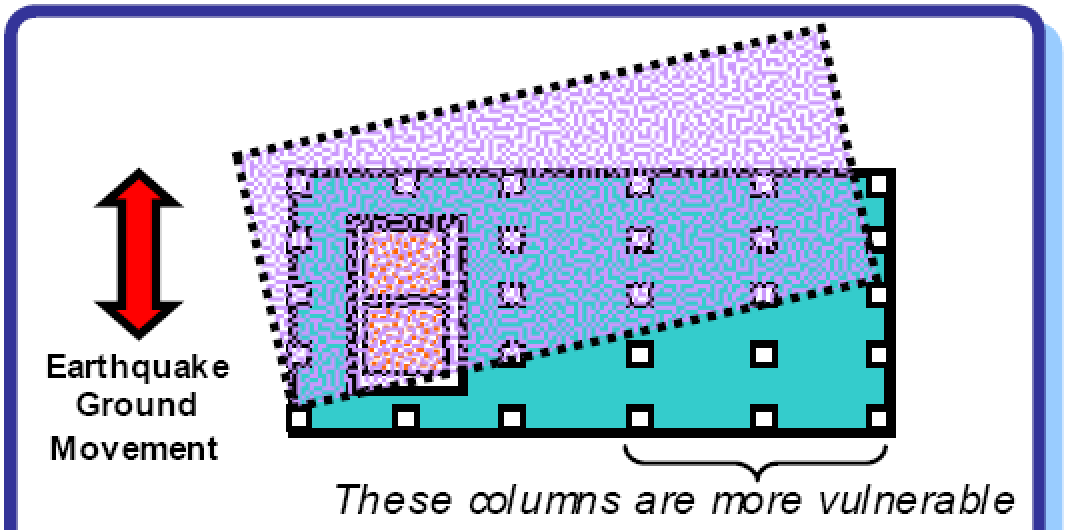


Figure 6: Vertical members of buildings that move more horizontally sustain more damage.

Material

Arnold,C., and Reitherman,R., (1982), Building Configuration and Seismic Design, John Wiley, USA.
Structural Seismic Hazard, John Wiley & Sons, Inc., USA.Next Upcoming Tip

15.2 What is the Seismic Design Philosophy for Buildings?

Authored by: C.V.R.MurtyIndian Institute of Technology Kanpur Kanpur, India
Sponsored by: Building Materials and Technology Promotion Council, New Delhi, India this release is a property of IIT Kanpur and BMTPC New Delhi. I t may be reproduced without changing its contents and with due acknowledgement. Suggestions/comments may be sent to: eqtips@iitk.ac.in. Visit www.nicee.org or www.bmtpc.org, to see previous IITK-BMTPC Earthquake Tips. October 2002 These columns are more vulnerable Figure 6: Vertical members of buildings that move more horizontally sustain more damage. Earthquake Ground Movement
Figure 5: One-side open ground storey building twists during earthquake shaking. Earthquake Ground Shaking Figure 4: Buildings have unequal vertical members;

they cause the building to twist about a vertical axis. Vertical Axis about which building twists Earthquake Ground Movement
(b) Building on slopy ground
(a) Swing with unequal ropes
(c) Buildings with walls on two/one sides (in plan)
Wall Columns ColumnsWall Wall 14

15.3 What is the Seismic Design Philosophy for Buildings?

Construction The Earthquake Problem Severity of ground shaking at a given location during an earthquake can be minor, moderate and strong. Relatively speaking, minor shaking occurs frequently, moderate shaking occasionally and strong shaking rarely. For instance, on average annually about 800 earthquakes of magnitude 5.0-5.9 occur in the world while the number is only about 18 for magnitude range 7.0-7.9 (see Table 1 of IITK-BMTPC Earthquake Tip 03 at www.nicee.org). So, should we design and construct a building to resist that rare earthquake shaking that may come only once in 50 years or even once in 2000 years at the chosen project site, even though the life of the building itself may be only 50 or 100 years? Since it costs money to provide additional earthquake safety in buildings, a conflict arises: Should we do away with the design of buildings for earthquake effects? Or should we design the buildings to be "earthquake proof" wherein there is no damage during the strong but rare earthquake shaking? Clearly, the former approach can lead to a major disaster, and the secondaapproach is too expensive. Hence, the designphilosophy should lie somewhere in between these two extremes. Earthquake-Resistant Buildings the engineers do not attempt to make earthquakeproof 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 inearthquake-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.

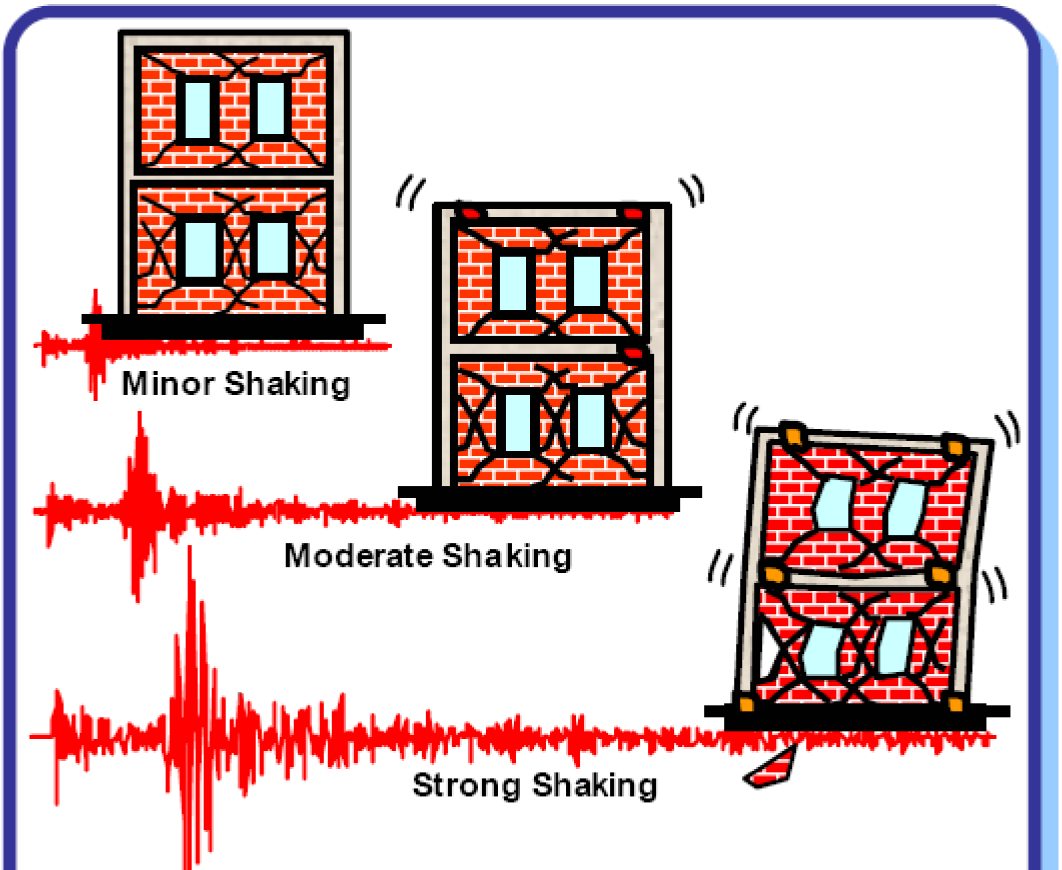


Figure 1: Performance objectives under different intensities of earthquake shaking – *seeking low repairable damage under minor shaking and collapse-prevention under strong shaking.*

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

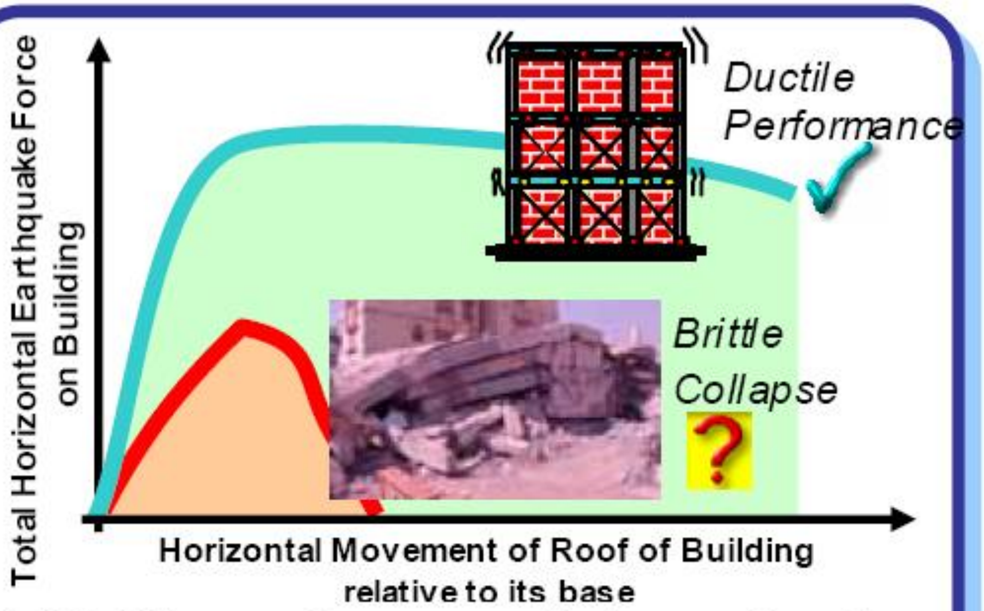
earthquake. These structures must sustain very little damage and should be designed for a higher level of earthquake protection. Collapse of dams during earthquakes can cause flooding in the downstream reaches, which itself can be a secondary disaster. Therefore, dams (and similarly, nuclear power plants) 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 Figure 1: Performance objectives under different intensities of earthquake shaking – seeking low repairable damage under minor shaking and
collapse-prevention under strong shaking. Minor Shaking Moderate Shaking
Strong Shaking15

16 What is the Seismic design Philosophy for Buildings?

Damage is unavoidable. Different types of damageMainly visualized though 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 earthquakeresistantbuildings.

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 capable 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 overcurrent.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 behavior duringearthquakes. To do this, let us first understand how different materials behave. Consider white chalk used 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 to -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 detailing at theselocations to ensure ductile behavior of the building strives to predetermine



(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***.**

good.

Resource Material

Naeim,F., Ed., (2001), The Seismic Design Handbook, Kluwer AcademicPublishers, Boston, USA. Ambrose,J., and Vergun,D., (1999), Design for Earthquakes, John Wiley & Sons, Inc.,

17 How to Make Buildings Ductile for Good Seismic Performance?

17.1 Construction Materials

In India, most non-urban buildings are made in masonry. In the plains, masonry is generally made of burnt clay bricks and cement mortar. However, in hilly areas, stone masonry with mud mortar is more prevalent; but, in recent times, it is being replaced with cement mortar. Masonry can carry loads that cause compression (i.e., pressing together), but can hardly take load that causes tension (i.e., pulling apart) (Figure 1).

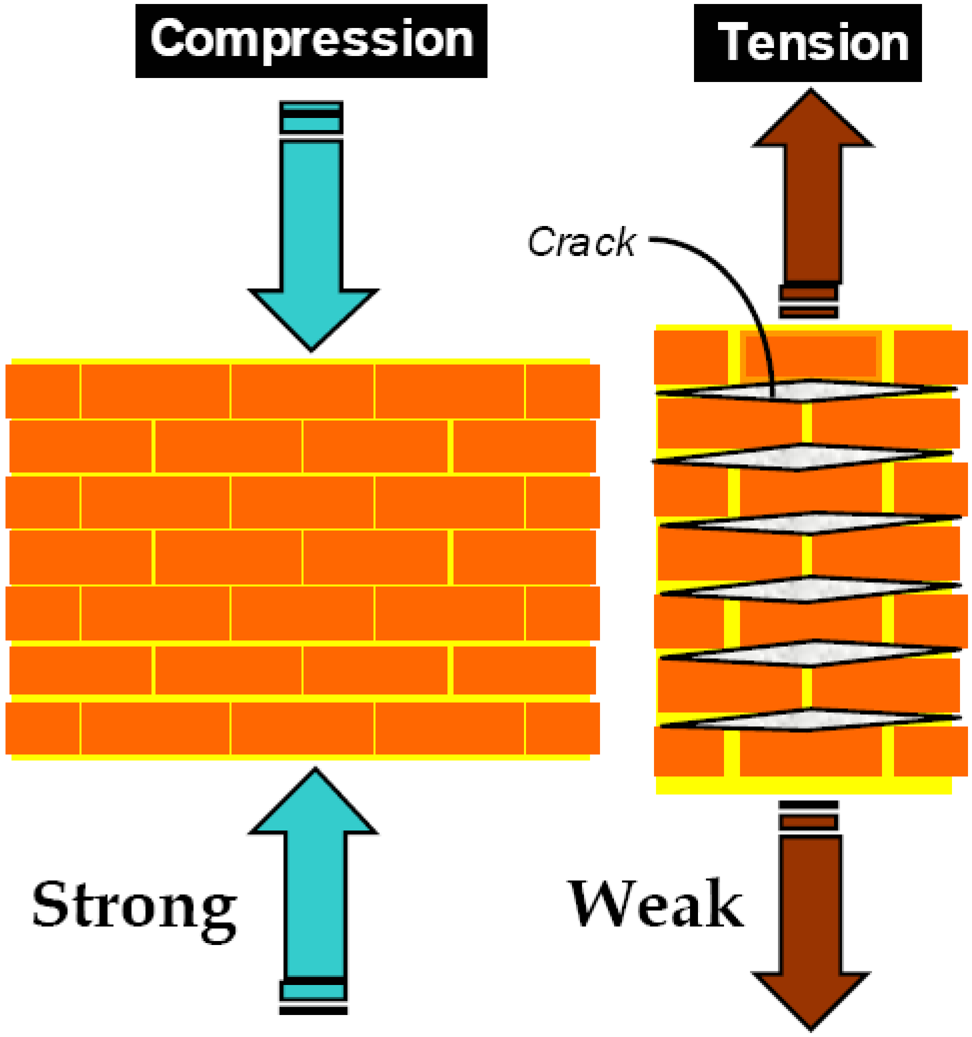


Figure 1: Masonry is strong in compression but weak in tension.

Concrete is another material that has been popularly used in building construction particularly over the last four decades. Cement concrete is made of crushed stone pieces (called aggregate), sand, cement and water mixed in appropriate proportions. Concrete is much stronger than masonry under compressive loads, but again its behavior in tension is poor. The properties of concrete critically depend on the amount of water used in making concrete; too much and too little water,

both can cause havoc. In general, both masonry and concrete are brittle, and fail suddenly. Steel is used in masonry and concrete buildings as reinforcement bars of diameter ranging from 6mm to 40mm. Reinforcing steel can carry both tensile and compressive loads. Moreover, steel is a ductile material. This important property of ductility enables steel bars to undergo large elongation before breaking. Concrete is used in buildings along with steel reinforcement bars. This composite material is called reinforced cement concrete or simply reinforced concrete (RC). The amount and location of steel in a member
should be such that the failure of the member is by steel reaching its strength in tension before concrete reaches its strength in compression. This type of failure is ductile failure, and hence is preferred over a failure where concrete fails first in compression. Therefore, contrary to common thinking, providing too much steel in RC buildings can be harmful even!!

17.2 Capacity Design Concept

Let us take two bars of same length and crosses ctionalarea - one made of a ductile material and another of a brittle material. Now, pull these two bars until they break!! You will notice that the ductile bar elongates by a large amount before it breaks, while the brittle bar breaks suddenly on reaching its maximum strength at a relatively small elongation (Figure 2). Amongst the materials used in building construction, steel is ductile, while masonry and concrete

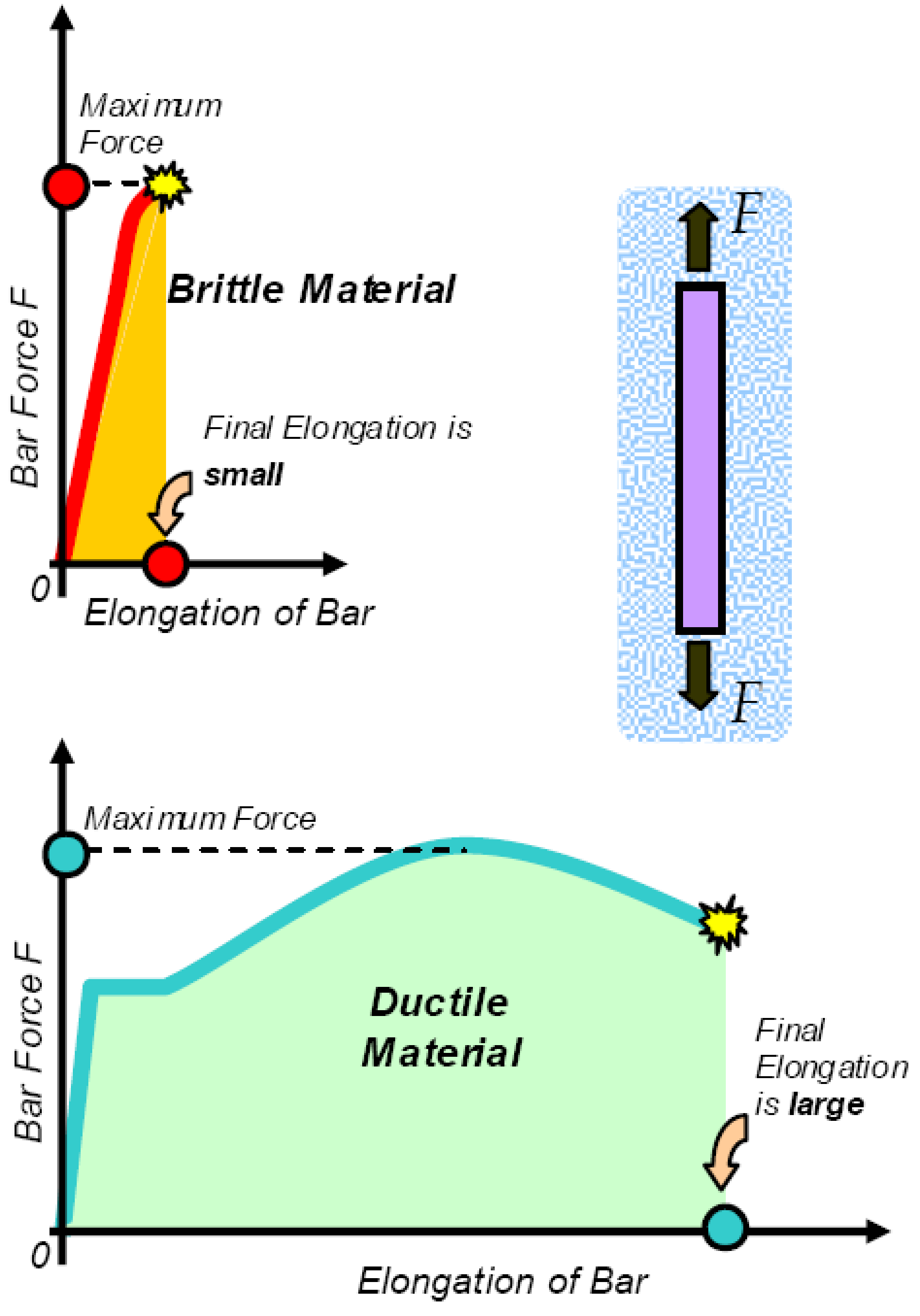


Figure 2: Tension Test on Materials – *ductile versus brittle materials*.

are brittle.

17.3 How to Make Buildings Ductile for Good Seismic Performance?

Now, let us make a chain with links made of brittle and ductile materials (Figure 3). Each of these links will fail just like the bars shown in Figure 2. Now, hold the last link at either end of the chain and apply a force Fascine the same force F is being transferred through a the links, the force in each link is the same, i.e., F. Asmore and more forces applied, eventually the chainwill break when the weakest link in it breaks. If theductile link is the weak one (i.e., its capacity to take load is less), then the chain will show large final elongation. Instead, if the brittle link is the weak one, then the chain will fail suddenly and show small final elongation. Therefore, if we want to have such a ductile chain, we have to make the ductile link to be the weakest link.

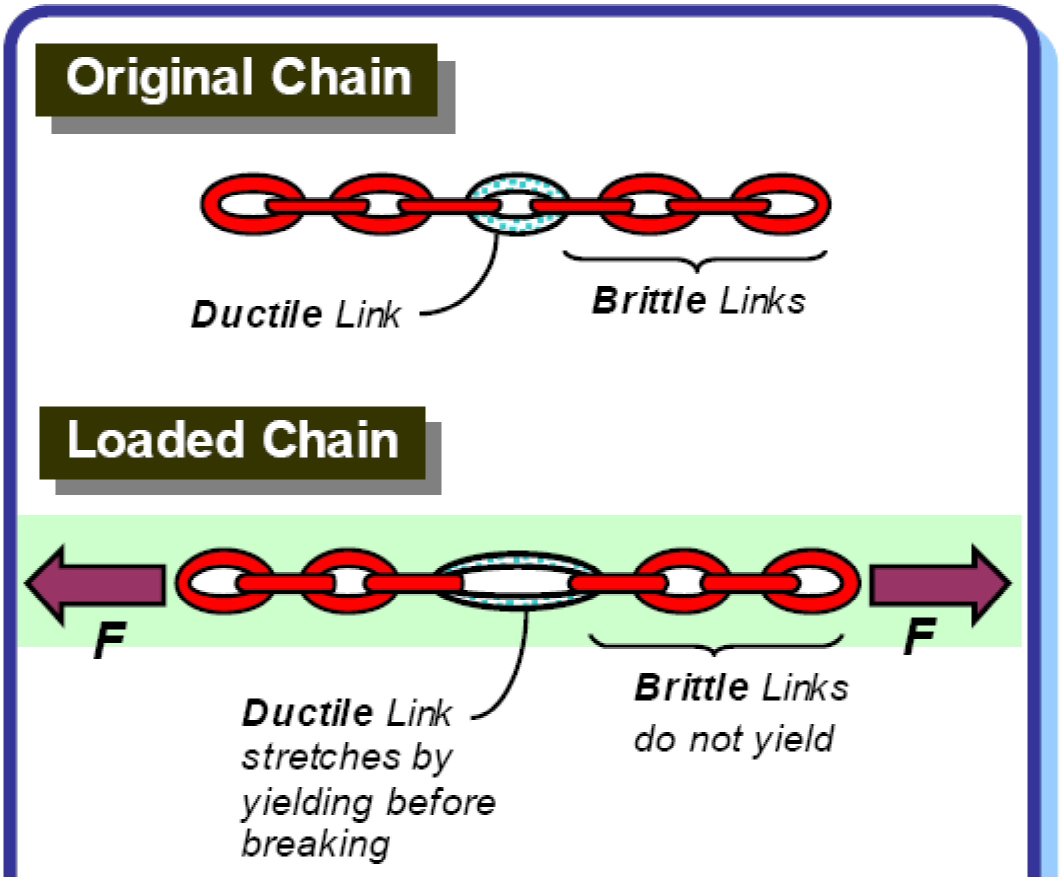


Figure 3: Ductile chain design.

17.4 **Earthquake-Resistant Design of Buildings**

Buildings should be designed like the ductile chain. For example, consider the common urban residential apartment construction – the multi-storeybuilding made of reinforced concrete. It consists of horizontal and vertical members, namely beams and columns. The seismic inertia forces generated at its floor levels are transferred through the various beams and columns to the ground. The correct buildingcomponents need to be made ductile. The failure of a column can affect the stability of the whole building, but the failure of a beam causes localized effect. Therefore, it is better to make beams to be the ductile weak links than columns. This method of designing RC buildings is called the strong-column weak-beam design method (Figure 4).

By using the routine design codes (meant for design against non-earthquake effects), designers may not be able to achieve a ductile structure. Special design provisions are required to help designers improve the ductility of the structure. Such provisions are usually put together in the form of a special seismic designcode, e.g., IS:13920-1993 for RC structures. These codes also ensure that adequate ductility is provided in the members where damage is expected

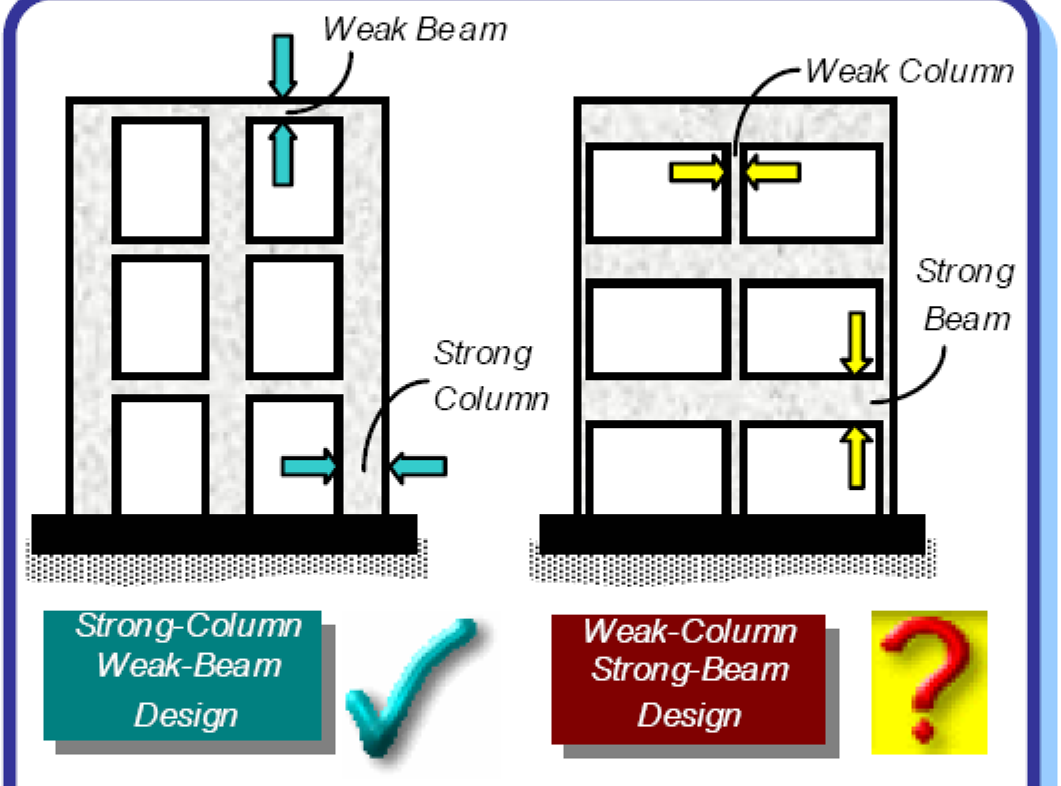


Figure 4: Reinforced Concrete Building Design: *the beams must be the weakest links and not the columns – this can be achieved by appropriately sizing the members and providing correct amount of steel reinforcement in them.*

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17.5 Quality Control in Construction

he capacity design concept in earthquakeresistantdesign of buildings will fail if the strengths of the brittle links fall below their minimum assured values. The strength of brittle construction materials, like masonry and concrete, is highly sensitive to the quality of construction materials, workmanship, supervision, and construction methods. Similarly, special care is needed in construction to ensure that the elements meant to be ductile are indeed provided with features that give adequate ductility. Thus, strict adherence to prescribed standards of construction materials and construction processes is essential in assuring an earthquake-resistantbuilding. Regular testing of construction materials at qualified laboratories (at site or away), periodic training of workmen at professional training houses, and on-site

Evaluations of the technical work are elements of good quality control.

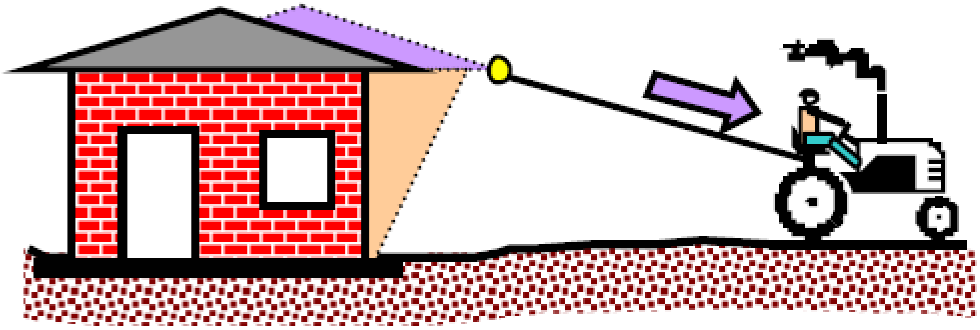
Resource Material

Paulay,T., and Priestley,M.J.N., (1992), Seismic Design of Reinforced Concrete Buildings and Masonry, John Wiley, USA. Mazzolani, F.M., and Piluso,V., (1996), Theory and Design of Seismic- Resistant Steel Frames, E&FN Spoon, UK.

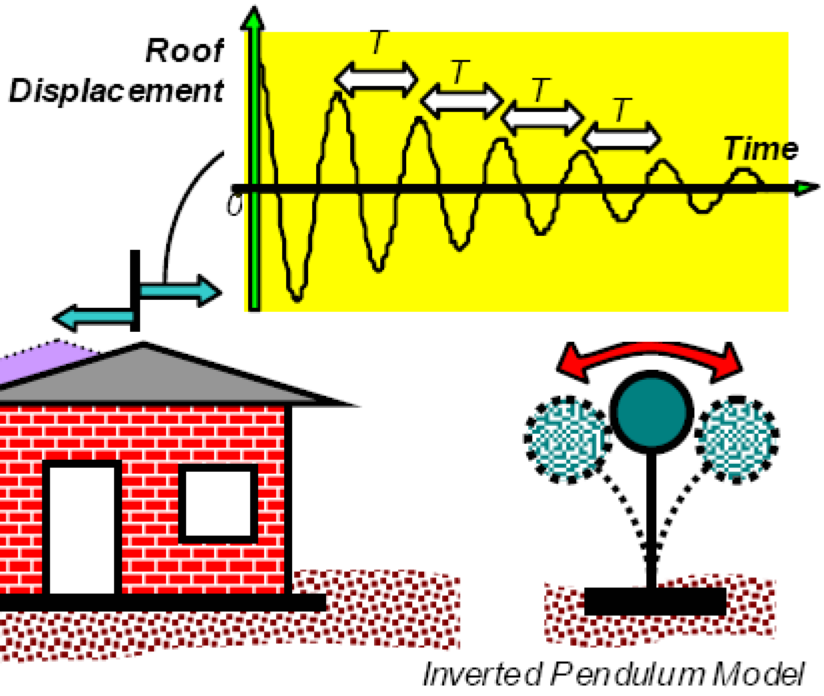
18 How Flexibility of Buildings Affects their Earthquake Response?

Oscillations of Flexible Buildings

When the ground shakes, the base of a building move with the ground, and the building swings back and- orth. If the building were rigid, then every point in it would move by the same amount as the ground. But, most buildings are flexible and different partscomeback-and-forth by different amounts. Are fat coir ropes and tie one end of it to the roof of a building and its other end to a motorized vehicle (say a tractor). Next, start the tractor and pull the building; it will move in the direction of pull (Figure 1a). For the same amount of pull force, the movement is larger for a more flexible building. Now, cut the rope! The building will oscillate back-and-forth horizontally and after some time come back to the original position (Figure 1b); these oscillations are periodic. The time taken (in seconds)for each completecycle of oscillation (i.e., one complete back-and-fordemotion) is the same and is called Fundamental Natural Period T of the building. Value of T depends on the building flexibility and mass; more the flexibility, the longer is the T, and more the mass, the longer is the T. In general, taller buildings are more flexible and have larger mass, and therefore have a longer T. On the contrary, low- to medium-rise buildings generally have shorter T (less than 0.4 sec).



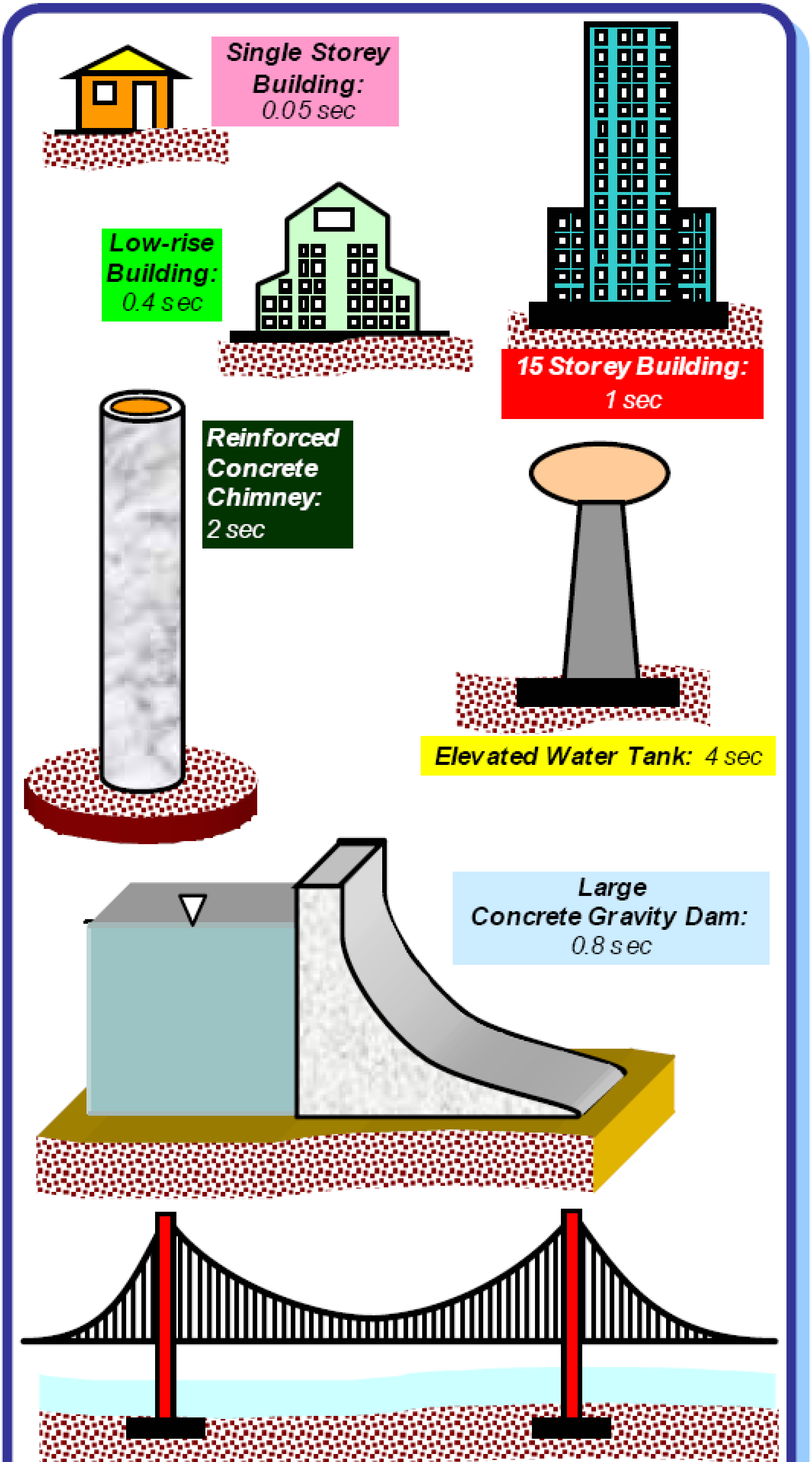
(a) Building pulled with a rope tied at its roof



(b) Oscillation of building on cutting the rope

Figure 1: Free vibration response of a building:
the back-and-forth motion is periodic.

Fundamental natural period T is an inherent property of a building. Any alterations made to the building will change its T. Fundamental natural periods T of normal single storey to 20 store buildings are usually in the range 0.05-2.00 sec. Some examples of natural periods of different structures are shown in Figure 2.0


Single Storey Building: 0.05 sec
Low-rise Building: 0.4 sec
15 Storey Building: 1 sec
Reinforced Concrete Chimney: 2 sec
Elevated Water Tank: 4 sec
Large Concrete Gravity Dam: 0.8 sec

(a) Building pulled with a rope tied at its roof
(b) Oscillation of building on cutting the rope
Figure 2: Fundamental natural periods of structures differ over a large range. Thenanural period values are only indicative; depending on actual properties of the structure, natural period may vary considerably. Adapted from: New mark, (1970), Current trends in the Seismic
Analysis and Design of Hi Gris e Structures, Chapter 16, in Wiesel, (1970), Earthquake Engineering, Prentice Hall, USA.
Suspension Bridge: 6 s ec Large Concrete Gravity Dam: 0.8 sec Elevated Water Tank: 4 sec Reinforced Concrete Chimney: 2 sec Single Storey Building: 0.05 sec Low-rise Building: 0.4 s ec 15 Storey Building: 1 sec 19 IITK-BMTPC

19 Flexibility of Buildings Affects their Earthquake Response?

Importance of Flexibility

The ground shaking during an earthquake contains a mixture of many sinusoidal waves of different frequencies, ranging from short to long periods (Figure 3). The time taken by the wave to complete one cycle of motion is called period of the earthquake wave. In general, earthquake shaking of the ground has waves whose periods vary in the range 0.03-33sec. Even within this range, some earthquake waves are stronger than the others. Intensity earthquake waves at a particular building location depends on a number of factors, including the magnitude of the earthquake, the epicentral distance, and the type of ground that the earthquake waves travelled through before reaching the location of interest.

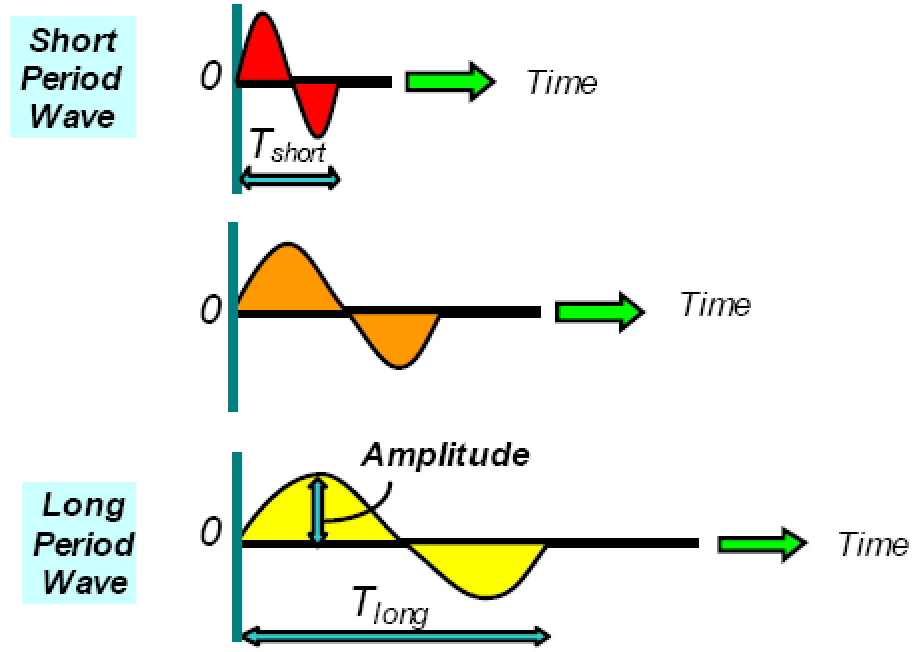
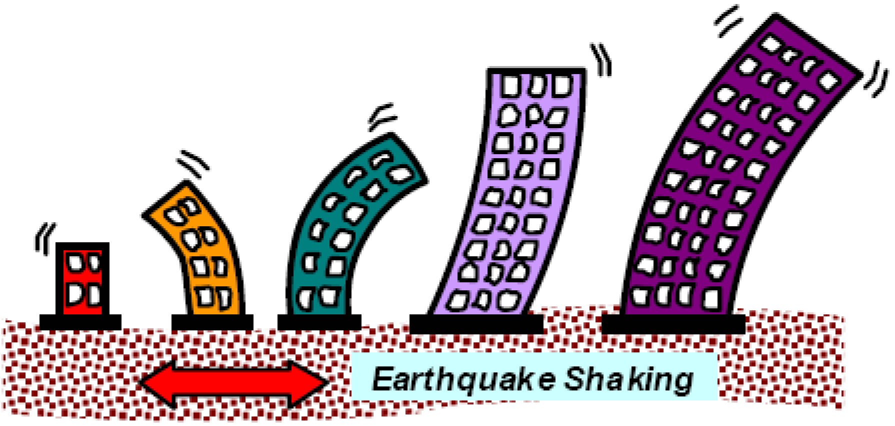
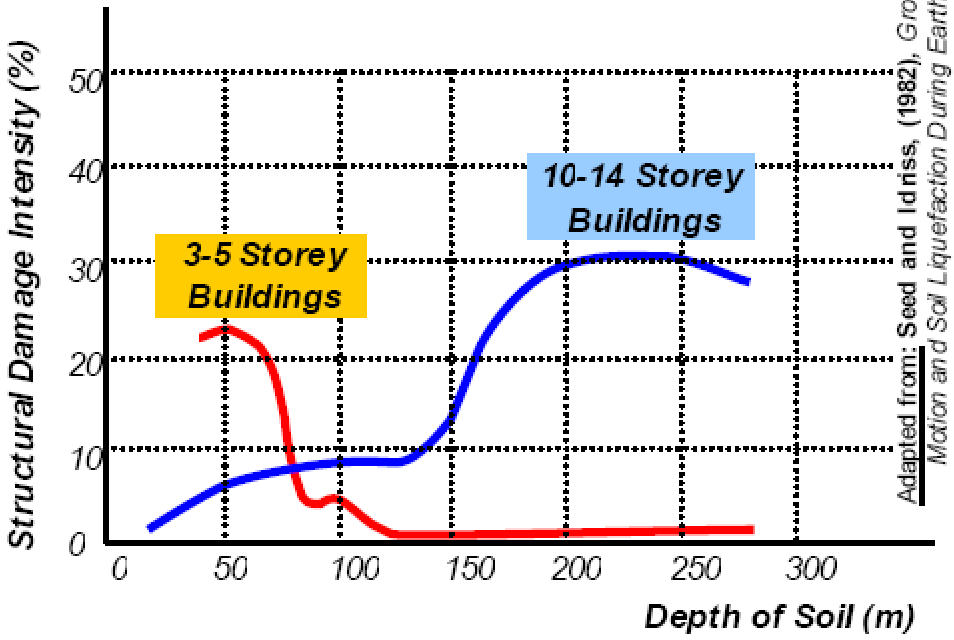


Figure 3: Strong Earthquake Ground Motion is transmitted by waves of different periods.

In a typical city, there are buildings of many different sizes and shapes. One way of categorizing them is by their fundamental natural period T. The ground motion under these buildings varies across the city (Figure 4a). If the ground is shaken back-and-forth by earthquake waves that have short periods, then short period buildings will have large response. Similarly, if the earthquake ground motion has long period waves, then long period buildings will havelarger response. Thus, depending on the value of T of the buildings and on the characteristics of earthquake ground motion (i.e., the periods and amplitude of the earthquake waves), some buildings will be shaken more than the others. During the 1967 Caracas earthquake in South depend on the thickness of soil under the buildings. Figure 4b shows that for buildings 3-5 stores tall, the damage intensity was higher in areas with underlying soil cover of around 40-60m thick, but was minimal in areas with larger thickness of soil cover. On the other hand, the damage intensity was just the reverse in the case of 10-14 store buildings; the damage intensity was more when the soil cover was in the range 150-300m, and small for lower thickness of soil cover. Here, the soil layer under the building plays the role of a filter, allowing some ground waves to pass through and filtering the rest.



(a) Buildings in a city lie on different soils



Adapted from: Seed and Idriss, (1982), *Ground Motion and Soil Liquefaction During Earthquakes*, EERI, USA.

(b) Intensity of damage depends on thickness of underlying soil layer: 1967 Caracas Earthquake

Figure 4: Different Buildings Respond Differently to Same Ground Vibration.

Flexible buildings undergo larger relative horizontal displacements, which may result in damage to various nonstructural building components and the contents. For example, some items in buildings, like glass windows, cannot take large lateral movements, and are therefore damaged severely or crushed. Unsecured shelves might topple, especially at upper stories of multi-storey buildings. These damages may not affect safety of buildings, but may cause economic losses, injuries and panic among its residents. Related Tip IITK-BMTPC Earthquake Tip 2: How the Ground Shakes?

20 What are the Indian Seismic Codes?

Importance of Seismic Design Codes

Ground vibrations during earthquakes cause forces and deformations in structures. Structures need to e designed to withstand such forces and deformations. Seismic codes help to improve the behavior of structures so that they may withstand the earthquake effects without significant loss of life and property. Countries around the world have procedures outlined in seismic codes to help design engineers in the planning, designing, detailing and constructing of structures. An earthquake-resistant building has four virtues in it, namely: (a) Good Structural Configuration: Its size, shape and structural system carrying loads are such that they ensure a direct and smooth flow of inertia forces to the ground.
(b) Lateral Strength: The maximum lateral (horizontal) force that it can resist is such that the damage induced in it does not result in collapse.
(c) Adequate Stiffness: Its lateral load resisting system is such that the earthquake-induced deformations in
it do not damage its contents under low-to moderateshiking.
(d) Good Ductility: Its capacity to undergo large deformations under severe earthquake shaking even after yielding is improved by favorabledesign and detailing strategies. Seismic codes cover all these aspects.

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 IS 1893 is the main code that provides the seismic zone map (Figure 1) and specifies seismic design force.

This force depends on the mass and seismic coefficient of the structure; the latter in turn depends on properties like seismic zone in which structure lies, importance of the structure, its stiffness, the soil on which it rests, and its ductility. For example, a building in Bhuj will have 2.25 times the seismic design force of an identical building in Bombay. Similarly, the seismic coefficient for a single-store building may have 2.5 times that of a 15-storey building.

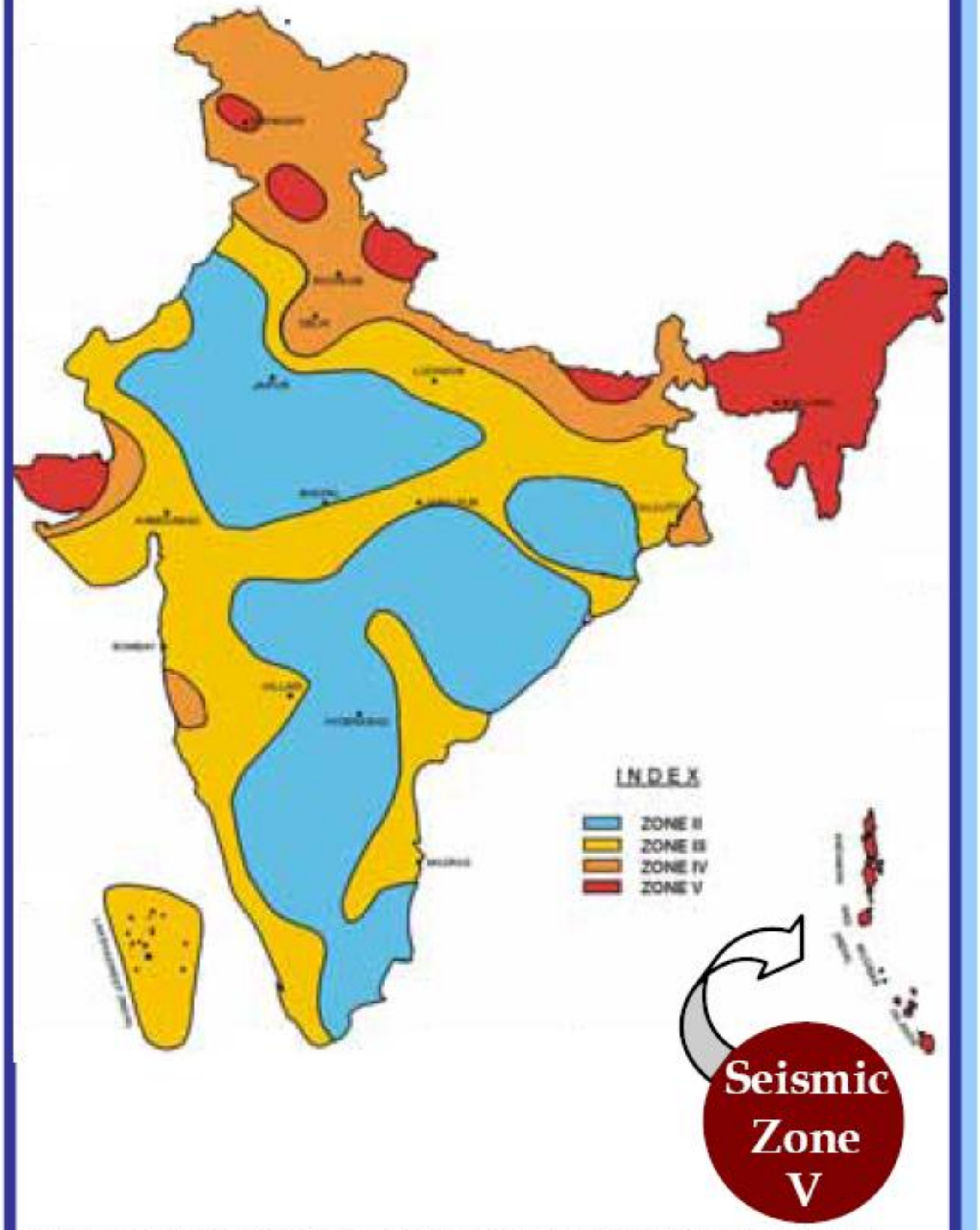


Figure 1: Seismic Zone Map of India showing *four seismic zones* - *over 60% of India's land under seismic zones III, IV and V*.

21 What are the Indian Seismic Codes?

The revised 2002 edition, Part 1 of IS1893, contains provisions that are general in nature and those applicable for buildings. The other four parts of IS 1893 will cover: Liquid-Retaining Tanks, both elevated and ground supported (Part 2); Bridges and Retaining Walls (Part 3); Industrial Structures including Stack- Like Structures (Part 4); and Dams and Embankments (Part 5). These four documents are under preparation. In contrast, the 1984 edition of IS1893 had provisions for all the above structures in a single document. Provisions for Bridges Seismic design of bridges in India is covered in three codes, namely IS 1893 (1984) from the BIS, IRC 6 (2000) from the Indian Roads Congress, and Bridge Rules (1964) from the Ministry of Railways. All highway bridges are required to comply with IRC 6, and all railway bridges with Bridge Rules. These three codes are conceptually the same, even though there are some differences in their implementation. After the 2001 Bhuj earthquake, in 2002, the IRC released interim provisions that make significant improvements to the IRC6 (2000) seismic provisions.

IS 4326, 1993

This code covers general principles for earthquake resistant buildings. Selection of materials and special features of design and construction are dealt with for the following types of buildings: timber constructions, masonry constructions using rectangular masonry units, and buildings with prefabricated reinforced concrete roofing/flooring elements.

IS 13827, 1993 and IS 13828, 1993

Guidelines in IS 13827 deal with empirical design and construction aspects for improving earthquake resistanceof earthen houses, and those in IS 13828 with general principles of design and special construction features for improving earthquake resistance of buildings of low-strength masonry. This masonry includes burnt clay brick or stone masonry in weak mortars, like clay-mud. These standards are applicable in seismic zones III, IV and V. Constructions based on them are termed non-engineered, and are not totally free from collapse under seismic shaking intensities VIII (MMI) and higher. Inclusion of features mentioned in these guidelines may only enhance the seismic resistance and reduce chances of collapse.

IS 13920, 1993

In India, reinforced concrete structures are designed and detailed as per the Indian Code IS 456 (2002). However, structures located in high seismic regions require ductile design and detailing. Provisions for the ductile detailing of monolithic reinforced concrete frame and shear wall structures are specified in IS 13920 (1993). After the 2001 Bhuj earthquake, this code has been made mandatory for all structures in zones III, IV and V. Similar provisions for seismicdesign and ductile detailing of steel structures are notyet available in the Indian codes.

IS 13935, 1993

These guidelines cover general principles of seismic strengthening, selection of materials, and techniques for repair/seismic strengthening of masonry and wooden buildings. The code provides a brief coverage for individual reinforced concrete members n such buildings, but does not cover reinforced concrete frame or shear wall buildings as a whole. Some guidelines are also laid down for non structural and architectural components of buildings.

InClosure…

Countries with a history of earthquakes have well developed earthquake codes. Thus, countries like Japan, New Zealand and the United States of America, have detailed seismic code provisions. Development of building codes in India started rather early. Today, India has a fairly good range of seismic codes covering a variety of structures, ranging from mud or lowstrengthmasonry houses to modern buildings. However, the key to ensuring earthquake safety lies in having a robust mechanism that enforces and implements these design code provisions in actual constructions.

Resource Material

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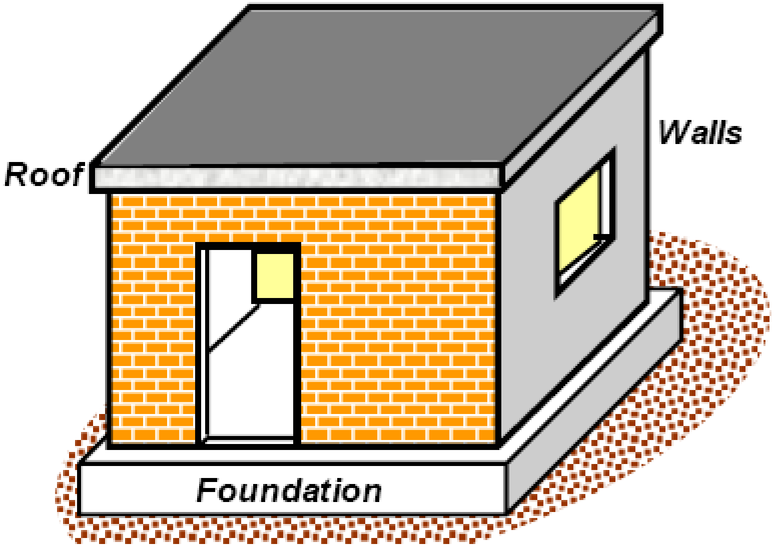
SP 22 (S&T), (1982), Explanatory Handbook on Codes for Earthquakes Engineering - IS 1893:1975 and IS 4326:1976, Bureau of Indian Standards, New Delhi.

22 How do brick masonry houses behave during earthquakes?

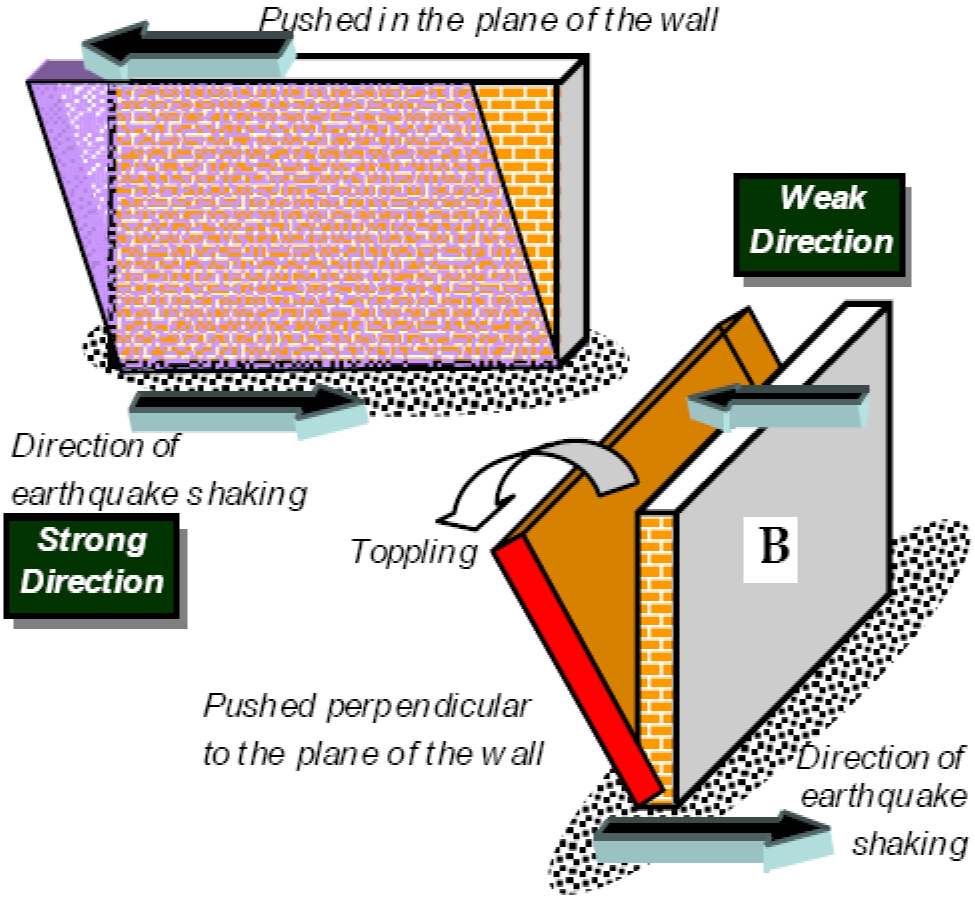
Learning Earthquake Design andConstruction

Behavior 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 behavior 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) Basic components of a masonry building

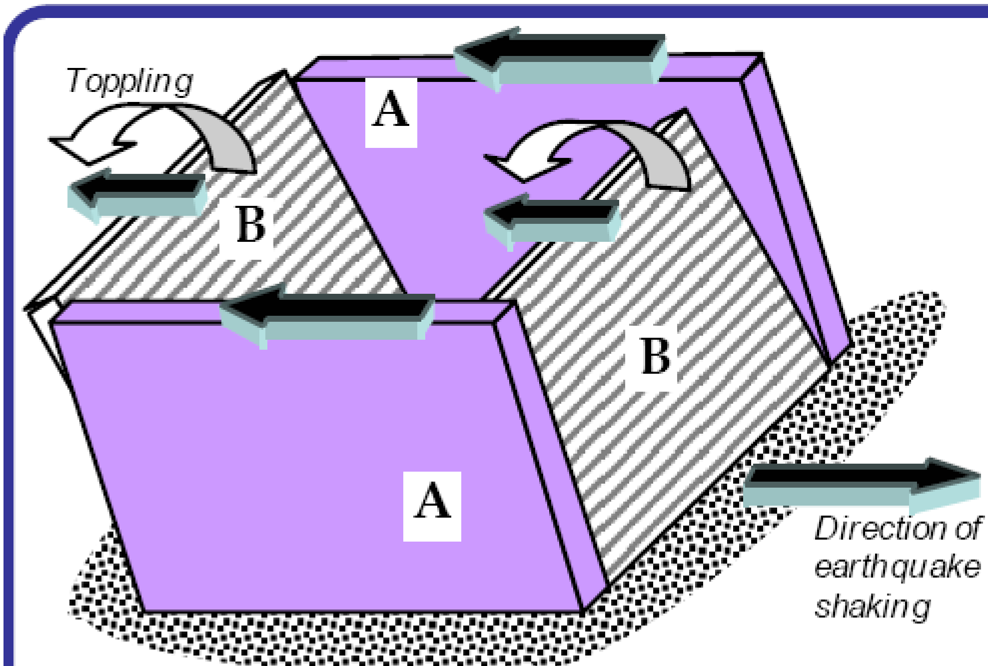


(b) Direction of force on a wall critically determines its earthquake performance

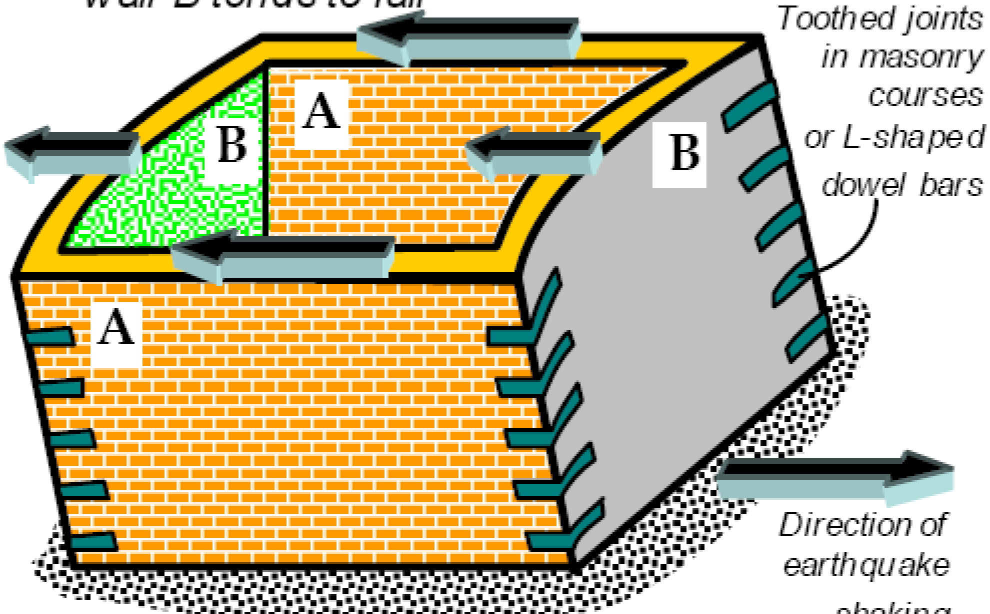
Figure 1: Basic components of a masonry building – *walls are sensitive to direction of earthquake forces.*

A 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 (IITK-BMTPC Earthquake Tip 5). 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 thisway, walls loaded in their weak direction can takeadvantage 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) 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 do brick masonry houses behave during earthquakes?

Masonry walls are slender because of their small thickness compared to their height and length. A simple way of making these walls behave well duringearthquake 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 are the resistance offered by the wall. Thirdly, the tendency of a wall 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).

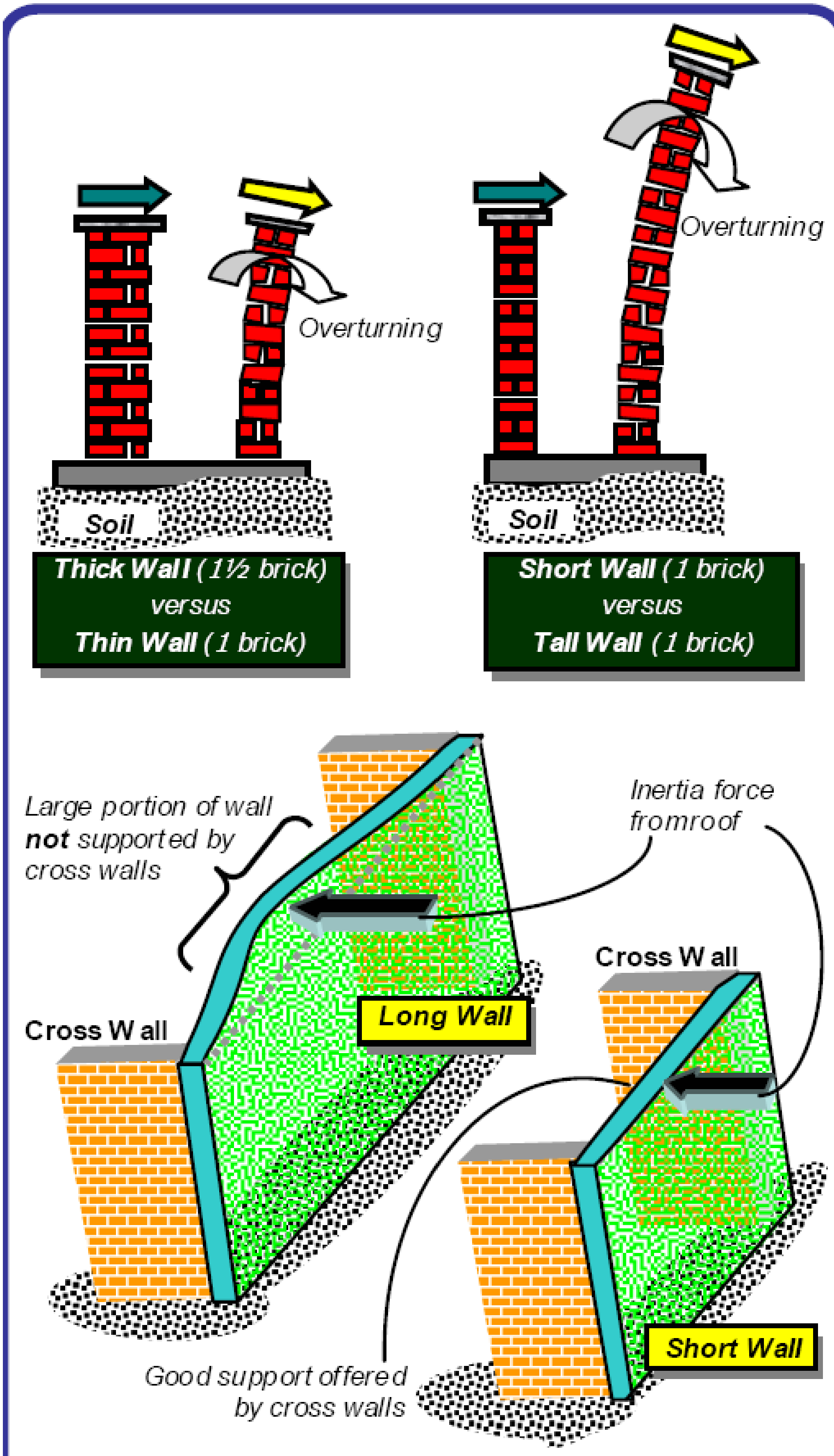


Figure 3: Slender walls are vulnerable – *height and length to be kept within limits.* **.** *Note: In this figure, the effect of roof on walls is not shown*

Choice and Quality of Building Materials

Earthquake performance of a masonry wall is verysensitive 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 sunburnt), 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 behavior 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 minimize 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
Strength 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. Related Earthquake Tip
Tip 5: What are the seismic effects on structures?

Resource Material

= IS 1905, (1987), Indian Standard Code of Practice for Structural Use of Unreinforced Masonry, Bureau of Indian Standards, New Delhi.
IS 4326, (1993), Indian Standard Code of Practice for Earthquake Resistant Design and Construction of Buildings, Bureau of Indian Standards, New Delhi.
IS 13828, (1993), Indian Standard Guidelines for Improving Earthquake Resistance of Low-strength Masonry Buildings, Bureau of Indian Standards, New Delhi.
Paulay,T., and Priestley,M.J.N., (1992), Seismic Design of ReinforcedConcrete and Masonry Buildings, John Wiley & Sons, New York.

Next Upcoming Tip

Why should masonry houses have simple structural configuration?

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23 Why should masonry buildings have simple structural configuration?

Box Action in Masonry Buildings

Brick masonry buildings have large mass and hence attract large horizontal forces during earthquake shaking. They develop numerous cracks under both compressive and tensile forces caused by earthquake shaking. The focus of *earthquake resistant* masonry building construction is to ensure that these effect cuts are sustained without major damage or collapse. Appropriate choice of structural configuration can help achieve this.

The structural configuration of masonry buildings includes aspects like (a) overall shape and size of the building, and (b) distribution of mass and (horizontal) lateral load resisting elements across the building. Large, tall, long and unsymmetrical buildings perform poorly during earthquakes. A strategy used in making them earthquake resistant is developing good *box action* between all the elements of the building, *i.e.*, between roof, walls and foundation (Figure 1). Loosely connected roof or unduly slender walls are threats to good seismic behavior. For example, a horizontal band introduced at the lintel level ties the walls together and helps to make them behave as a single unit.

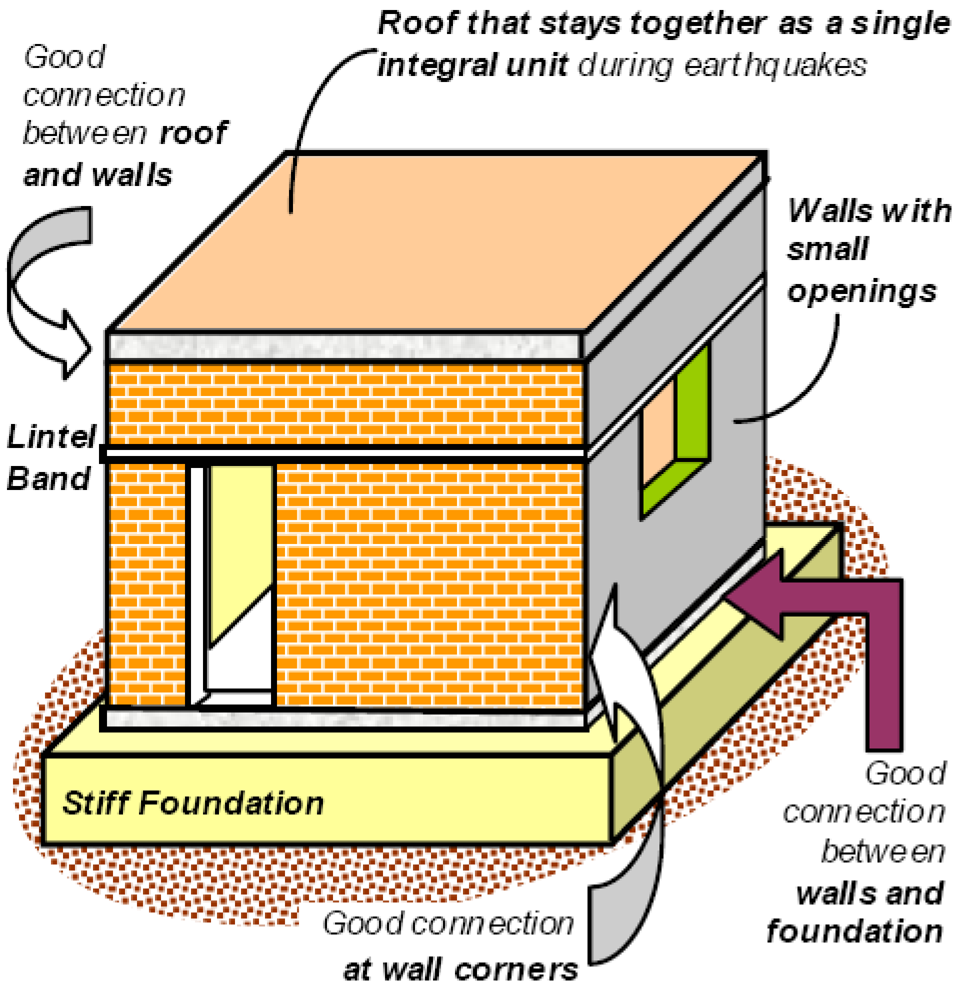


Figure 1: Essential requirements to ensure *box action* in a masonry building.

Influence of Openings

Openings are functional necessities in buildings. However, location and size of openings in walls assume significance in deciding the performance of masonry buildings in earthquakes. To understand this, consider a four-wall system of a single story masonry building (Figure 2). During earthquake shaking, inertia forces act in the strong direction of some walls and in the weak direction of others. Walls shaken in the weak direction seek support from the other walls, *i.e.*, walls B1 and B2 seek support from walls A1 and A2 for shaking in the direction shown in Figure 2. To be more specific, wall B1 pulls walls A1 and A2, while wall B2 pushes against them. At the next instance, the direction of shaking could change to the horizontal direction perpendicular to that shown in Figure 2. Then, walls A and

B change their roles; Walls B1 and B2 become the strong ones and A1 and A2 weak.

Thus, walls transfer loads to each other at their junctions (and through the lintel bands and roof). Hence, the masonry courses from the walls meeting at corners must have good interlocking. For this reason, openings near the wall corners are detrimental to good seismic performance. Openings too close to wall corners hamper the flow of forces from one wall to another (Figure 3). Further, large openings weaken walls from carrying the inertia forces in their own plane. Thus, it is best to keep all openings as small as possible and as far away from the corners as possible.

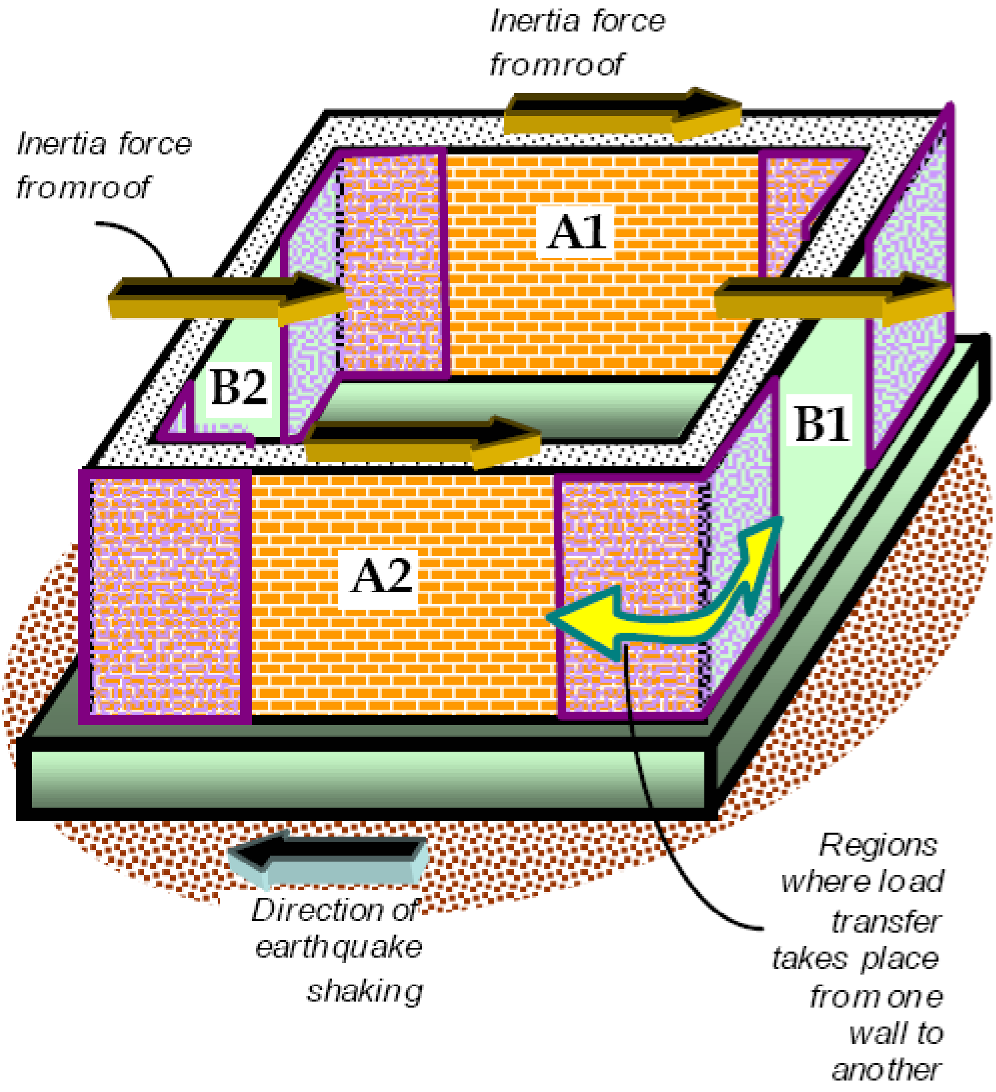


Figure 2: Regions of force transfer from weak walls to strong walls in a masonry building – *wall B1 pulls walls A1 and A2, while wall B2 pushes walls A1 and A2.*

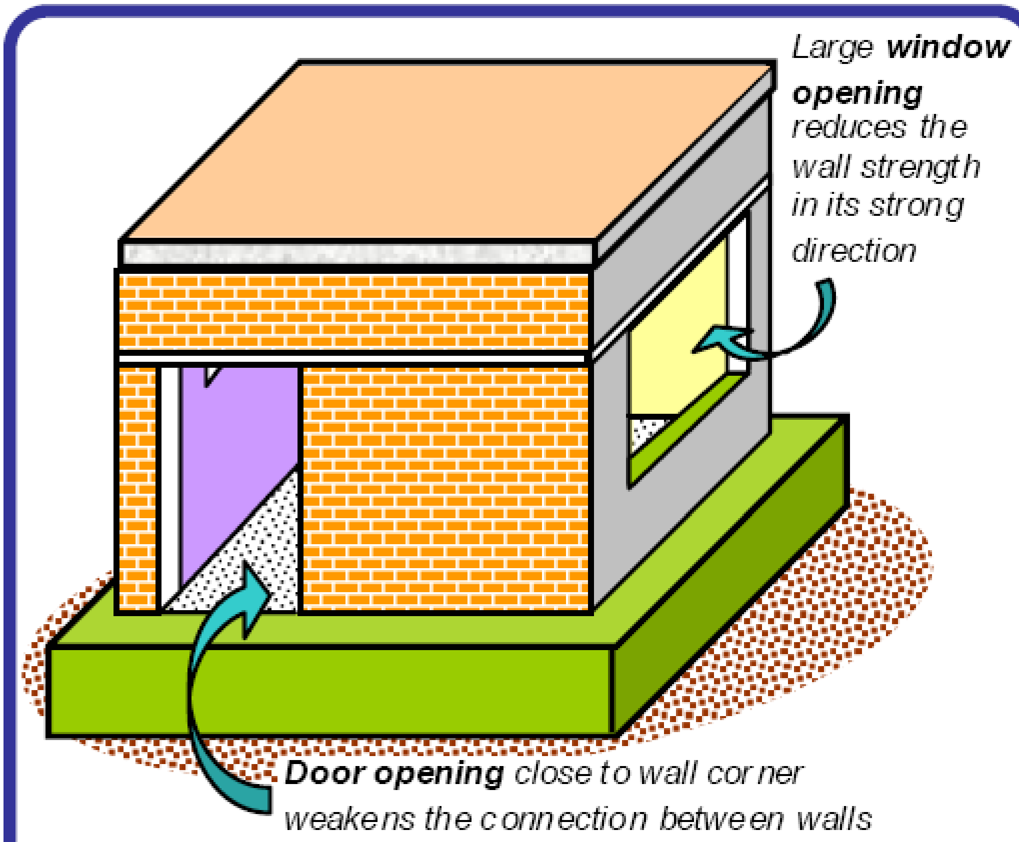


Figure 3: Openings weaken walls in a masonry building *–a single closed horizontal band must be provided above all of them.*

Earthquake-Resistant Features

Indian Standards suggest a number of earthquake resistant measures to develop good *box-type* action in Masonry buildings and improve their seismic performance. For instance, it is suggested that a building having horizontal projections when seen from the top, *e.g.*, like a building with plan shapes L, T, E and Y, be separated into (*almost*) simple rectangular blocks in plan, each of which has simple and good earthquake behavior . During earthquakes, separated blocks can oscillate independently and even hammer each other if they are too close. Thus, adequate gap is necessary between these different blocks of the building. The Indian Standards suggest minimum seismic separations between blocks of buildings. However, it may not be necessary to provide such separations between blocks, if horizontal projections in buildings are small, say up to ~15-20% of the length of building in that direction.

Inclined staircase slabs in masonry buildings offer another concern. An integrally connected staircase slab acts like a cross-brace between floors and transfers large horizontal forces at the roof and lower levels (Figure 4a). These are areas of potential damage in masonry buildings, if not accounted for in staircase design and construction. To overcome this, sometimes, staircases are completely separated (Figure 4b) and built on a separate reinforced concrete structure. Adequate gap is provided between the staircase tower and the masonry building to ensure that they do not pound each other during strong earthquake shaking.

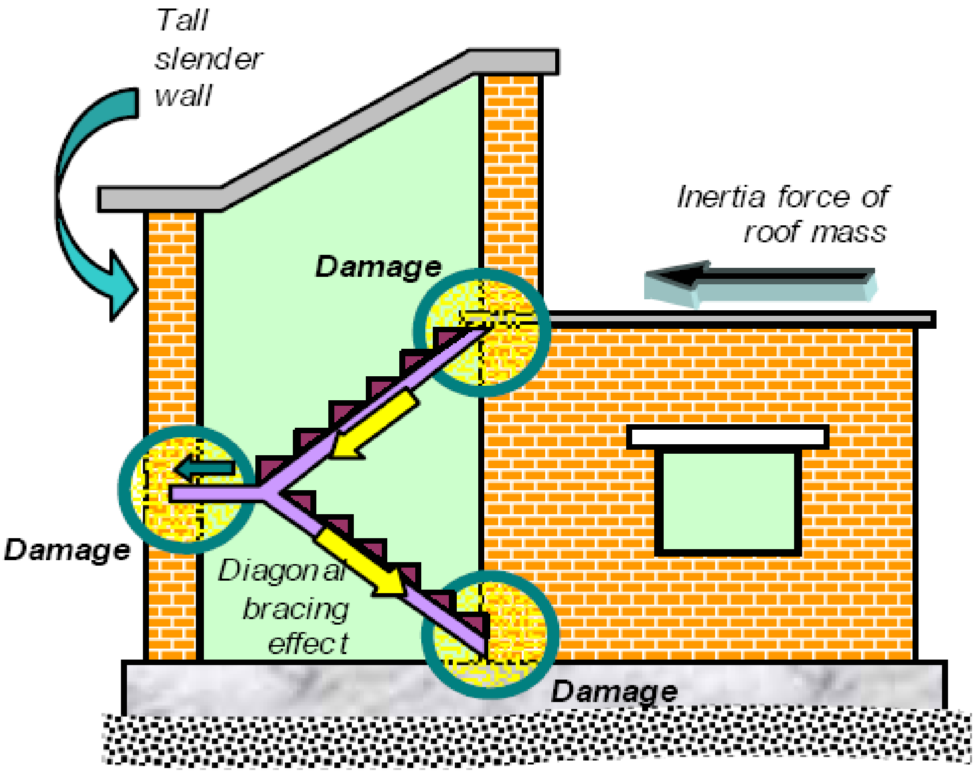
Resource Material

IS 1905, (1987), *Indian Standard Code of Practice for Structural Use of Unreinforced Masonry*, Bureau of Indian Standards, New Delhi.

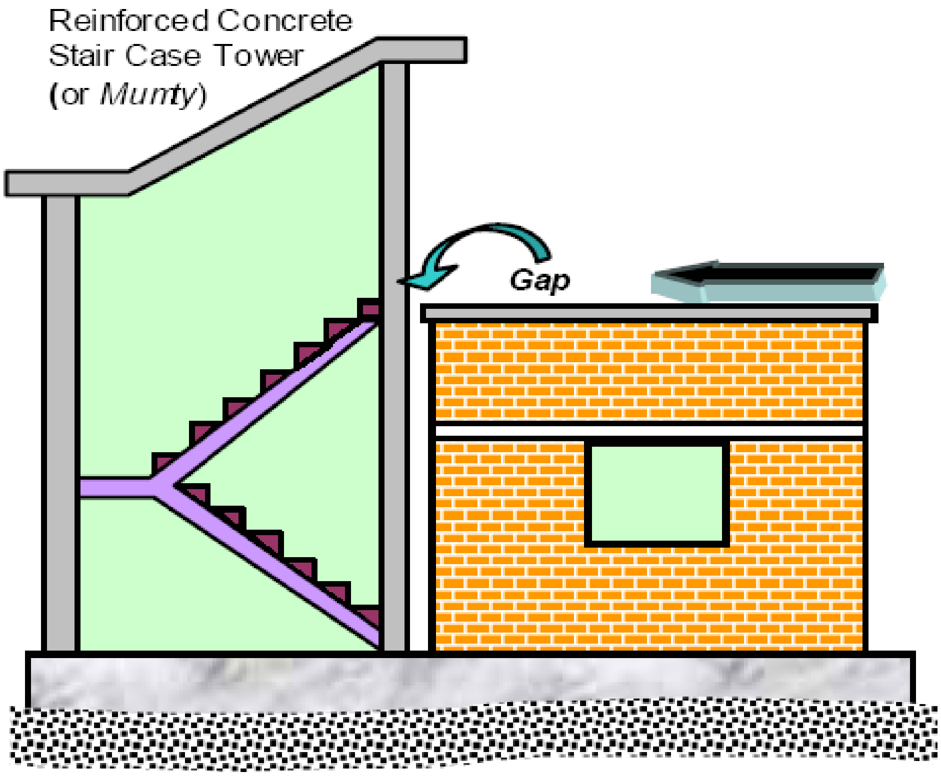
IS 42326, (1993), *Indian Standard Code of Practice for Earthquake Resistant Design and Construction of Buildings*, Bureau of Indian Standards, New Delhi.

IS 13828, (1993), *Indian Standard Guidelines for Improving Earthquake Resistance of Low-strength Masonry Buildings*, Bureau of IndianStandards, New Delhi.

Tomazevic,M., (1999), Earthquake Resistant Design of Masonry Buildings, Imperial College Press, London, UK



(a) Damage in building with rigidly built-in staircase



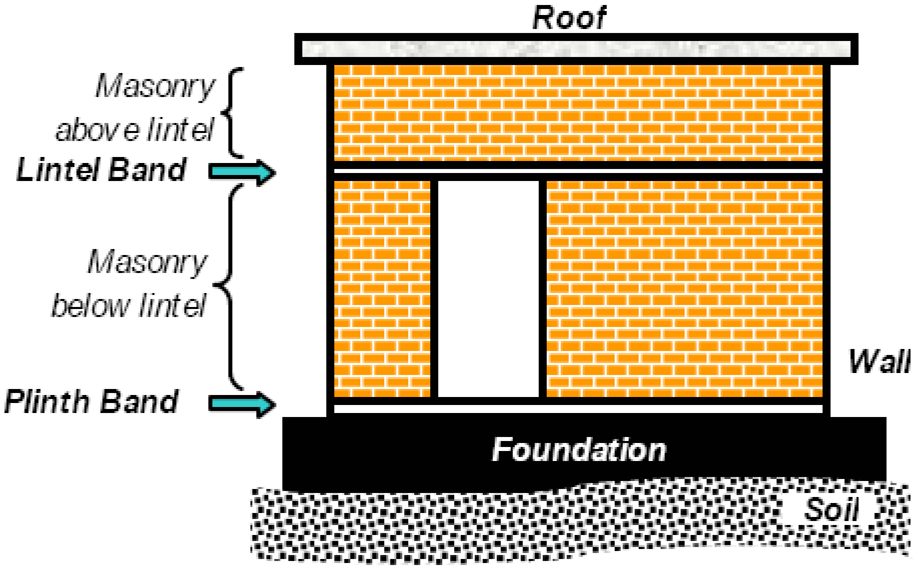
(b) Building with separated staircase

Figure 4: Earthquake-resistant detailing of staircase in masonry building
– must be carefully designed and constructed.

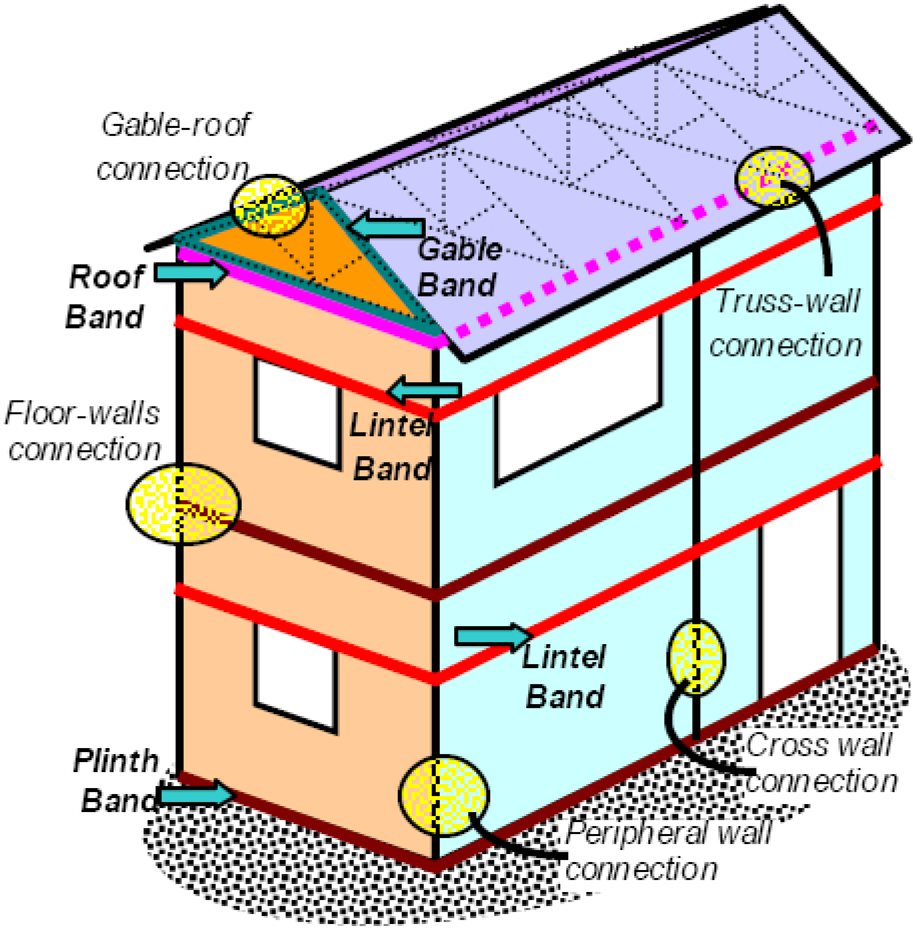
24 Why are horizontal bands necessary in masonry buildings?

Role of Horizontal Bands

Horizontal bands are the most important earthquake-resistant feature in masonry buildings. The bands are provided to hold a masonry building as a single unit by tying all the walls together, and are similar to a closed belt provided around cardboard boxes. There are four types of bands in a typical
Masonry building, namely *gable band*, *roof band*, *lintel band* and *plinth band* (Figure 1), named after theirlocation in the building. The lintel band is the mostimportant of all, and needs to be provided in almost allbuildings. The gable band is employed only inbuildings with pitched or sloped roofs. In buildingswith flat reinforced concrete or reinforced brick roofs, theroof band is not required, because the roof slab alsoplays the role of a band. However, in buildings withflat timber or CGI sheet roof, roof band needs to beprovided. In buildings with pitched or sloped roof, theroof band is very important. Plinth bands areprimarily used when there is concern about uneven
Settlement of foundation soil.



(a) Building with Flat Roof



(b) Two-storey Building with Pitched Roof

Figure 1: Horizontal Bands in masonry building – *Improve earthquake-resistance*.

The lintel band ties the walls together and create s a support for walls loaded along weak direction from walls loaded in strong direction. This band also reduces the unsupported height of the walls and thereby improves their stability in the weak direction. During the 1993 later earthquake (Central India), the intensity of shaking in Killer village was IX on MSK scale. Most masonry houses sustained partial or complete collapse (Figure 2a). On the other hand, there was one masonry building in the village, which had a lintel band and it sustained the shaking very well with hardly any damage (Figure 2b).

(a) Building with no horizontal lintel band: collapse of roof and walls

(b) A building with horizontal lintel band in Killari village: no damage

Figure 2: The 1993 Latur Earthquake (Central India) - one masonry house in Killari village had horizontal lintel band and sustained the shaking without damage.

Design of Lintel Bands

During earthquake shaking, the lintel band undergoes bending and pulling actions (Figure 3). To resist these actions, the construction of lintel band requires special attention. Bands can be made of wood (including bamboo splits) or of reinforced concrete (RC) (Figure 4); the RC bands are the best. The straight Lengths of the band must be properly connected at the wall corners. This will allow the band to support walls loaded in their weak direction by walls loaded in their strong direction. Small lengths of wood spacers (in wooden bands) or steel links (in RC bands) are used to make the straight lengths of wood runners or steel bars act together. In wooden bands, proper nailing of straight lengths with spacers is important. Likewise, in RC bands, adequate anchoring of steel links with steel bars is necessary.

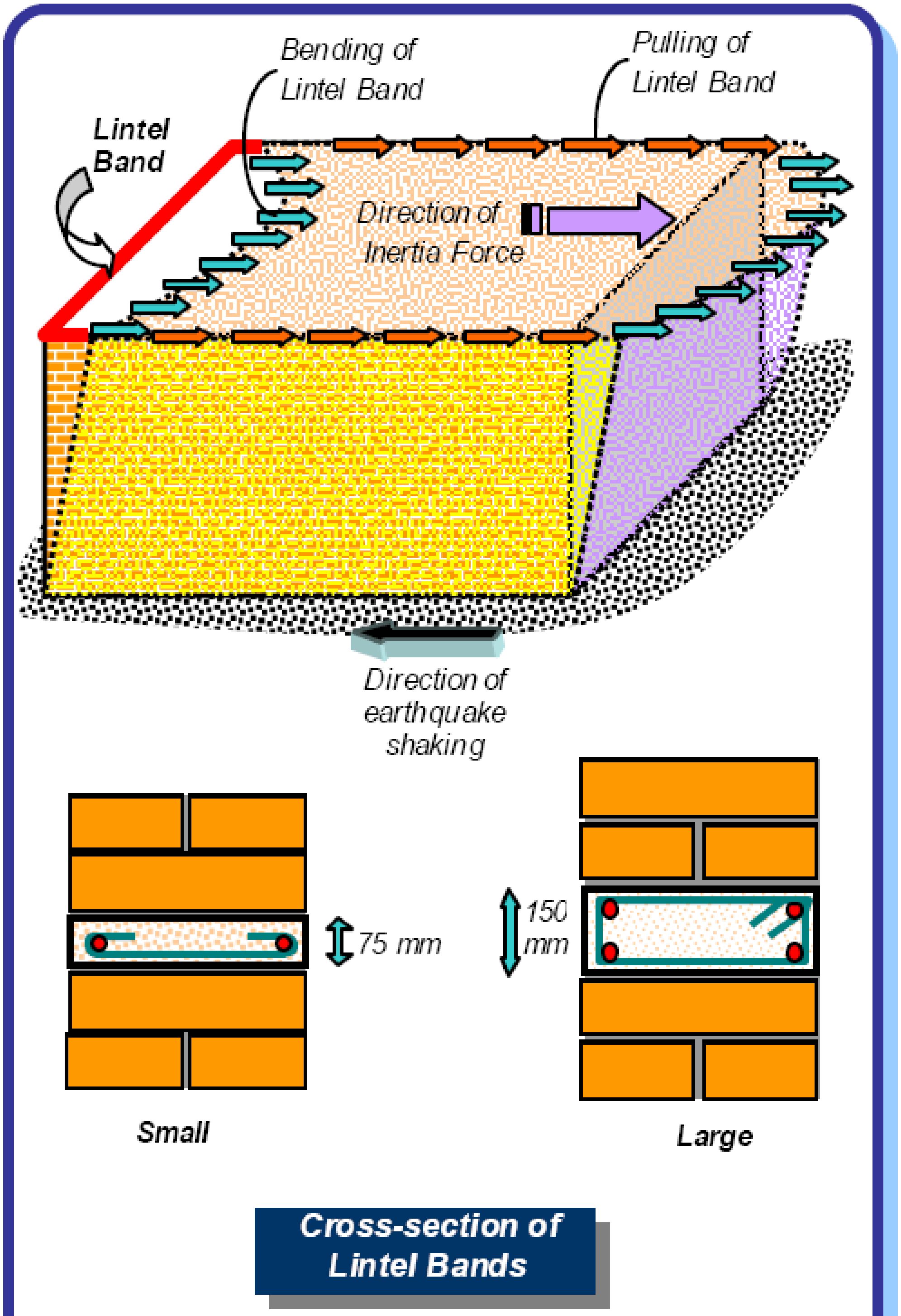
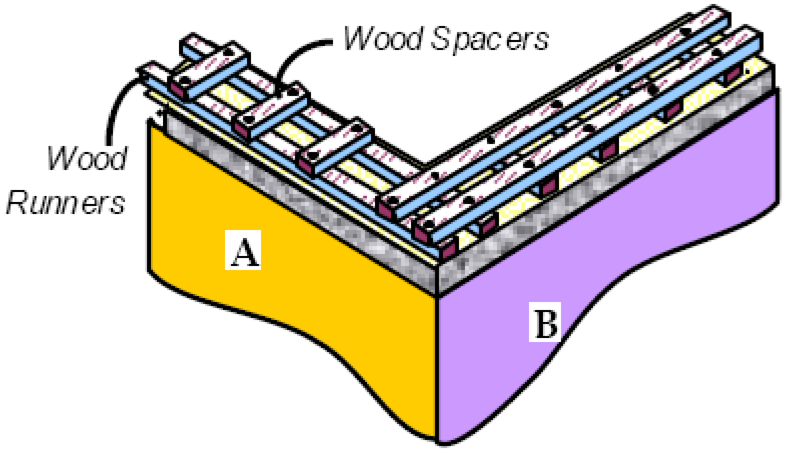


Figure 3: Bending and pulling in lintel bands – *Bands must be capable of resisting these.*

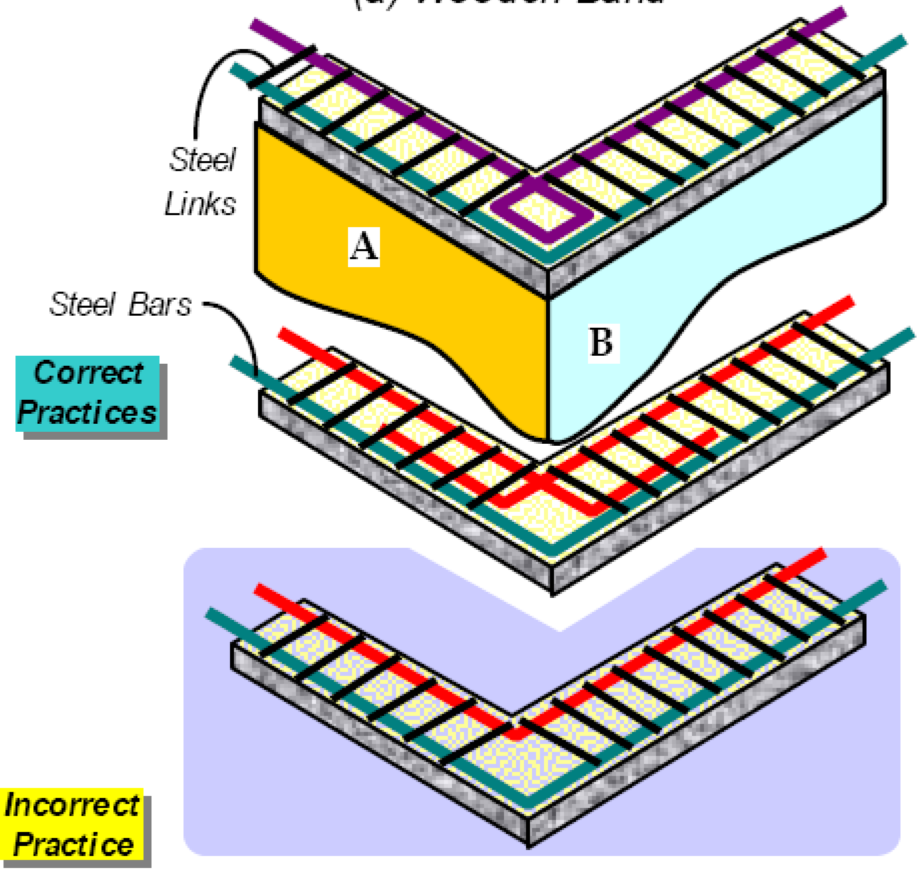
Indian Standards

The Indian Standards IS: 4326-1993 and IS: 13828 (1993) provide sizes and details of the bands. When wooden bands are used, the cross-section of *runners* is to be at least 75mm×38mm and of *spacers* at least 50mm×30mm. When RC bands are used, the minimum thickness is 75mm, and at least two bars of 8mm diameter are required, tied across with steel links of at least

6mm diameter at a spacing of 150 mm centers.



(a) Wooden Band



(b) RC Band

Figure 4: Horizontal Bands in masonry buildings – *RC bands are the best.*

25 Why is vertical reinforcement required in masonry buildings?

Response of Masonry Walls

Horizontal bands are provided in masonry Buildings to improve their earthquake performance. These bands include plinth band, lintel band and roofband. Even if horizontal bands are provided, masonry buildings are weakened by the openings in their walls (Figure 1). During earthquake shaking, the masonry walls get grouped into three sub-units, namely *spandrel masonry, wall pier masonry* and *sill masonry*.

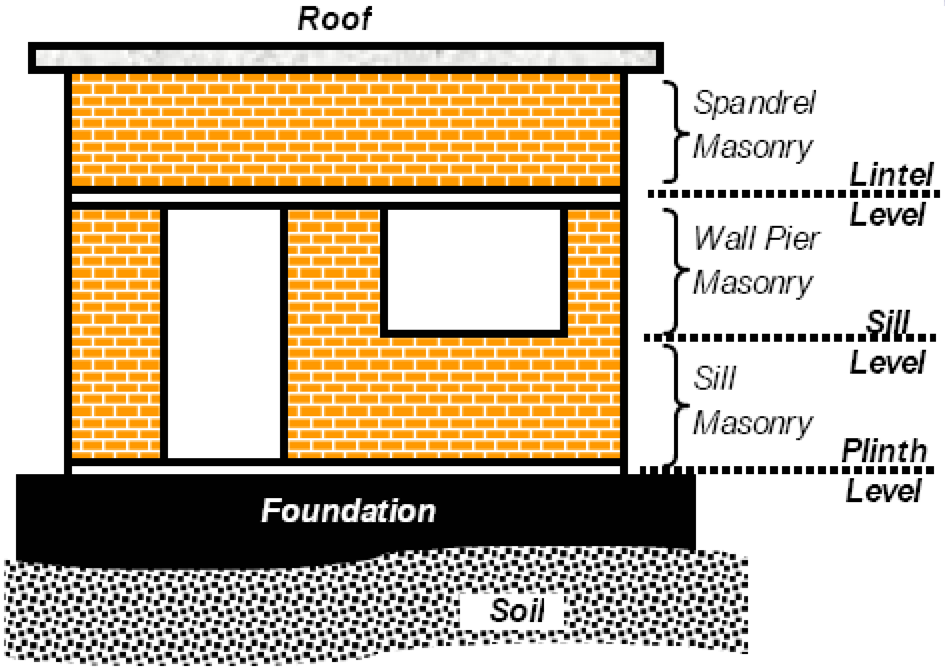
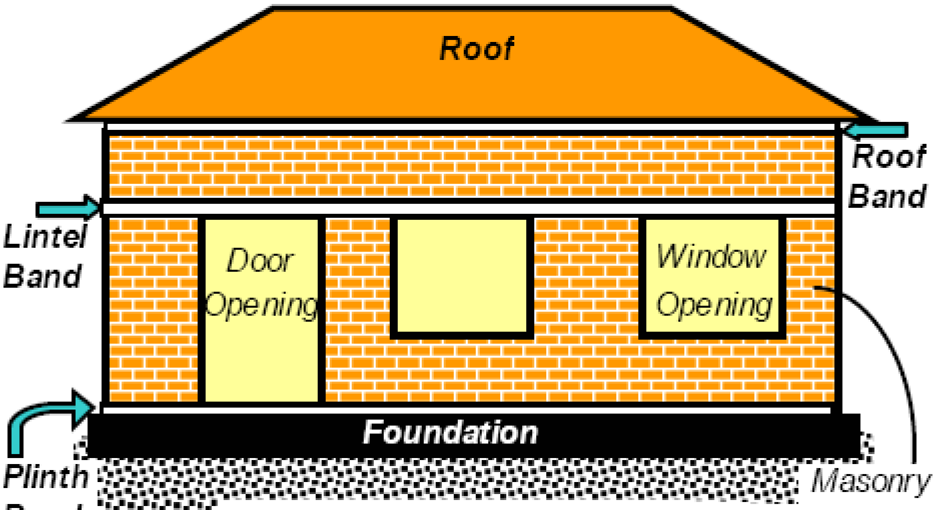
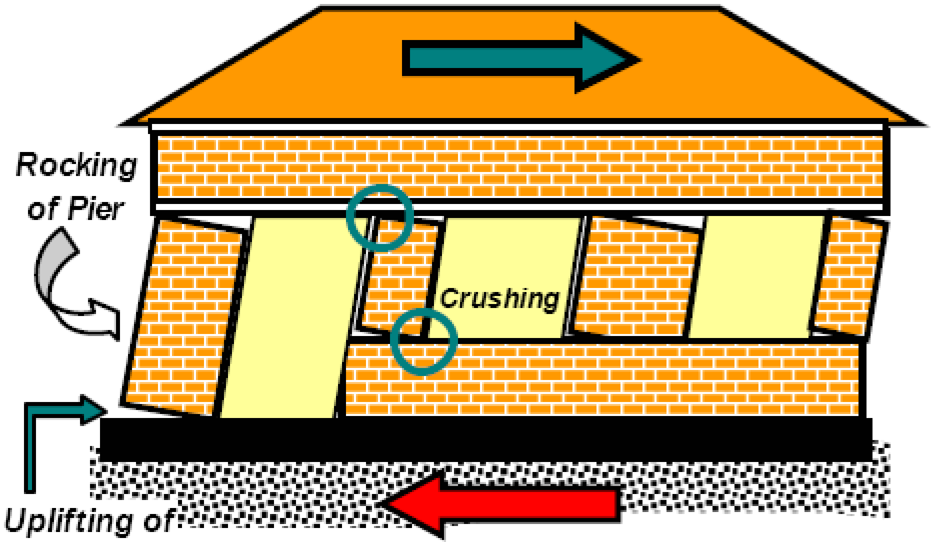


Figure 1: Sub-units in masonry building – *walls behave as discrete units during earthquakes.*

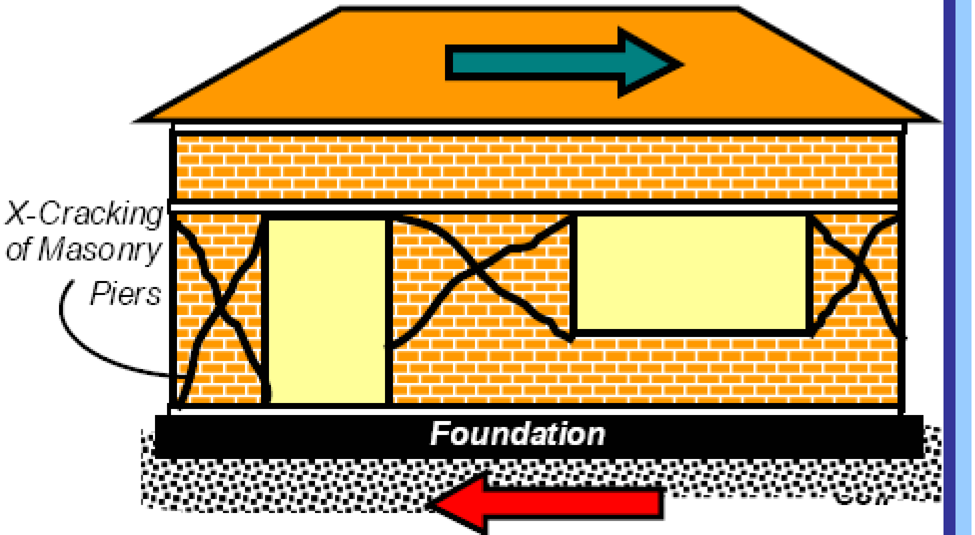
Consider a hipped roof building with two window openings and one door opening in a wall (Figure 2a). It has *lintel* and *plinth bands*. Since the roof is a hipped one, a *roof band* is also provided. When the ground shakes, the inertia force causes the small-sized masonry *wall piers* to disconnect from the masonry above and below. These masonry sub-units rock back and forth, developing contact only at the opposite diagonals (Figure 2b). The rocking of a masonry pier can crush the masonry at the corners. Rocking is possible when masonry piers are slender, and when weight of the structure above is small. Otherwise, the piers are more likely to develop diagonal (X-type) shear cracking (Figure 2c); this is the most common failure type in masonry buildings. In un-reinforced masonry buildings (Figure 3), the cross-section area of the masonry wall reduces at the opening. During strong earthquake shaking, the building may *slide* just under the roof, below the lintel band or at the skill level. Sometimes, the building may also slide at the plinth level. The exact location of sliding depends on numerous factors including building weight, the earthquake-induced inertia force, the area of openings, and type of doorframes used.



(a) Building Components



(b) Rocking of Masonry Piers



(c) X-Cracking of Masonry Piers

Figure 2: Earthquake response of a hipped roof masonry building – *no vertical reinforcement is provided in walls.*

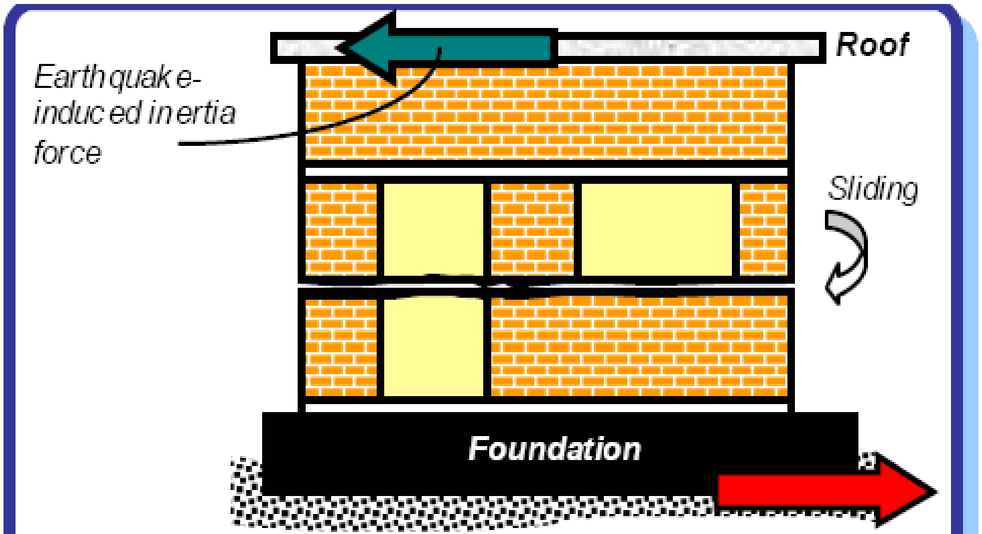
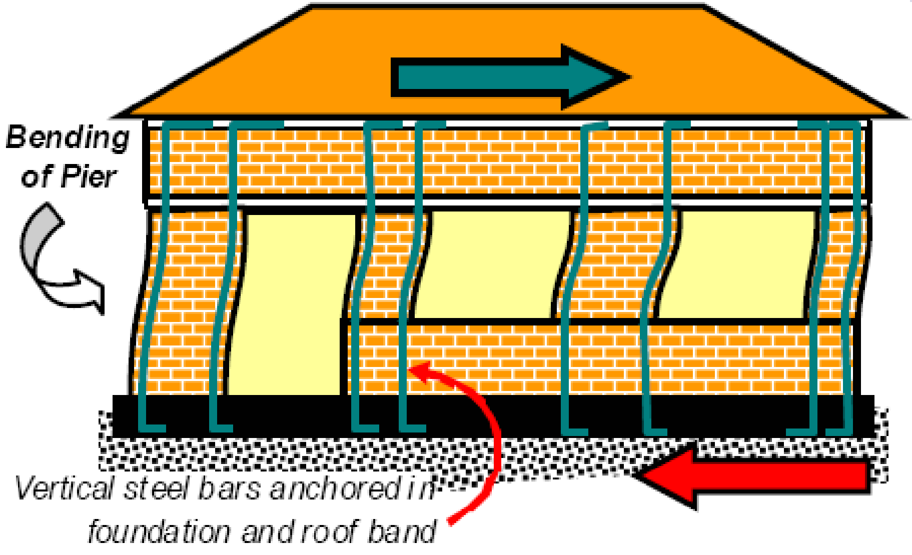


Figure 3: Horizontal sliding at sill level in a masonry building – *no vertical reinforcement*.

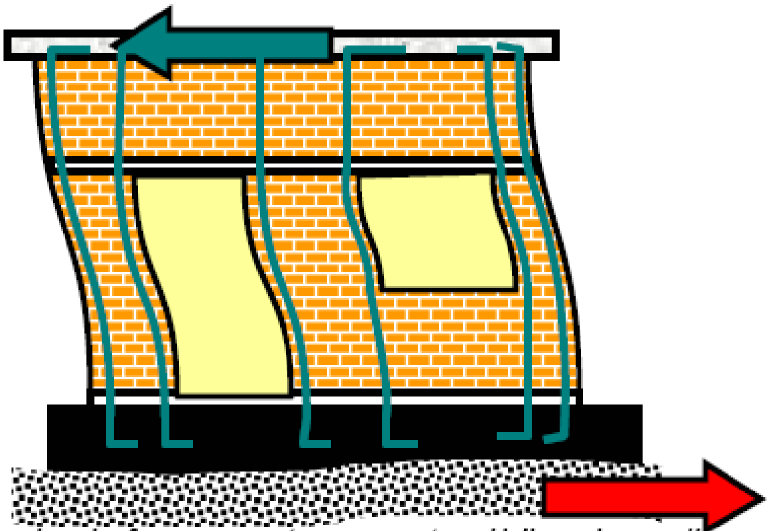
How Vertical Reinforcement Helps

Embedding vertical reinforcement bars in the edges of the wall piers and anchoring them in the foundation at the bottom and in the roof band at the top (Figure 4), forces the slender masonry piers to undergo *bending* instead of *rocking*. In wider wall piers, the vertical bars enhance their capability to resist horizontal earthquake forces and delay the X-cracking.

Adequate cross-sectional area of these vertical bars prevents the bar from yielding in tension. Further, the vertical bars also help protect the wall from sliding as well as from collapsing in the weak direction.



(a) Vertical reinforcement causes bending of masonry piers in place of rocking (See Figure 2).

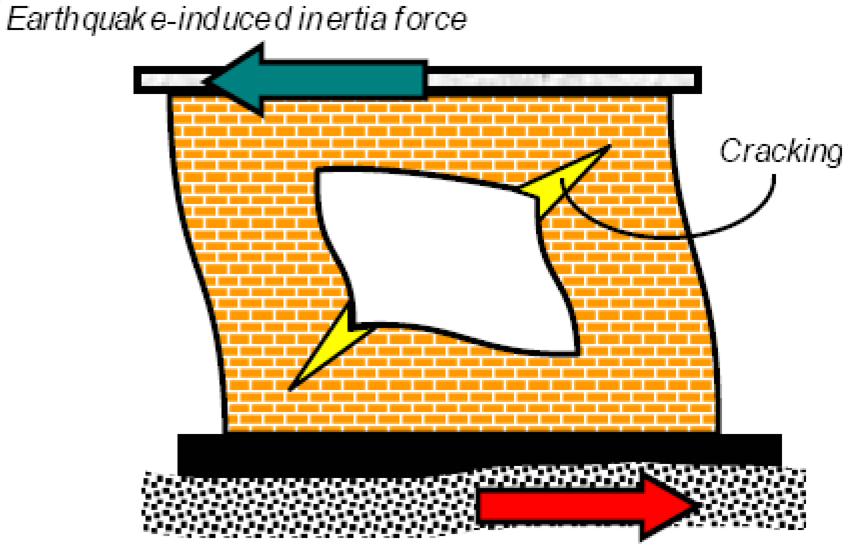


(b) Vertical reinforcement prevents sliding in walls (See Figure 3).

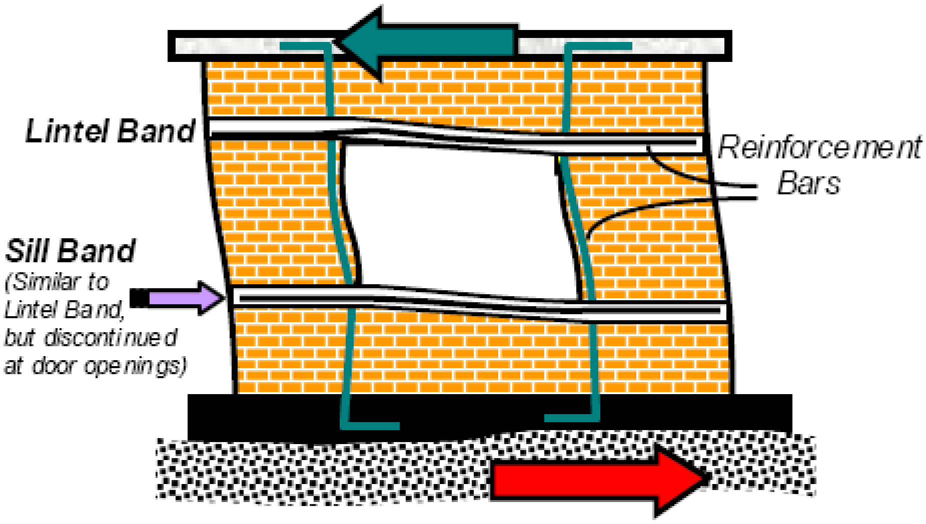
Figure 4: Vertical reinforcement in masonry walls – *wall behaviour is modified*.

Protection of Openings in Walls

Sliding failure mentioned above is rare, even in unconfined masonry buildings. However, the most diagonal X-cracking of wall piers, and also inclined cracks at the corners of door and window openings. When a wall with an opening deforms during earthquake shaking, the shape of the opening distort and becomes more like a *rhombus* - two opposite corners move away and the other two come closer. Under this type of deformation, the corners that come closer develop cracks (Figure 5a). The cracks are bigger when the opening sizes are larger. Steel bars provided in the wall masonry all around the openings restrict these cracks at the corners (Figure 5b). In summary, lintel and sill bands above and below openings, and vertical reinforcement adjacent to vertical edges, provide protection against this type of damage.



(a) Cracking in building with ***no*** *corner reinforcement*



(b) No cracks in building ***with*** *vertical reinforcement*

Figure 5: Cracks at corners of openings in a masonry building – *reinforcement around them helps.*

25 Why are Open-Ground Storey Buildings Vulnerable in Earthquakes?

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, 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.

Ground storey's of reinforced concrete
Buildings are left open to facilitate parking

This is common in urban areas in India.

Columns in the ground storey and both partite on walls and columns in the upper storeys, have two distinct characteristics, namely:

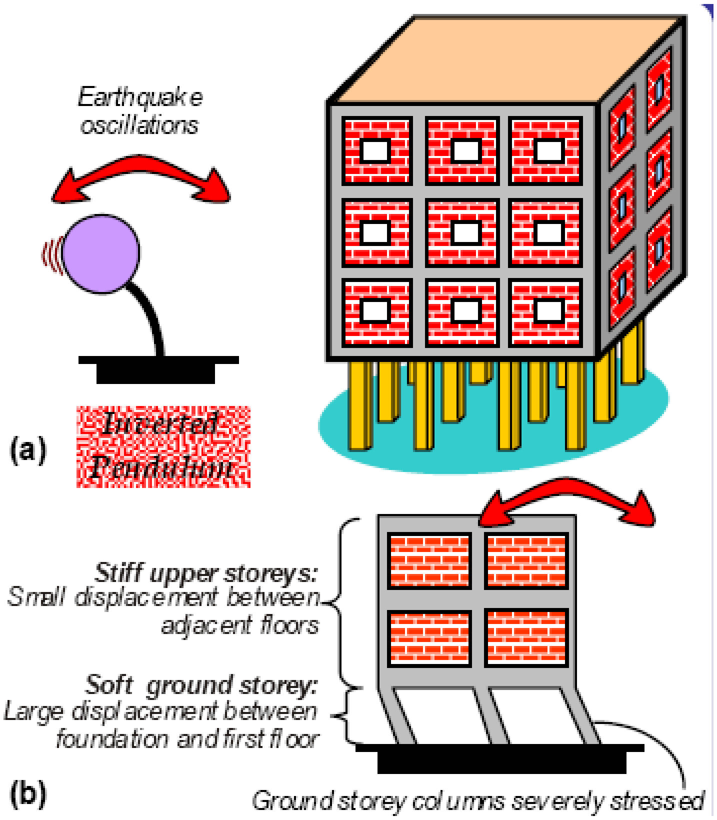
(a) It is relatively flexible in the ground storey, i.e., the relative horizontal displacement it undergoes in the ground storey is much larger than what each of the storey's above it does. This flexible ground storey is also called soft storey.

(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 storey's 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 Behavior

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 Ahmadabad 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 storey's at Ahmadabad (~225km away from epicenter) during the 2001 Bhuj earthquake has emphasized that such buildings are extremely vulnerable under earthquake shaking. The presence of walls in upper stores makes them much stiffer than the open ground storey. Thus, the upper storey's 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, and the columns in the open ground storey are severely stressed. 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 which may even lead to collapse of the building.



Upper storey's of open ground storey Buildings move together as a single block – Such buildings are like inverted pendulums.

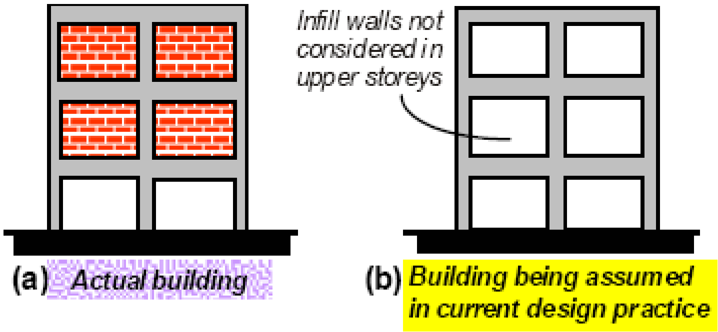
The Problem

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 are neglected and only bare frames are considered in design calculations. Thus, the inverted pendulum effect is not captured in design.

1971 San Fernando Earthquake

2001 Bhuj Earthquake

Consequences of open ground stores in RC frame buildings



Open ground storey building

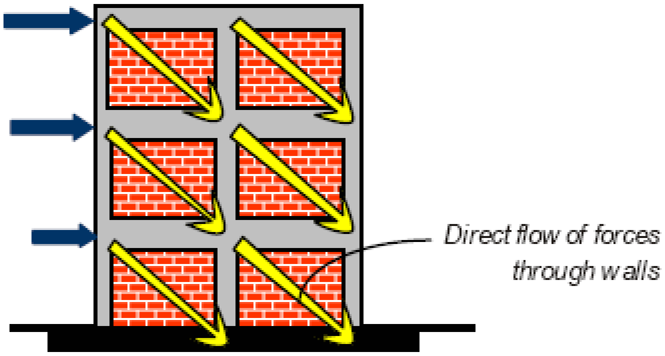
Improved design strategies

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 infill's) (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 stores 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.

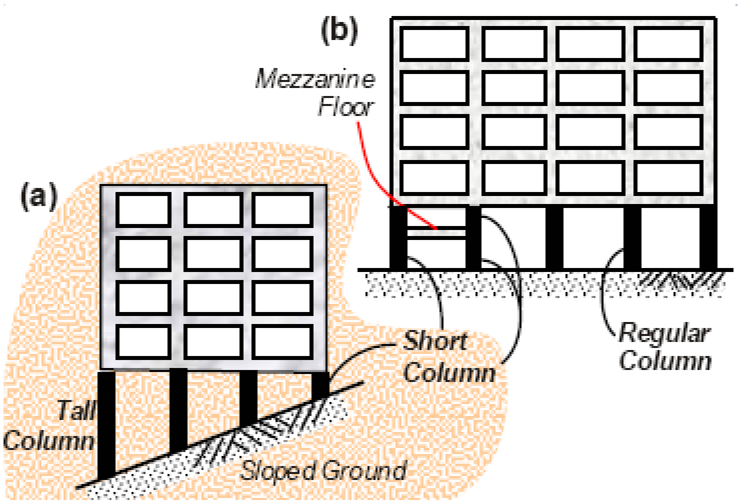


Avoiding open ground storey problem

Why are Short Columns more Damaged During Earthquakes?

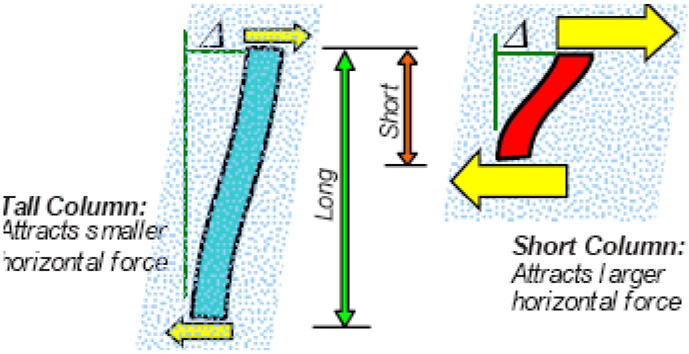
Which Columns are short?

During past earthquakes, reinforced concrete (RC) frame buildings that have columns of different heights within one storey, suffered more damage in the shorter columns as compared to taller columns in the same storey. Two examples of buildings with short columns are shown in buildings on a sloping ground and buildings with a mezzanine floor.



Buildings with short columns

Poor behavior of short columns is due to the fact that in an earthquake, a tall column and a short column of same cross-section move horizontally by same amount. However, the short column is stiffer as compared to the tall column, and it attracts larger earthquake force. Stiffness of a column means resistance to deformation – the larger is the stiffness, larger is the force required to deform it. If a short column is not adequately designed for such a large force, it can suffer significant damage during an earthquake. This behavior is called Short Column Effect. The damage in these short columns is often in the form of X-shaped cracking – this type of damage of columns is due to shear f allure.



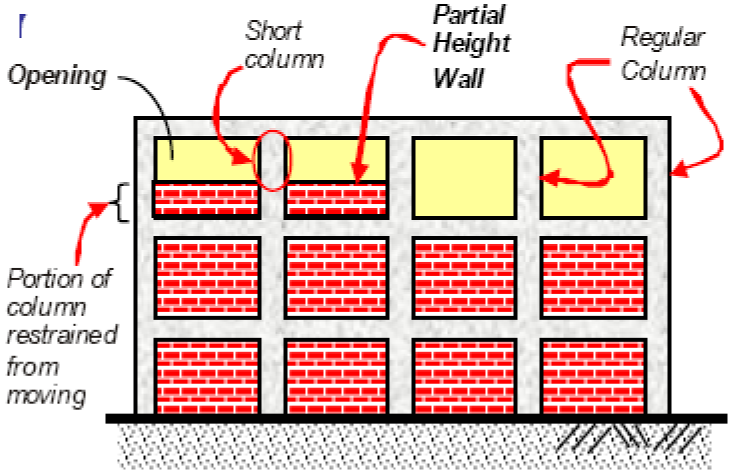
Short columns are stiffer and attract larger forces during earthquakes

The Short Column Behaviors

Many situations with short column effect arise in buildings. When a building is rested on sloped ground, during earthquake shaking all columns move horizontally by the same amount along with the floor slab at a particular level. If short and tall columns exist within the same storey level, then the short columns attract several times larger earthquake force and suffer more damage as compared to taller ones.

The short column effect also occurs in columns that support mezzanine floors or loft slabs that are added in between two regular floors.

There is another special situation in buildings when short-column effect occurs. Consider a wall (masonry or RC) of partial height built to fit a window over the remaining height. The adjacent columns behave as short columns due to presence of these walls. In many cases, other columns in the same storey are of regular height, as there are no walls adjoining them. When the floor slab moves horizontally during an earthquake, the upper ends of these columns undergo the same displacement. However, the stiff walls restrict horizontal movement of the lower portion of a short column, and it deforms by the full amount over the short height adjacent to the window opening. On the other hand, regular columns deform over the full height. Since the effective height over which a short column can freely bend is small, it offers more resistance to horizontal motion and thereby attracts a larger force as compared to the regular column. As a result, short column sustains more damage. Shows X-cracking in a column adjacent to the walls of partial height.



***Short columns effect* in RC buildings**
When partial height walls adjoin columns

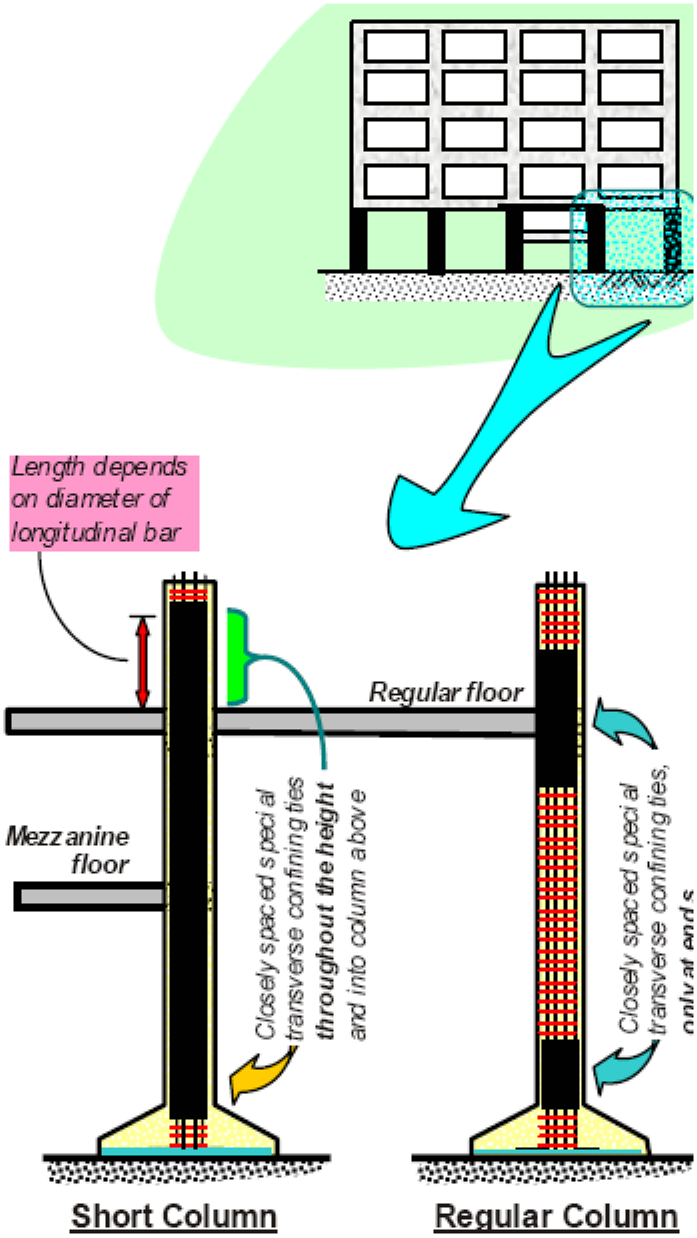
Source:
Wakabayashi,M.,
Design of Earthquake-Resistant Buildings,
McGraw Hill Book Company, New York,

Effective height of column over which it
Can bend is restricted by adjacent walls

The Solution

In new buildings, short column effect should be avoided to the extent possible during architectural design stage itself. When it is not possible to avoid short columns, this effect must be addressed in structural design. The Indian Standard IS: 13920-1993 for ductile detailing of RC structures requires special confining reinforcement to be provided over the full height of columns that are likely to sustain short column effect. The special confining reinforcement (i.e., closely spaced closed ties) must extend beyond the short column into the columns vertically above and below by a certain distance. See for details of the special confinement reinforcement.

In existing buildings with short columns, different retrofit solutions can be employed to avoid damage in future earthquakes. Where walls of partial height are present, the simplest solution is to close the openings by building a wall of full height – this will eliminate the short column e effect. If that is not possible, short columns need to be strengthened using one of the well established retrofit techniques. The retrofit solution should be designed by a qualified structural engineer with requisite background.

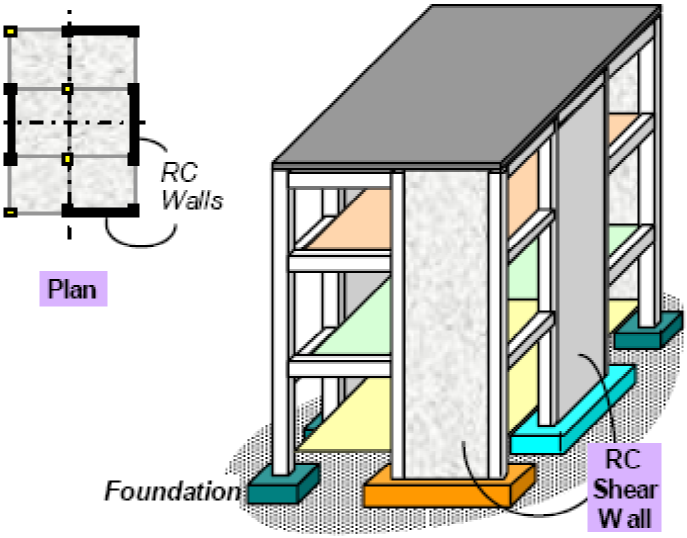


Details of reinforcement in a building with short column effect in some columns

26 Why are Buildings with Shear Walls Preferred in Seismic Regions

What is a Shear Wall Building?

Reinforced concrete (RC) buildings often have vertical plate-like RC walls called Shear Walls 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. Shear walls are like vertically-oriented wide beams that carry earthquake loads downwards to the foundation.



Reinforced concrete shear walls in Buildings

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 summarized in the quote:

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

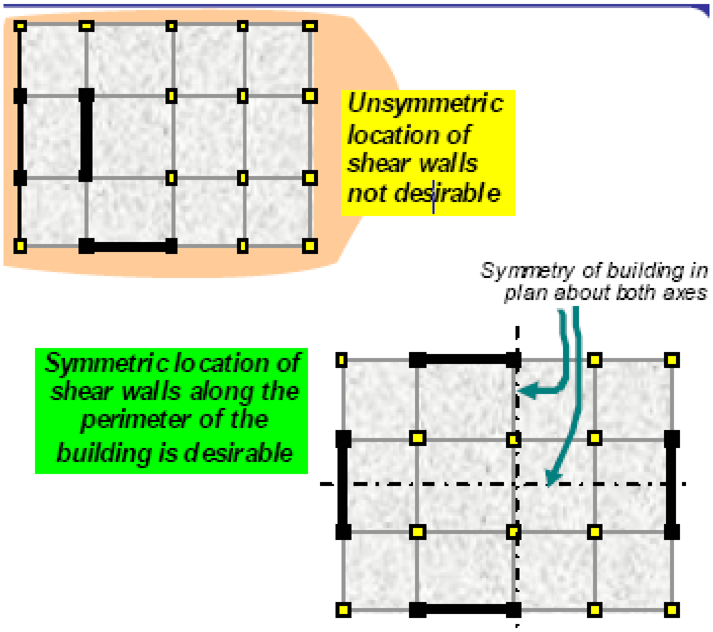
and effectiveness in minimizing earthquake damage in structural and nonstructural elements (like glass windows and building contents).

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. 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.

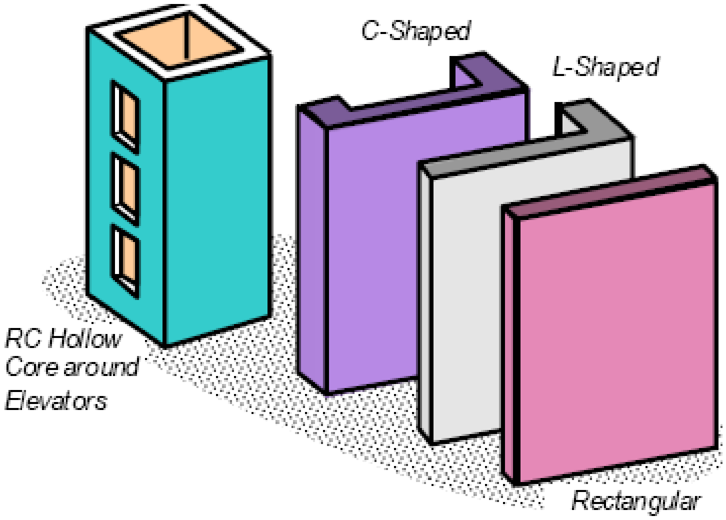


Shear walls must be symmetric in plan
Layout

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.

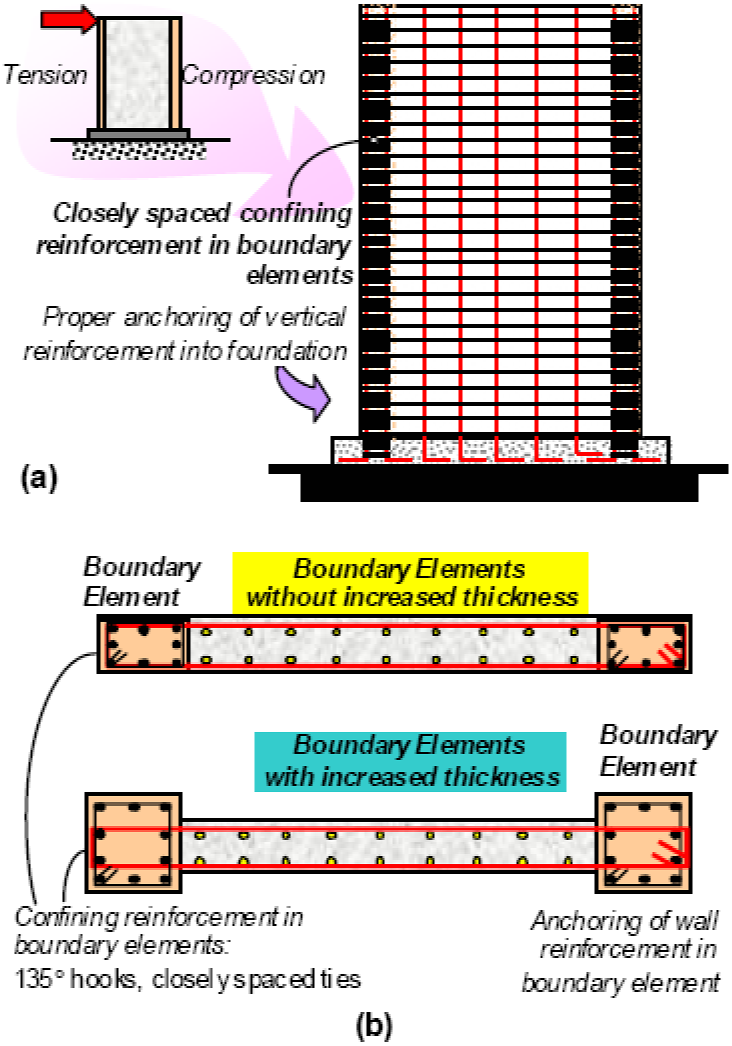
Overall Geometry of Walls: Shear walls are oblong in cross-section, i.e., one dimension of the cross-section is much larger than the other. While
Rectangular cross-section is common; L- and U-shaped sections are also used Thin-walled hollow RC shafts around the elevator core of buildings also act as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



Shear walls in RC Buildings

Reinforcement Bars in RC Walls: Steel reinforcing bars are to be provided in walls in regularly spaced vertical and horizontal grids. 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 losing strength. 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.



Layout of main reinforcement in shear
Walls as per IS: 13920-1993

27 How to Reduce Earthquake Effects on Buildings?

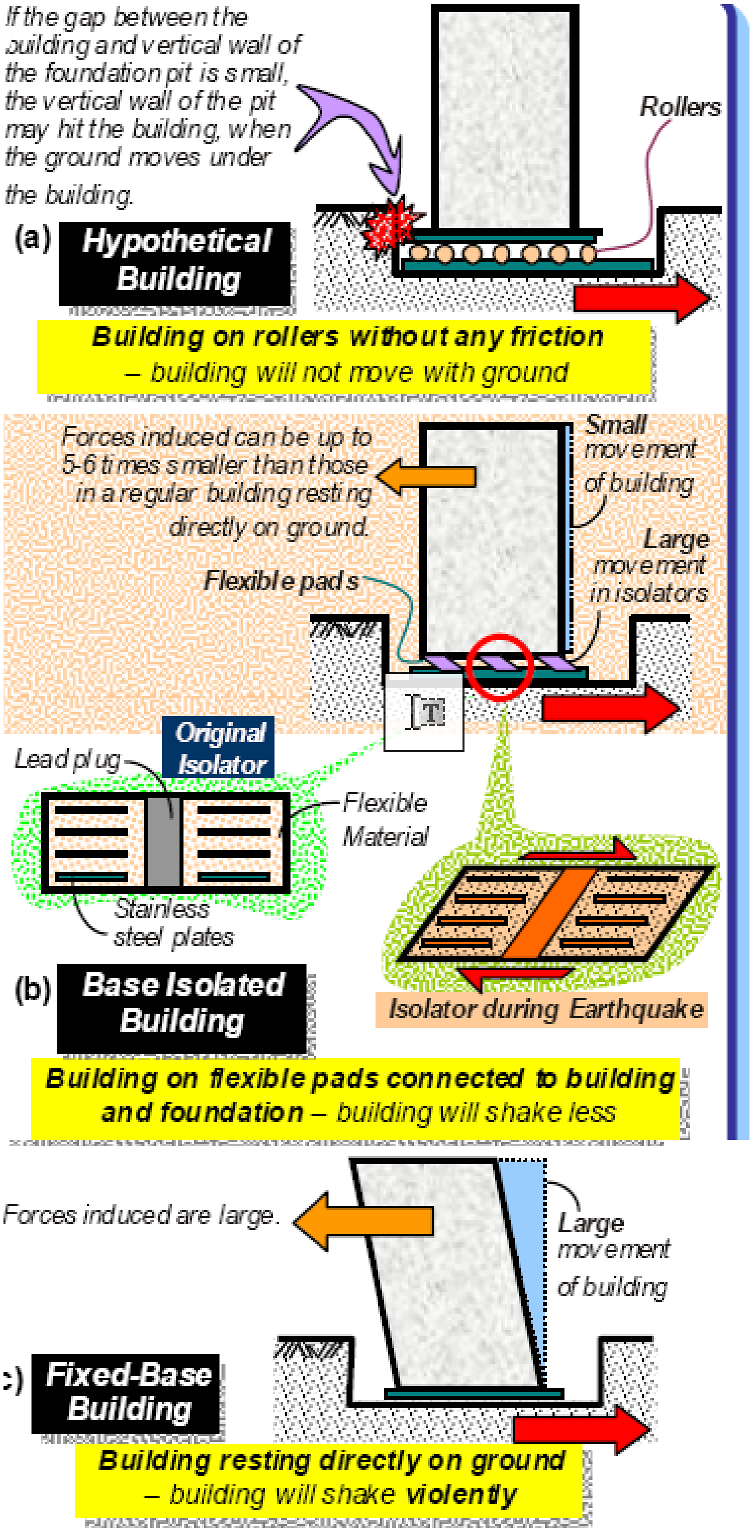
Why Earthquake Effects are to be Reduced

Conventional seismic design attempts to make buildings that do not collapse under strong earthquake shaking, but may sustain damage to non-structural elements (like glass facades) and to some structural members in the building. This may render the building non-functional after the earthquake, which may be problematic in some structures, like hospitals, which need to remain functional in the aftermath of the earthquake. Special techniques are required to design buildings such that they remain practically undamaged even in a severe earthquake. Buildings with such improved seismic performance usually cost more than normal buildings do. However, this cost is justified through improved earthquake performance.

Two basic technologies are used to protect buildings from damaging earthquake effects. These are Base Isolation Devices and Seismic Dampers. The idea behind base isolation is to detach (isolate) the building from the ground in such a way that earthquake motions are not transmitted up through the building, or at least greatly reduced. Seismic dampers are special devices introduced in the building to absorb the energy provided by the ground motion to the building (much like the way shock absorbers in motor vehicles absorb the impacts due to undulations of the road).

Base Isolation

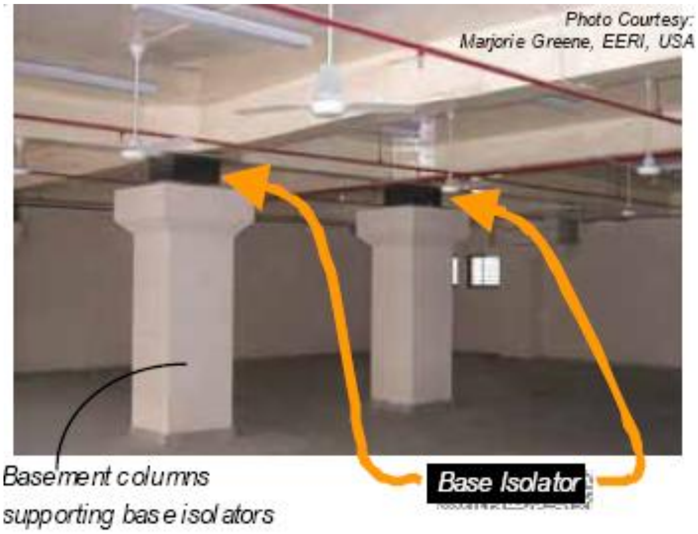
The concept of base isolation is explained through an example building resting on frictionless rollers. When the ground shakes, the rollers freely roll, but the building above does not move. Thus, no force is transferred to the building due to shaking of the ground; simply, the building does not experience the earthquake. Now, if the same building is rested on flexible pads that offer resistance against lateral movements (Figure 1b), then some effect of the ground shaking will be transferred to the building above. If the flexible pads are properly chosen, the forces Induced by ground shaking can be a few times smaller than that experienced by the building built directly on ground, namely a fixed base building. The flexible pads are called base-isolators, whereas the structures protected by means of these devices are called base-isolated buildings. The main feature of the base isolation technology is that it introduces flexibility in the structure. As a result, a robust medium-rise masonry or reinforced concrete building becomes extremely flexible. The isolators are often designed to absorb energy and thus add damping to the system. This helps in further reducing the seismic response of the building. Several commercial brands of base isolators are available in the market, and many of them look like large rubber pads, although there are other types that are based on sliding of one part of the building relative to the other. A careful study is required to identify the most suitable type of device for a particular building. Also, base isolation is not suitable for all buildings. Most suitable candidates for base-isolation are low to medium-rise buildings rested on hard soil underneath; high-rise buildings or buildings rested on soft soil are not suitable for base isolation



Building on flexible supports shakes Lesser

Base Isolation in Real Buildings

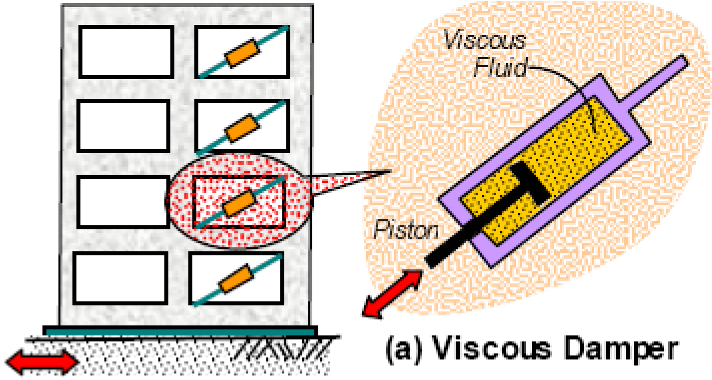
Seismic isolation is a relatively recent and evolving technology. It has been in increased use since the 1980s, and has been well evaluated and reviewed internationally. Base isolation has now been used in numerous buildings in countries like Italy, Japan, New Zealand, and USA. Base isolation is also useful for retrofitting important buildings (like hospitals and historic buildings). By now, over 1000 buildings across the world have been equipped with seismic base isolation. In India, base isolation technique was first demonstrated after the 1993 Killer (Maharashtra) Earthquake [EERI, 1999]. Two single storey buildings (one school building and another shopping complex building) in newly relocated Killer town were built with rubber base isolators resting on hard ground. Both were brick masonry buildings with concrete roof. After the 2001 Bhuj (Gujarat) earthquake, the four-storey Bhuj Hospital building was built with base isolation Technique.



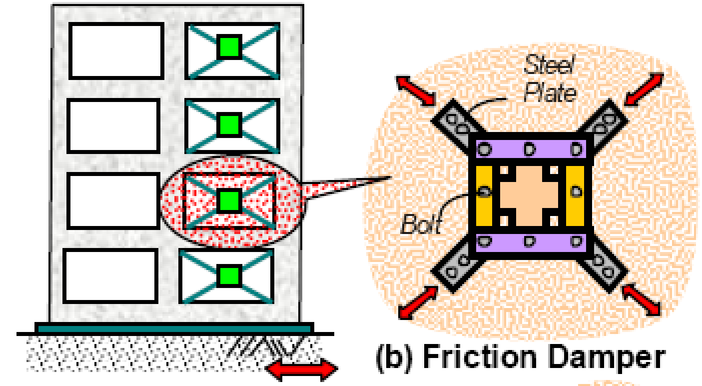
View of Basement in Bhuj Hospital Building

Seismic Dampers

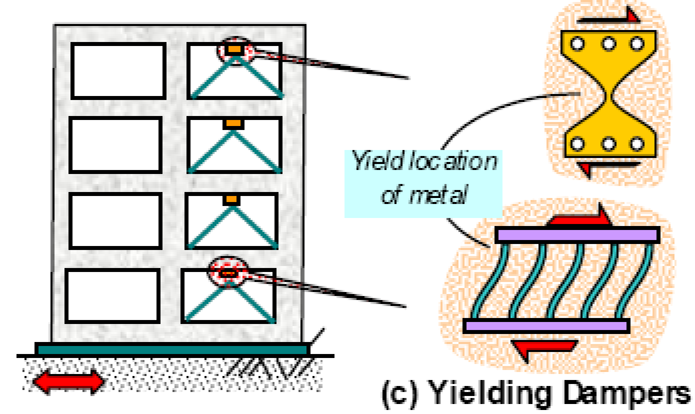
Another approach for controlling seismic damage in buildings and improving their seismic performance is by installing seismic dampers in place of structural elements, such as diagonal braces. These dampers act like the hydraulic shock absorbers in cars – much of the sudden jerks are absorbed in the hydraulic fluids and only little is transmitted above to the chassis of the car. When seismic energy is transmitted through them, dampers absorb part of it, and thus damp the motion of the building. Dampers were used since 1960s to protect tall buildings against wind effects. However, it was only since 1990s, that they were used to protect buildings against earthquake effects. Commonly used types of seismic dampers include viscous dampers (energy is absorbed by silicone-based fluid passing between piston-cylinder arrangement), friction dampers (energy is absorbed by surfaces with friction between them rubbing against each other), and yielding dampers (energy is absorbed by metallic components that yield). In India, friction dampers have been provided in an 18-storey RC frame structure in Gudgeon



(a) Viscous Damper



(b) Friction Damper



(c) Yielding Dampers

Seismic Energy Dissipation Devices

28 CONCLUSIONS

The effects of building form and configuration refers not only to the overall building shape but to its design and constructional details also. Study of building performance in the past earthquakes indicates that the performance is quiet sensitive to even a small variation in the overall form. This is particularly true in relation to shear wall design and the location of service core, which acts as a major lateral resistance elements. Many buildings that were symmetrical and simple in overall plan suffered because of unsymmetrical location of service cores and escape staircases. Moreover, as soon as the structure begin to suffer damage (cracking in shear wall or columns) the distribution of its resistant elements change and thus most symmetrical structure becomes dynamically asymmetrical and is subjected to tensional forces.

Finally it must be recognized that the architectural requirements will often make asymmetrical design difficult or sometimes impossible. In these circumstances it is necessary, depending upon the size of the building and the type of asymmetry, to subdivide the major masses of the building to improve the seismic performance.