MAKING BUILDINGS SAFE AGAINST EARTHQUAKES

A PRIMER




Central Public Works Department

Indian Buildings Congress

Indian Institute of Technology Madras

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PREFACE

Earthquakes are one of nature's greatest hazards to life on our planet. The impact of this natural phenomenon is sudden, with little or no warning to make preparations against damages and collapse of buildings/structures. India is an earthquake prone country and has experienced several major/moderate earthquakes during the last 15 years. The earthquakes at Latur (1993), Jabalpur (1997), Chamoli (1999), Bhuj (2001), Andaman and Nicobar Islands (2004) and Kashmir (2005) have exposed the vulnerability of buildings in India. Many existing buildings do not meet the requirements of seismic design. Almost 85% of the total buildings are non-engineered buildings made up of earthen, stone or brick masonry walls and timber, thatch, tile or slate roofs. In the event of a major earthquake, there is likely to be substantial loss of lives and property.

The present booklet has been envisaged to address the serious and widespread problem of seismic vulnerability of buildings. It is written in a simple language for the lay reader to broadly understand the aspects of seismic design and retrofit of buildings. A handout is also prepared to generate awareness about the do's and don'ts of seismic design of buildings and questions to be asked before buying a house. The owner of a building will know when he or she needs to consult a structural consultant for detailed evaluation and retrofit measures.

Seismic retrofit is primarily applied to achieve public safety and is determined by economic considerations. Considering this, the Central Public Works Department (CPWD) and the Indian Buildings Congress (IBC) conceived a *Handbook on Seismic Retrofit of Buildings*. CPWD and IBC are pleased to associate the Indian Institute of Technology Madras, in the endeavour of preparing the Handbook and this booklet. The project was funded by CPWD. The Handbook covers the methods of evaluation of buildings for seismic forces, retrofitting measures for a wide range of buildings: non-engineered buildings, buildings made of masonry, reinforced concrete or steel, and historical cum heritage structures. The geotechnical aspects of seismic hazards, retrofit of foundations, retrofitting using fibre reinforced polymer and other advanced technologies, issues of quality assurance and control and two case studies are also covered.

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PREAMBLE

This booklet gives a simple overview of the main aspects of the *Handbook on Seismic Retrofit of Buildings*, and is meant especially for the lay reader — the common man who is not expected to have a background in the design of buildings.

Is my building safe against earthquakes? This is a question that everybody should be concerned about. Many earthquakes have taken place recently in India and its neighbourhood [e.g., Uttarkashi (1991), Latur (1993), Jabalpur (1997), Bhuj (2001), Sumatra and Andaman Islands (2004), Kashmir (2005)], and these have proved to be disastrous. A large number of buildings have collapsed and countless lives have been lost.

There is usually a huge public outcry after every disaster. But public memory is short-lived, and people tend to forget, until another major tremor occurs to wake them up. When and where will that quake happen? Nobody can predict this. But when it comes one day, unexpectedly, it destroys our buildings and takes our lives. Can we do something to save our lives and protect our buildings? Yes!

A typical earthquake lasts for less than a minute, but can destroy a city built over a period of centuries. The earthquakes that last longer often cause more damage than earthquakes of shorter duration. The time is too short for people to escape from most buildings. Therefore, the only way to ensure survival is by ensuring that buildings do not collapse during earthquakes, even though damage may be unavoidable.

Earthquakes do not kill, unsafe buildings do.

This introductory material provides basic education on earthquake safety of buildings. Find out how safe is your building against earthquakes, by getting it assessed for *seismic safety*. Understand the risk involved and the necessary action to be taken. If the building is unsafe and the strengthening of the building is financially viable, get it done. It is an insurance worth having. The strengthening of a building for earthquakes is referred to as *seismic retrofitting*. The present material will give you some ideas on how a building can be retrofitted.

Also, if you are planning to invest in a new building, the information given in this booklet will enable you to identify and demand the desirable earthquake resistant features in the building. You will know what questions to pose to your builder. You will realize the importance of getting multi-storeyed buildings (such as apartment blocks) proof-checked and certified for compliance with the prevailing design standards[1], so as to make sure that your investment and life are reasonably safe.

Prevention is better than cure.

FACTS YOU NEED TO KNOW ABOUT EARTHQUAKES

Why Does the Earthquake Occur?

An earthquake is a natural phenomenon associated with violent shaking of the ground. To understand why the ground shakes, it is necessary to know something about the interior of the earth. The earth is not a simple solid sphere as it appears to be on the surface. It is made up of several layers (crust, mantle, outer core, inner core), some of which are far from solid (Figure 1). The outermost layer (soil and rock), called the *crust* of the earth (thickness ~5 to 40 km), is over another layer called the *mantle* (thickness ~2900 km). The mantle is fluid in nature and is over the *core*. The outer portion of the core (thickness ~2200 km) is made of a very hot and dense liquid, while the inner core (radius ~1290 km) is solid and metallic.

The differences in temperature and pressure across the interior of the earth results in continuous dynamic activity, although this cannot be easily sensed from the surface where we live. The activity is felt periodically at different locations on the surface crust through various types of disruptions (volcanoes, earthquakes, tsunamis).

The crust is fractured into many pieces, called tectonic plates, which tend to move continually on the mantle (which sets up 'convection' currents). The various plates move in different directions and at different speeds. When two adjoining plates collide against each other, they often end up forming mountains on the earth's surface over a period. Continued movement of the plates will cause these mountains to increase in height, as in the case of the Himalayas. Other types of relative motions at the plate boundaries are also possible, causing earthquakes.

[1] Standards and codes of practice in India are published by the Bureau of Indian Standards.

Owing to the friction generated at the plate boundaries, the free relative movement between plates is prevented and a large amount of energy (called strain energy) gets built up along the plate boundaries. The resulting high stress eventually exceeds the strength of the rock along weak regions (called faults). This local failure results in a sudden release of a tremendous amount of the built up energy, which is felt in the form of sudden and violent ground shaking in a very short time (often less than a minute).

The released energy spreads through seismic waves (such as 'body waves' and 'surface waves') in all directions, reflecting and refracting, as they travel across various strata (Figure 2).

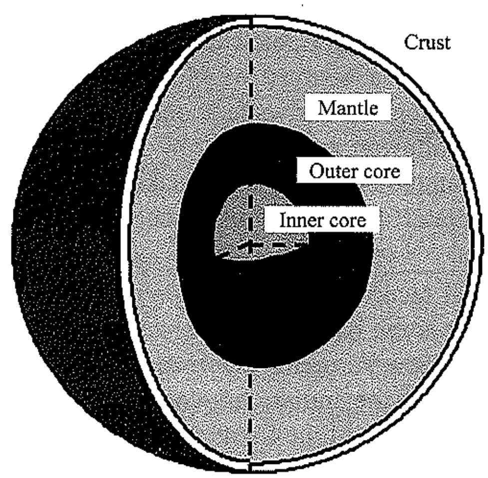


Figure 1 The earth and its interior (Murty, 2005)

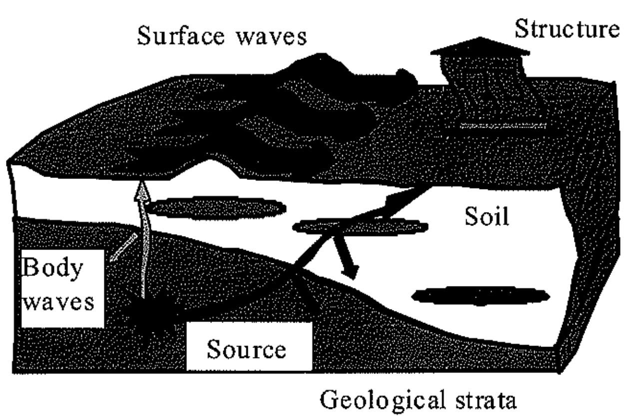


Figure 2 Movement of waves during an earthquake (Murty, 2005)

When and Where Does the Earthquake Occur?

When and where exactly does the release of the built-up energy take place? If only we had some fore-warning about this, we could do much to save lives, if not buildings. Unfortunately, this cannot be predicted scientifically, as of now.

The timing of this natural phenomenon eludes the scientists, unlike other natural events like eclipses, whose occurrence can be predicted with accuracy. In the case of earthquakes, we have no idea when and where the next one will occur. When, for example, will the next major earthquake hit an urban centre like Delhi or Mumbai? It could happen today, or after a month, or a year, or several decades later.

Historical records reveal the tendency of earthquakes to revisit regions after an interval of time (called *return period*), which is variable (random). That is why there is concern when several decades (or, sometimes, a century or more) have elapsed since the last major earthquake had hit a particular region. Conversely, once a major earthquake has occurred at a particular place (sometimes followed immediately by a series of minor tremors called after-shocks), there is less danger of another major earthquake (of similar intensity) occurring at the same location in the immediate future. For this to occur, the strain energy has to build up again over many more years.

We know, from historical records that some regions of the earth are more vulnerable to earthquakes than others. This is the basis of *seismic zonation.* However, with the passage of time, the earth can throw up new surprises (such as dormant faults becoming active). For example, the Deccan plateau of the Indian sub-continent was considered to be relatively earthquake-free, until the occurrence of the Latur earthquake in 1993. There is a need to keep monitoring and updating the activity of the faults.

The current seismic zones in India are codified in the Indian Standard IS 1893: 2002 and are reproduced in Figure 3. There are four zones in the country and they are denoted as II, III, IV and V. Zone I which existed in the earlier versions of the code, has been upgraded to Zone II or higher. The higher the zone, the more vulnerable is that region to a major earthquake.

Location and Size of an Earthquake

The location of an earthquake is described by the *epicentre.* As illustrated in Figure 4, the epicentre is the location on the surface of the earth, exactly above a point called focus, from where the seismic waves have initiated. The epicentre is identified from the data of ground motion recorded by several seismograms. The depth of the focus below the epicentre is designated as the focal depth, which can extend up to several kilometers. The distance of a location on the earth surface from the epicentre is termed as the epicentral distance.

The size of an earthquake is measured by the strain energy released along the fault. It is expressed as a *magnitude.* The commonly used scale for expressing the magnitude is the Richter scale. An earthquake with a magnitude of 8.0 is referred to as M8.0 earthquake. Every unit increase in magnitude implies an increase of about 31 times the energy. Thus, the energy

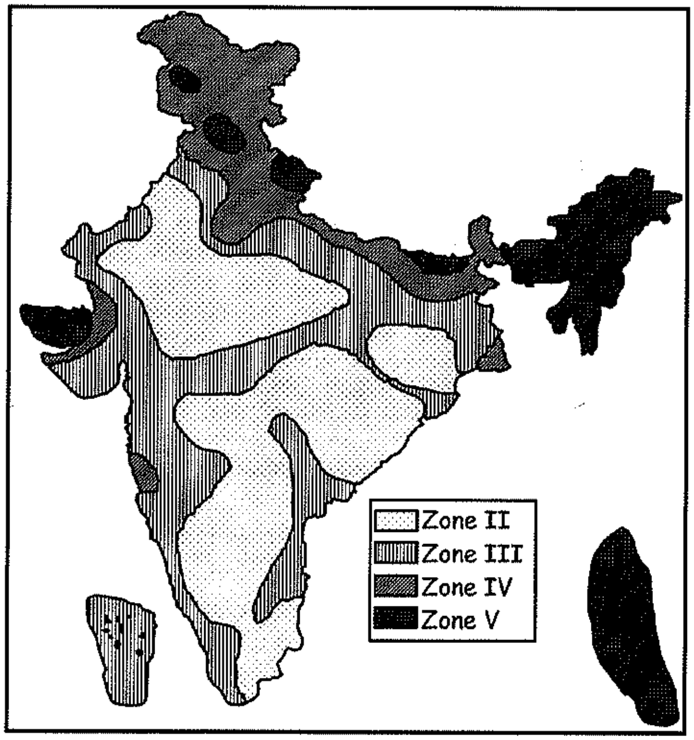


Figure 3 Seismic zones in India (IS 1893: 2002)

released during the M8.0 earthquake is 31 times that of an M7.0 earthquake, and $(31)^2$ times (close to 1000 times) the energy of an M6.0 earthquake.

The effect of an earthquake on a building depends on various factors, including how close is the building from the epicentre (epicentral distance as shown in Figure 4). The magnitude of an earthquake does not give an indication of the effect experienced at different locations on the surface, having different epicentral distances. For this, the appropriate measure is *intensity*, which is a qualitative description of the effects of the earthquake at a particular location. The Modified Mercalli Intensity (MMI) Scale, ranging from I to XII, is commonly used to measure intensity. It is based on the observed damage and human reactions at a location. The Indian standard IS 1893: 2002 refers to the Medvedev-Sponheuer-Karnik (MSK) intensity scale with 12 categories of damage: I) Not noticeable, II) Scarcely noticeable, III) Weak, partially observed, IV) Largely observed, V) Awakening, VI) Frightening, VII) Damage of building, VIII) Destruction of building, IX) General damage to buildings, X) General destruction of buildings, XI) Destruction, XII) Landscape changes.

Damage Caused by an Earthquake

The extent of damage depends not only on the size of an earthquake (either in terms of magnitude or intensity), but also on the type of construction practice followed in a particular

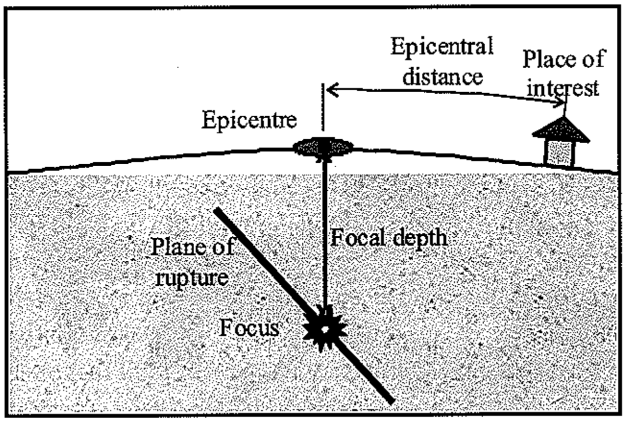


Figure 4 Terminology related with the location of an earthquake (Murty, 2005)

region or country. For example, an earthquake in Tokyo or Los Angeles may result in damage of only a few buildings because strict construction regulations are adopted; but a similar earthquake may be catastrophic in Mumbai or Delhi, in terms of buildings damaged and lives lost, because the building design and construction practice are not adequately regulated.

Let us not forget: ***earthquakes do not kill, unsafe buildings do.***

Our efforts should be directed to mitigating the potential disaster, by ensuring that buildings have the desired resistance to withstand the forces, to the extent possible. Seismic retrofit of existing buildings is probably the surest way to mitigate the disaster.

Do's and Dont's during an Earthquake

The earthquake, when it occurs, catches human beings by surprise. Sometimes, the earthquake announces its imminent arrival with a rumbling noise. It makes its presence felt by shaking, which may be mild or violent, but not lasting for more than a minute. In those precious moments, we must try to remain calm and take appropriate action. What action to take depends on whether we are located indoors or outdoors. The following are some simple and practical suggestions to follow.

If indoors, and if we suspect that the building is structurally weak, our safety lies in making an exit from the building by the shortest and fastest route. Do not use the lift. On the other hand, if the building is structurally safe, remaining indoor is the best option. Do not try to exit the building during the shaking. Avoid doorways, as doors may slam and cause injuries. For safety, drop to the floor, get underneath a sturdy cot or table and hold on to its base (Figure 5). Keep away from possible falling objects. If the tremor is violent, then after the shaking is over, it is wise to exit the building, in view of possible after-shocks and damage to the structure.

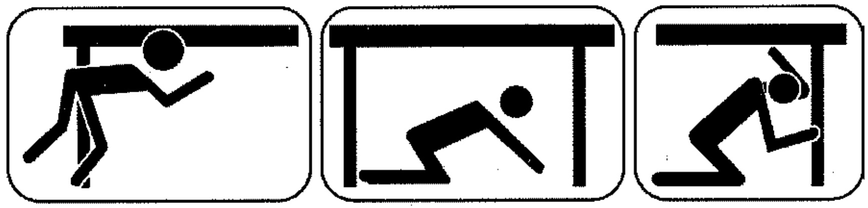


Figure 5 Safety measures while indoors

If outdoors, move to an open area, away from buildings and objects that could possibly fall (such as sign boards, poles and overhead power lines). If driving, pull over to the side of the road and park at a safe place, not blocking the road. Additional guidelines are published by the National Institute of Disaster Management.

FACTORS AFFECTING THE RESPONSE OF A BUILDING

Types of Buildings

Ordinary buildings are commonly classified as either *load bearing* or *framed* structures. Most low-rise buildings are load bearing buildings made of masonry walls, which resist both gravity loads and lateral loads due to wind and earthquake. As the building height increases, and in high seismic zones, lateral loads tend to govern the design. In such cases, it is structurally efficient and economical to adopt framed buildings.

Basic Components of a Masonry Building

The basic components of masonry buildings are roofs, floor slabs, walls and foundations (spread wall footings). The floor and roof slabs in modern buildings are made of reinforced concrete[2]. In traditional buildings, these have been made using other materials such as timber, lime concrete jack arch, metallic sheets, thatch or tiles. The walls and footings are mainly made of bricks or stones, laid in horizontal courses, with mortar filling up the gaps and providing the required bond between the units. The mortar is usually made with sand, mixed with cement, lime and/or mud, and water. Modern buildings are usually built using cement mortar, while traditional building have been built using lime mortar or mud mortar. Mud mortar, which continues to be used in low-cost construction, is relatively weak and unsafe.

Basic Components of a Framed Building

In a framed building, the basic skeleton (frames) comprises of beams, columns and footings (Figure 6). In India, the framed buildings are commonly made of reinforced concrete. The

[2] Concrete is made of stone chips, sand, cement and water. Concrete is strong in compression and weak and brittle in tension. Hence, steel bars are placed in concrete to strengthen it for tension. This composite material is termed as reinforced concrete. Otherwise the concrete is termed as plain concrete.

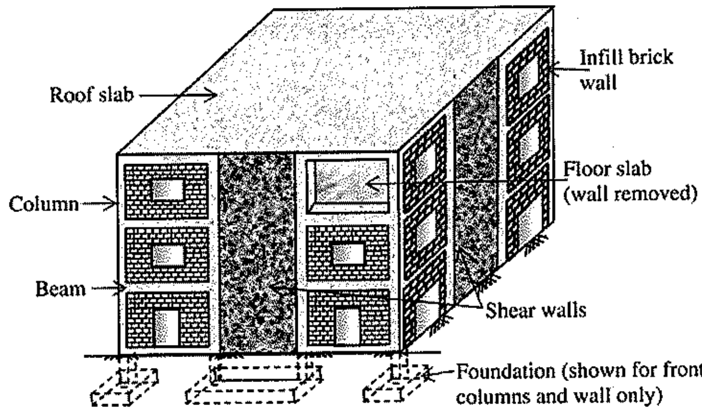


Figure 6 Components of a reinforced concrete building

framework resists both vertical and lateral loads. The walls in the framed buildings are not treated as load bearing. In high-rise buildings, properly designed reinforced concrete walls are often introduced to enhance the lateral strength. These walls are called *shear walls*.

The important factors that affect the response of a building to seismic forces are discussed. The essentials of design of the two types of buildings are briefly presented in subsequent sections.

Effect of Mass and Height

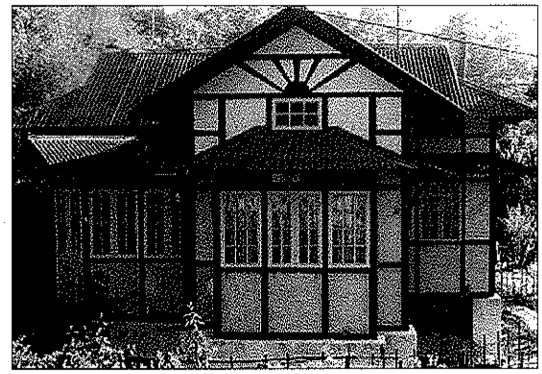
The earthquake as well as wind load acting on buildings are termed as 'lateral loads' since their effect is felt mainly in the horizontal direction. This is in contrast to the weights of the building and occupants, which act vertically down due to gravity. The forces during an earthquake, called *seismic forces*, are induced in the heavy masses present at various floor levels. This type of force is called inertial force and is calculated by the product of a mass and its acceleration during vibration.

If the mass is more, the seismic force is more.

For single storeyed buildings, there have been several failures due to heavy roof made up of stones, slates, poorly reinforced concrete slabs etc (Figure 7a). On the other hand, lighter buildings are affected less. This was an important lesson learned from the great Assam earthquake of 1897 (magnitude 8.1), which destroyed almost all buildings (up to 3 storeyed). Following this disaster, constructions were limited to single and double storeyed "Assam type" dwellings with light roof (Figure 7b). This was considered the ideal earthquake-resistant construction in North-East India, which falls under the highest seismic zone (Zone V) in the country.

For a multi-storeyed building, when the ground shakes during an earthquake, the building swings back and forth almost like an inverted pendulum, with the masses at higher levels

a) Failure of a house with heavy roof (after Chamoli earthquake, 1999) (Source: www.nicee.org)



b) "Assam type" building with light roof

Figure 7 Examples of low-rise buildings with heavy and light roofs

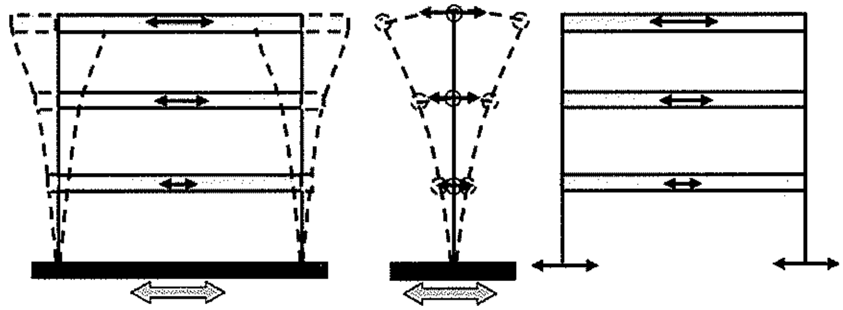


Figure 8 Generation of inertial forces and base shear due to ground motion

swinging more (Figure 8). Hence, the generated inertial forces are higher at the higher floor levels. Because of the cantilever action of the building (fixed to the ground and free at the top), the forces accumulate from top to bottom. The total horizontal force acting on the ground storey columns is a sum of the inertial forces acting at all the levels above. This is termed as the *base shear* and it leads to highest stresses in the lowermost columns. The base shear is expressed as a fraction of the weight of the building.

Heavier buildings attract larger seismic forces and hence, are prone to damage. Over the years, this basic lesson has been forgotten, and numerous high-rise buildings have mushroomed, especially in recent times in the urban centres of the country. Many of these buildings are deficient to resist seismic forces. Figure 9 shows an old building in Guwahati, originally 4-storeyed, to which three additional storeys were added recently – an example of a

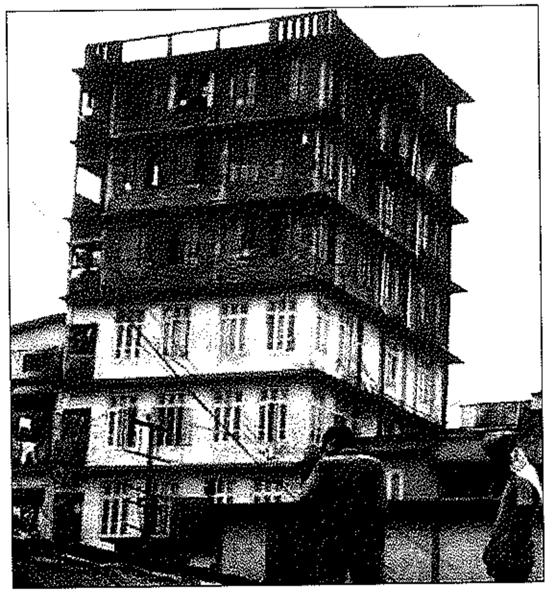


Figure 9 A 4-storeyed old building (in Zone V) extended to 7-storeyed!

potential man-made disaster, waiting to happen, in a highly congested area. To avert such disasters, local building authorities must strictly ensure that all new constructions comply with design standards. Existing buildings that are highly unsafe must be declared unfit for occupation (and, if located in congested areas, must be demolished), unless they are retrofitted appropriately.

Importance of Lateral Strength

A building is designed for adequate strength to resist the seismic forces that are expected to be generated due to a severe earthquake during the design lifetime of the building. This requirement is called *lateral strength*. This can be achieved by providing adequate lateral load resisting systems (such as reinforced concrete bands in single or double storeyed masonry buildings; frames, braces or shear walls in large buildings).

The strength of a building depends on the strength of every structural component. The strength is the magnitude of the maximum internal force (such as axial force or bending moment or shear) that a component can resist. When this strength is exceeded by the applied load, the component fails. The strength depends not only on the type of material (for example, steel is stronger than brick), but also on other factors, such as the size of the cross-section (for example, a 230 mm thick exterior brick wall is twice as strong as a 115 mm thick interior wall).

A structural component of a building should be designed to have a strength that is not less than the maximum internal force, associated with the seismic forces and gravity loads on the building. If the strength is not adequate, the component will fail. The failure of the vertical components in a building (such as load bearing walls, columns or footings) is more critical than that of the horizontal components (such as beams and slabs). This is because the former type of failure is likely to trigger a collapse of the entire building, whereas the failure of a beam may cause only a local damage. In the Gujarat earthquake in 2001, multi-storeyed buildings collapsed because of the failure of the columns in the ground storey (Figure 10).

An important principle adopted in the design of framed buildings is the following:

The soil must be stronger than the foundations.
The foundations must be stronger than the columns.
The columns must be stronger than beams.

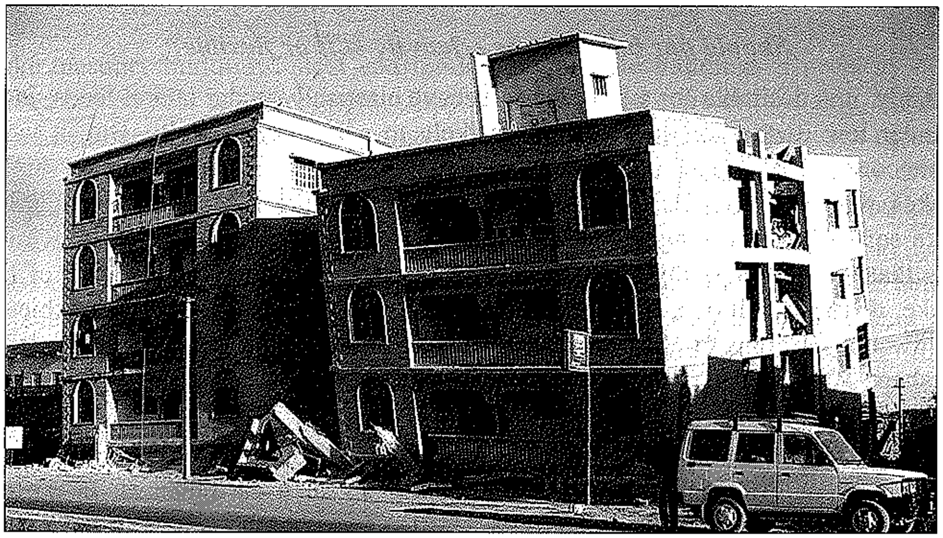


Figure 10 Collapse of the ground storey of a building (after Bhuj earthquake, 2001) (Source: www.nicee.org)

Effect of Lateral Stiffness

Elasticity is a property by which a body or a structure, displaced by a load, regains its original shape upon unloading. It is by virtue of this property, that buildings that are pushed horizontally by wind or mild earthquake loads, return to the original vertical configuration after the wind or the tremor has passed (Figure 11). The building is said to behave *elastically*. Of course there can be some limited damage.

How much the building deflects under a given load is measured by a property called stiffness, which may be defined as the force required to cause unit deflection. The stiffness required to resist lateral forces is termed as *lateral stiffness*. The stiffer the building, the lesser it will drift (as indicated in Figure 11)

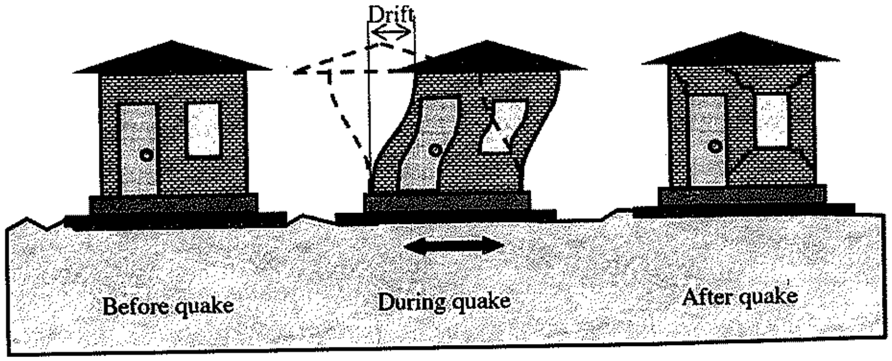


Figure 11 Elastic behaviour of a building (Murty, 2005)

Should our buildings be relatively stiff or flexible?

Certainly, it is desirable for a building to behave elastically under lateral loads, including forces under low earthquake levels that are likely to occur occasionally. But, it would be highly uneconomical to design ordinary buildings to behave elastically under high level earthquakes, which are rare. Because of the limitation of resources, the design standards allow us to take some risk of damage in the event of a rare severe earthquake. What we need to ensure is that the building, although likely to be severely damaged in the event of the rare earthquake, does not collapse, so that lives are not lost. How do the engineers achieve this? They allow the building to behave inelastically (that is, the building does not regain its original shape after the earthquake) at such high load levels. The building's original stiffness gets degraded, and it becomes flexible.

Of course, there must be adequate lateral stiffness in buildings for low level earthquakes. Otherwise, they will get damaged beyond repair under such earthquakes. In the case of exceptionally important buildings (such as nuclear reactors), it is desirable to have sufficient stiffness to ensure elastic behaviour even under rare earthquakes. They must survive at all cost, and that too without damage.

The mass and lateral stiffness of the building contribute to another important structural property, called the *natural period* of vibration. It is the time taken by the building to undergo a cycle of to-and-fro movement (like a pendulum). Buildings with high stiffness and low mass have low natural periods, whereas buildings with low stiffness and high mass have high natural periods. The value of this natural period also governs the magnitude of seismic force that the building will attract. This is similar to the effect of resonance in a vibrating system. The conventional buildings of a few storeys, common in urban areas, have low natural periods and attract seismic forces which are high fractions of their weight.

Importance of Ductility

The ability of a structure to deform with damage, without breaking suddenly (without warning), is termed as *ductility*. With ductility, a building can continue to resist seismic forces without collapsing. There is a story of a proud tree teasing a blade of grass for not being able to stand erect in the wind. But, when a very severe storm came, it was the tree which fell down. The blade of grass survived, although it was tilted (Figure 12). This is because the blade of grass was able to undergo very large deformation without breaking down, unlike the big tree which snapped suddenly at its base, when its strength was exceeded.

In a similar way, buildings too can exhibit either ductile or brittle (non-ductile) behaviour, depending on the structural material, design and detailing. Materials like brick, stone and plain concrete are relatively brittle. When bricks or stones are used in masonry wall construction without adequate bond, they can fall apart suddenly, even if the walls are relatively thick. This indeed is how many buildings collapsed during the Latur earthquake and Kashmir earthquake (Figure 13). Many such buildings have weak mud mortar or no mortar at all. On the other hand, masonry buildings with reinforced concrete bands can exhibit better behaviour.

Unlike masonry buildings, steel and reinforced concrete buildings if properly designed and detailed can possess considerable ductility. In a reinforced concrete building, the ductility is achieved by allowing the reinforcing steel to yield (to deform substantially at a certain level of stress) at certain locations while retaining the load carrying capacity in concrete. The requirement of reinforcement is explained in Section 5.4. Similarly, in a steel building, the ductility is achieved by the yielding of the steel at certain locations.

If the beams and columns in a framed building can "hang on" through ductile behaviour, without breaking down during the brief period of the major earthquake, the building will not collapse, even though it may get damaged. Such ductile buildings attract lesser load with increasing deformation (since stiffness gets reduced) than the buildings which remain stiff.

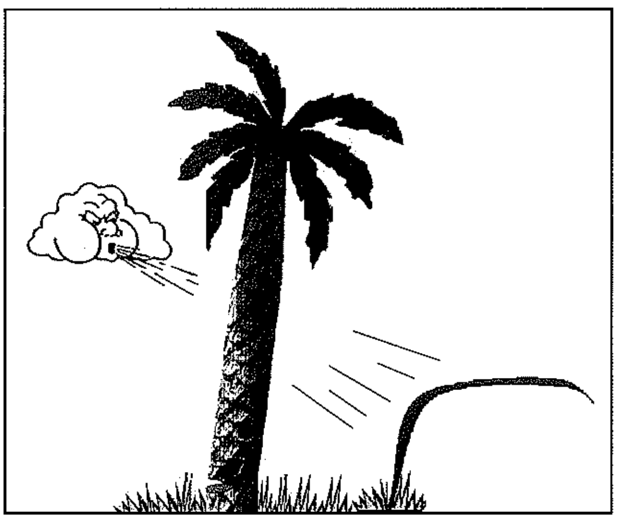


Figure 12 Blade of grass survives, but the tree does not!

a) After Latur earthquake, 1993
(Source: www.nicee.org)

b) After Kashmir earthquake, 2005
(Courtesy: Central Public Works Department)

Figure 13 Collapse of brittle and poorly bonded stone masonry walls

Also, a significant amount of the energy that generates in the building during the earthquake gets dissipated, with reduced chances of sudden collapse.

Sadly, most of the existing buildings in our country seem to lack adequate ductility – even the so called "engineered" buildings, primarily due to lack of attention paid to seismic design and detailing.

Importance of Integrity

To ensure that the seismic forces are safely transmitted from the floor levels to the foundations, the connections of the various components should be adequate. This requirement is part of ensuring the *integrity* of the building. In a masonry building, the roof and any intermediate floor slab (between the roof and ground floor) should be strongly connected to the walls. Also, the walls should be properly inter-connected. If the connections between the walls or between the slab and the walls are not effective, a building has limited strength to resist seismic forces. The walls can collapse even under a minor earthquake shaking (Figure 14b). Figure 15 illustrates the collapse of walls due to poor integrity.

In a masonry building, if reinforced concrete bands are provided in walls at plinth, lintel, sill and roof (for sloping roofs) levels and the wall-to-wall connections provide good bond (that is, the walls do not "open out"), the walls and roof will act together like a box. This will enable the building to resist even a major earthquake effectively (Figure 16).

In a framed building, the beam-column joints and the column-foundation joints should have the required strength. The more the number of adequate frames in a building, the less is the potential for collapse of the building. This is because when one component fails, other components take an increasing share of the load. This provision of having multiple load paths in a building is called redundancy and it makes the building stronger as a whole.

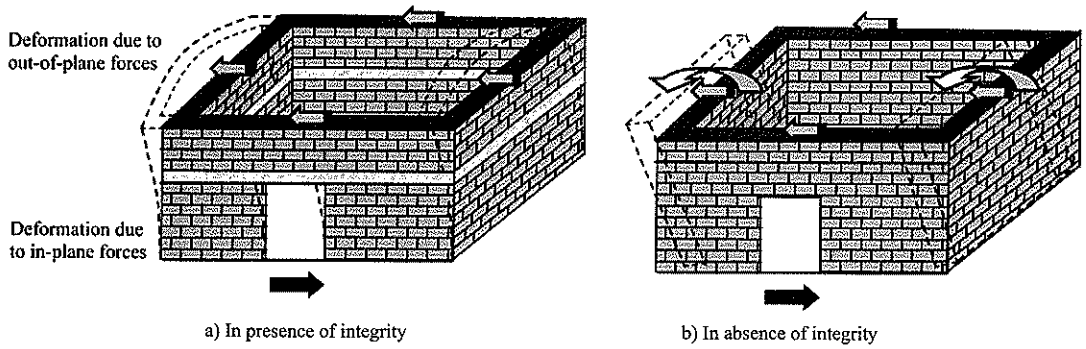


Figure 14 Behaviour of walls in a box type building (Murty, 2005)

Figure 15 Poor integrity in a masonry building (after Latur earthquake, 1993) (Source: www.nicee.org)

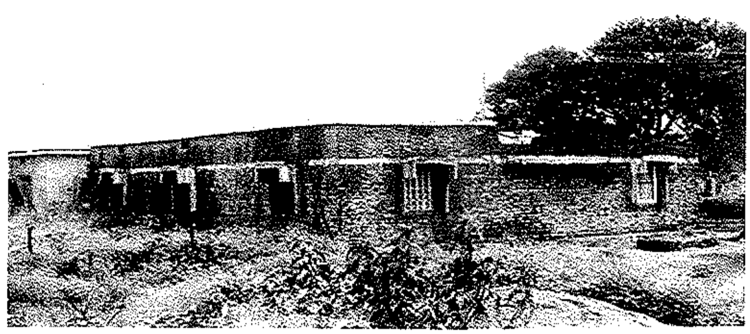


Figure 16 Good integral action in a masonry building with lintel band (after Latur earthquake, 1993) (Source: www.nicee.org)

Figure 17 Lack of integrity between lift core and rest of the building (after Bhuj earthquake, 2001) (Source: www.nicee.org)

Reinforced concrete shear walls, commonly provided around lift cores, are usually very strong and stiff. However, unless these shear walls are integrally connected to the rest of the building framework, they will not serve the desired purpose. Figure 17 illustrates such a situation where the lift core alone is found to survive with relatively little damage, but the rest of the building separated out due to lack of integrity and collapsed.

Providing resistance to buildings for seismic forces is primarily the responsibility of the engineers. But architects also have a major role to play. Some architectural features, relating to the layout in plan, shape and vertical configuration, are unfavourable for seismic forces and invite potential disaster. It is desirable that the persons owning or using a building knows something of these features, if the building is located in a high seismic zone. In such regions, safety should be given priority to fancy looks. Otherwise, structural design has to be done carefully and competently. In general, if the basic architectural features favouring good seismic resistance are adopted, the cost of making the building resistant to seismic forces is less.

Effect of Layout in Plan

The *plan* implies the view of the building vertically down from a point sufficiently above the building. A building should have a simple geometrical shape in plan, such as rectangular or circular. All rectangular shapes are not uniformly good. If the building is too long in one direction, it is likely to be damaged during an earthquake. A building with large cut-outs (or openings) in the floors and roofs is undesirable, as these affect the integrity of the building. Buildings which are 'H', 'L' 'T', 'U', '+', or similar shapes in plan are also undesirable, because these shapes generate severe stresses at the interior corners of the buildings (Figure 18). Each wing of such a building tends to vibrate separately in the event of an earthquake, causing serious damage that may lead to collapse (Figure 19).

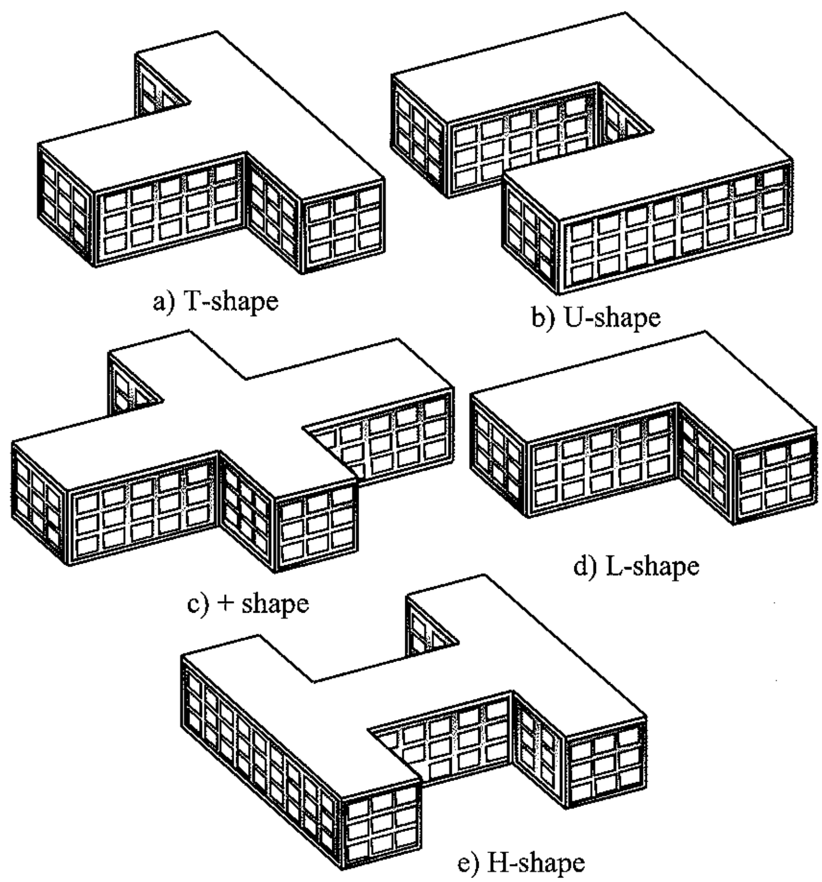


Figure 18 Layout of buildings with high potential of damage during an earthquake

Figure 19 Collapse of an "L" shaped building (after Skopje earthquake, Macedonia, 1963)

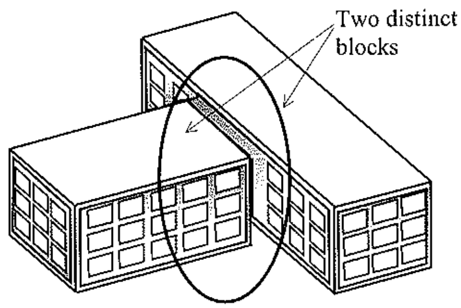


Figure 20 Building with separation joint between its two distinct "wings"

Buildings which are not symmetric in plan tend to twist under an earthquake, inviting further damage. A general rule of thumb is to make the building as simple, solid and symmetric in plan as possible. If complex geometries are absolutely required, then it is desirable to break up the building plan into separate simple rectangular segments with proper separation joints, so that they behave as individual units during an earthquake (Figure 20).

When a huge mass, such as a roof-top water tank, is not placed symmetrically or when the layout of the frames is asymmetric in plan or the building is long and narrow, the resultant line of action of the inertial force at a level is likely to be substantially off from that of the resisting forces in the storey underneath. In such cases, the buildings will not only sway to-and-fro, but also twist in plan. This twisting action (torsional effect) introduces additional stress in the corners, that must be accounted for in the design. It is best to avoid such problem, by removing the asymmetry.

Effect of Configuration in Elevation

The *elevation* refers to the horizontal view of the building from a point sufficiently away. Buildings should be simple not only in plan but also in elevation. The walls and columns should continue uninterrupted from top to bottom, to ensure transmission of forces to the supporting ground through the shortest and simplest path. If there is any discontinuity in the path of load transmission, there is a high potential of damage in the event of an earthquake. Hence, hanging or floating columns (columns which are supported on beams and do not continue to the foundation) and discontinuity of walls in the ground storey (open ground storey) should be avoided (Figure 21). Walls are not continued in the ground storey for the requirement of parking or shop space. The height of the ground storey is increased for the head room requirement or for the comfort of the first floor tenants. Figure 22 shows an existing residential multi-storeyed building with an open ground storey for car parking.

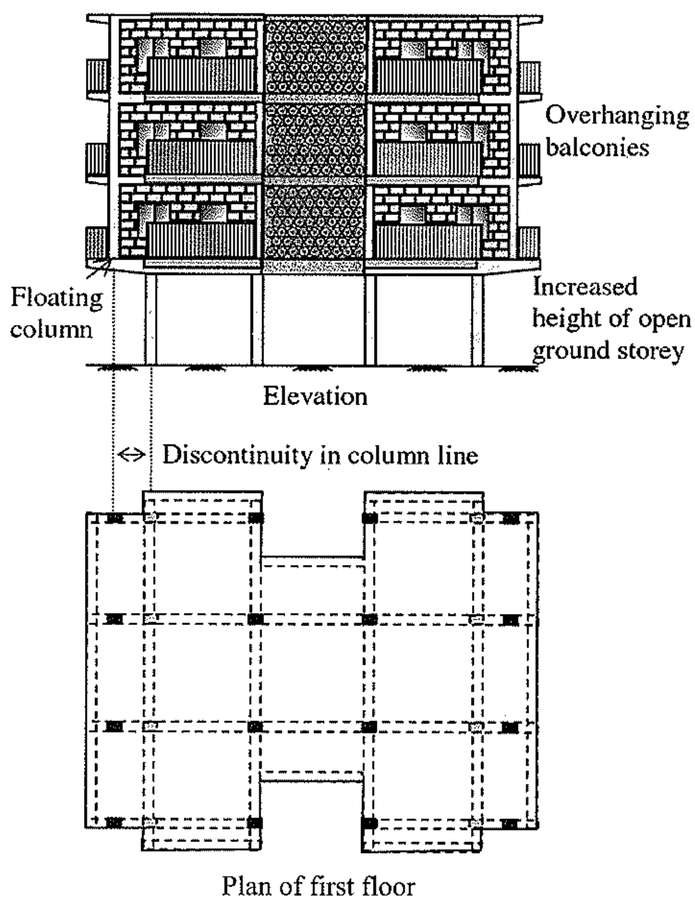


Figure 21 Buildings with discontinuities in columns or walls

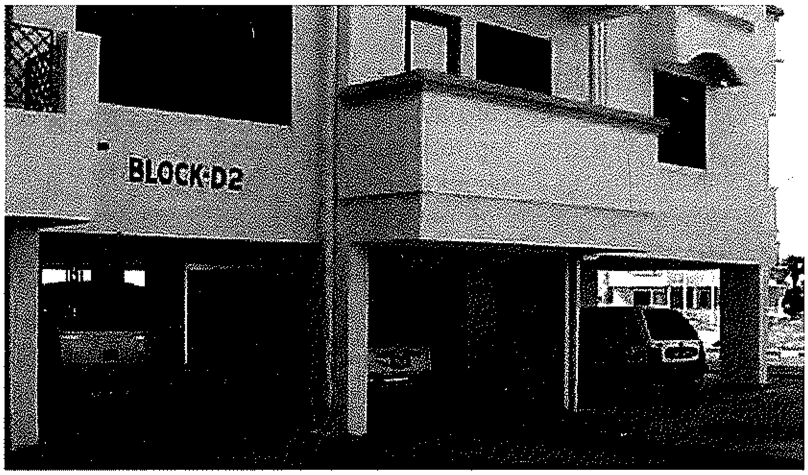
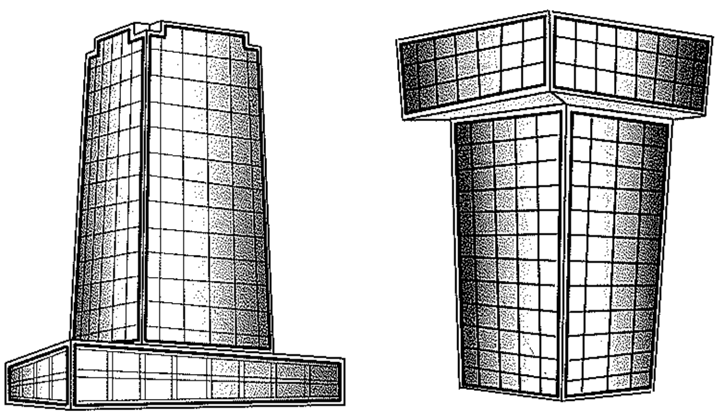


Figure 22 Building with open ground storey (Source: www.nicee.org)

In the 2001 Gujarat earthquake, many buildings with open ground storey collapsed and the parked cars were flattened. This is because the sudden change in stiffness at the ground storey induces extreme high stresses in the ground storey columns, which were not accounted for in the design.

Buildings with vertical setbacks (either set-back towers or cantilever projection at the top, Figure 23) have higher potential of failure at the root of the setbacks.

When columns with unequal heights are provided in a storey, such as in the ground storey of a building located on a sloping site (Figure 24), then the shorter columns being stiffer



a) Building with set-back tower

b) Building with cantilever projection

Figure 23 Buildings with vertical setbacks

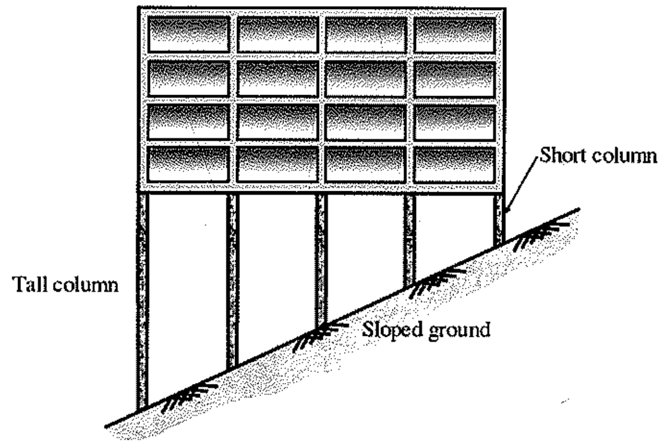


Figure 24 "Short column" effect due to sloping site (Murty, 2005)

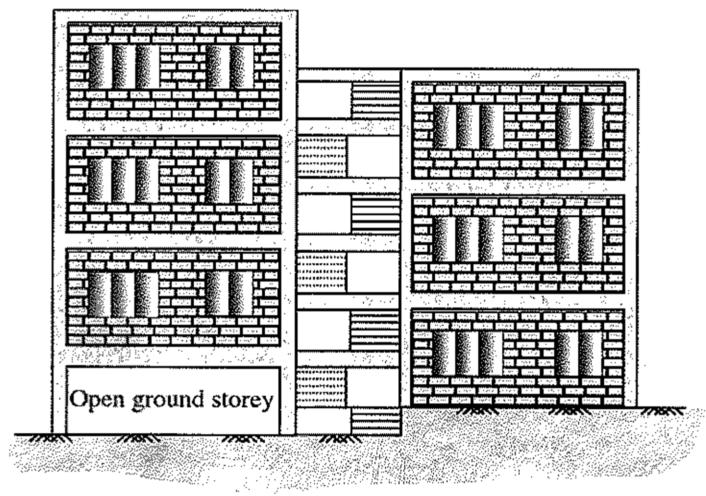


Figure 25 Building with mezzanine floors and split diaphragms

attract more horizontal forces and are liable to fail in shear, unless they are specially designed for this effect.

The "short column" effect is also encountered when the effective height of some columns in a particular storey is reduced on account of an intermediate (mezzanine) floor (Figure 25). The effect can also happen when masonry infill walls are provided with openings adjoining the columns. The "short column" effect is often not anticipated in design, and can result in a column shear failure. It is best to avoid such construction practices.

Miscellaneous Considerations

When overhanging projections are not properly anchored (Figure 26), they tend to fall during an earthquake. In fact, all large overhanging projections including balconies should be avoided or properly anchored to frames.

Special attention should be given to the planning of the staircases, as these vital escape routes are at times the first ones to attract damage in a major earthquake (Figure 27).

Two buildings or two structurally isolated sections of a single building should not be too close to each other, as there is a danger of possible collision against each other (Figure 28). This effect is called pounding and is usually not considered in design. Pounding can occur in row housing. The effect is more severe for tall buildings. It is recommended that a calculated gap subject to a minimum value be maintained between the buildings to avoid pounding. Otherwise, there can be serious damage to both the buildings, or building sections, even if they are designed adequately individually.

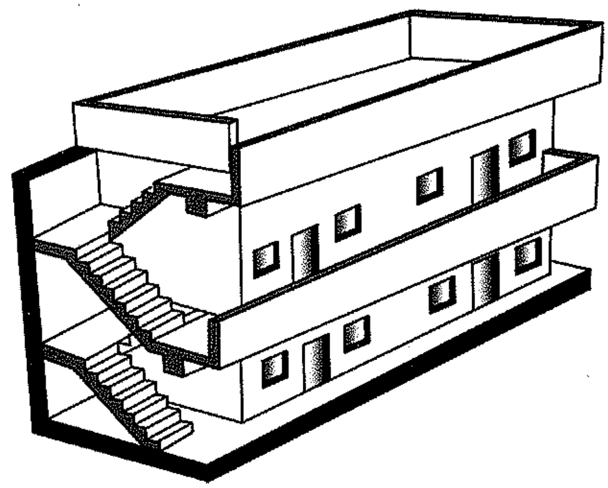


Figure 26 A building with overhanging projections and a water tank

Effect of Soil

The accelerations that occur in the rock layer of the crust during an earthquake get transmitted to the building through the soil over the rock layer. When the soil is relatively soft, the accelerations tend to get magnified, resulting in higher seismic forces in the structure. This must be taken into account during structural design. Knowledge of the soil strata is also essential for designing the foundations of the building.

In the presence of subsoil water, buildings located in loose granular soils (sands) have another potential danger that can occur during an earthquake. The soil can behave like

Figure 27 Collapse of stair slabs
(after Bhuj earthquake, 2001) (Source: www.nicee.org)

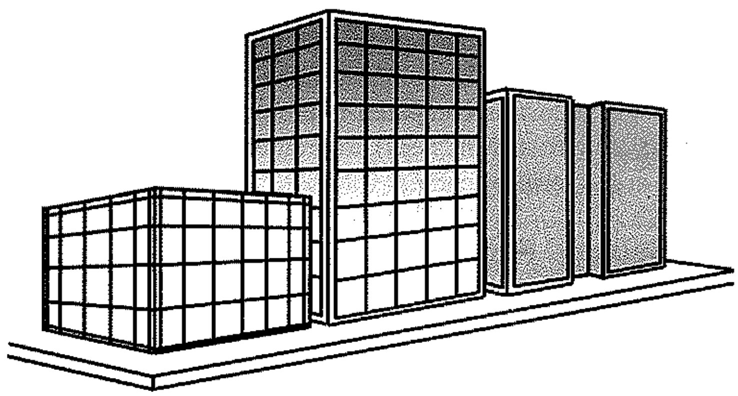


Figure 28 Closely spaced buildings can be subjected to pounding

quicksand through a phenomenon called liquefaction. This happens because of a sudden increase in the pressure of the water in the granular spaces, causing the soil to behave like a liquid. Buildings located in such soils may sink or tilt significantly and collapse (Figure 29).

Figure 29 Buildings tilted due to liquefaction of soil (after Nigata earthquake, Japan, 1964) (Source: nisee.berkeley.edu)

ESSENTIALS OF SEISMIC DESIGN OF MASONRY BUILDINGS

Transmission of Gravity Loads

The permanent load on buildings is the self-weight ("dead load") due to gravity and the weight due to human occupancy as well as furniture and storage ("live load"). Under these gravity loads, the slabs undergo bending and transmit the forces through the walls to the foundation below. This structural action induces compression in the bricks and stones. The forces are eventually transmitted to the soil below the foundation through bearing. As the bearing capacity of the soil is low as compared to the compressive strength of masonry, the width of the wall footing is increased (in steps), to provide for larger bearing width, and hence lesser bearing stresses, at the level of contact with soil.

Transmission of Seismic Forces

The buildings also have to resist lateral loads induced by wind and earthquake. As discussed earlier, seismic forces are generated due to the various masses in the building undergoing accelerations. The floor slabs tend to move rigidly in the horizontal plane, transmitting their inertial forces to the masonry walls, inducing moment and shear forces in these walls (Figure 30). Eventually, the forces are transmitted to the soil below.

Distress in Masonry Buildings

The moment causes in-plane bending of the wall leading to one-half (roughly) of the wall to undergo tension and the other half to undergo compression. The generated tension can exceed

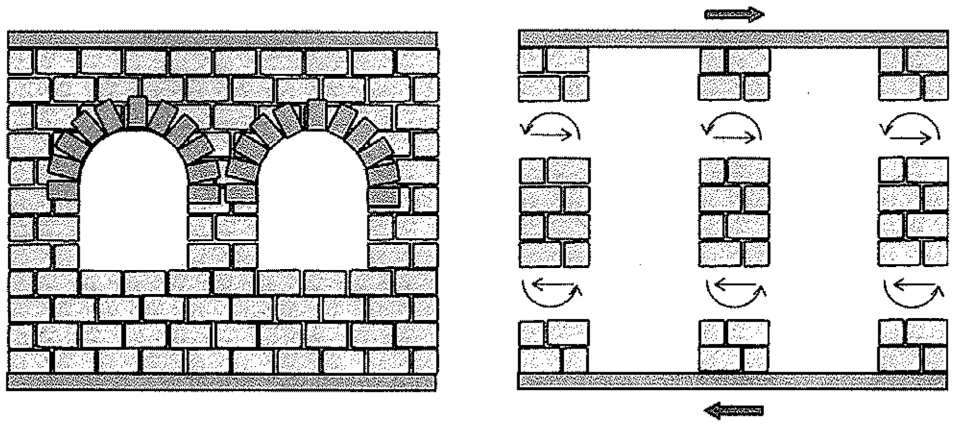


Figure 30 Transmission of seismic forces in a masonry building

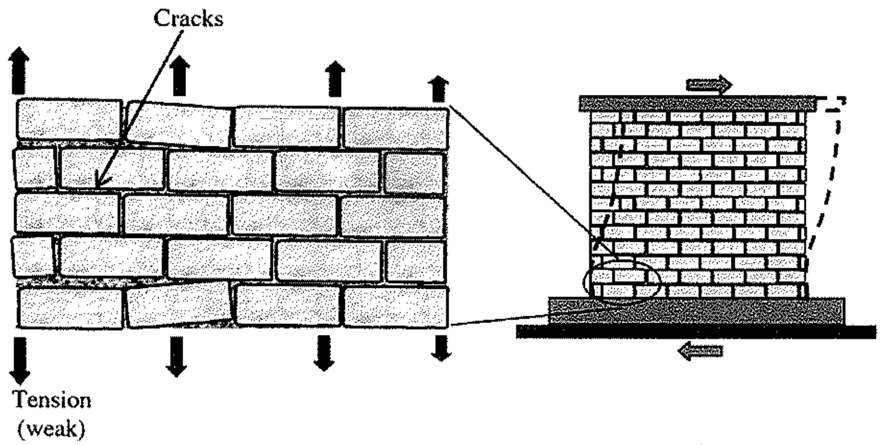


Figure 31 Cracks in a wall due to moment

the compression induced due to the dead loads. As masonry is weak in tension, this can cause cracking (Figure 31).

The shear causes a rectangular wall to take the shape of a parallelogram, in which one diagonal gets compressed and the other gets extended. Cracking is likely to occur in a direction perpendicular to the direction of extension (Figure 32). As the seismic loads are reversible, this cracking occurs along both diagonals. Such diagonal 'X-cracks' are characteristic tell-tale signs left behind by an earthquake.

To design a masonry building for resisting seismic forces, certain features are recommended in addition to the good quality and layout of bricks or stones, good quality mortar and proper layout in plan.

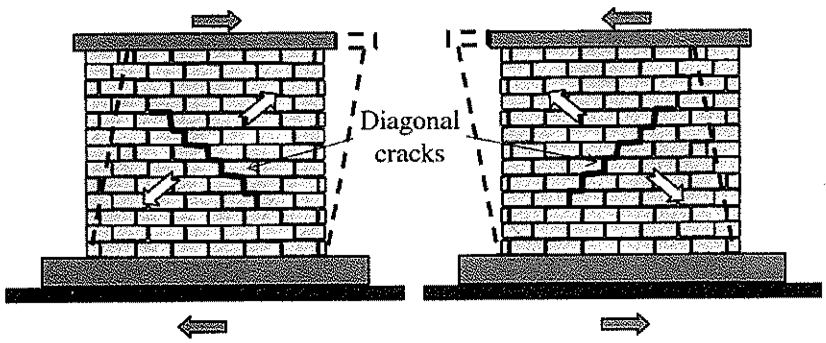


Figure 32 Diagonal cracks in a wall under shear

Provision of Horizontal Bands and Vertical Bars

In order to ensure integral action of the walls, horizontal bands (preferably made of reinforced concrete) at the plinth, sill and lintel levels are to be provided (IS 4326: 1993). The absence of such bands, combined with poor bonding of walls at the junctions, is a primary cause for collapse of many masonry buildings during an earthquake.

Also, roof and gable bands are required in the case of sloped roofs and roofs with pre-fabricated materials, to provide integral action between the roof and the walls. The steel bars in the bands provide the desired tensile resistance to horizontal load by tying up the walls

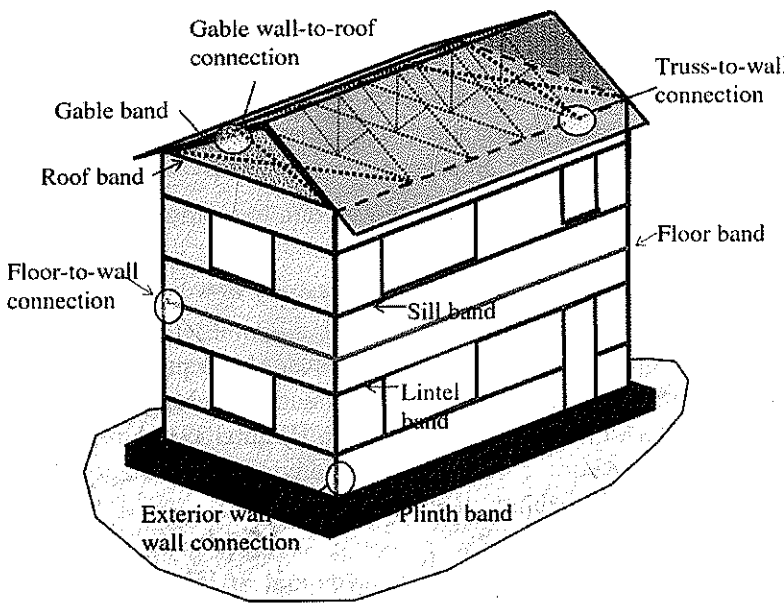


Figure 33 Bands and connections for a masonry building (Murty, 2005)

together and by strengthening the horizontal edges around doors and window openings. They also reduce the tendency of the walls to collapse out-of-plane. There should be proper connection between two perpendicular walls, between the floor slab or roof truss and the walls. The set of horizontal bands and connections required in a typical masonry building is illustrated in Figure 33.

It is also desirable to have steel bars in the vertical edges of all walls segments. These bars provide the required tensile resistance due to in-plane bending of the wall segments between the door and window openings. The vertical bars should be anchored to the foundation and the roof bands. The bars should be continuous through the upstairs floor slab. The scheme is illustrated in Figure 34.

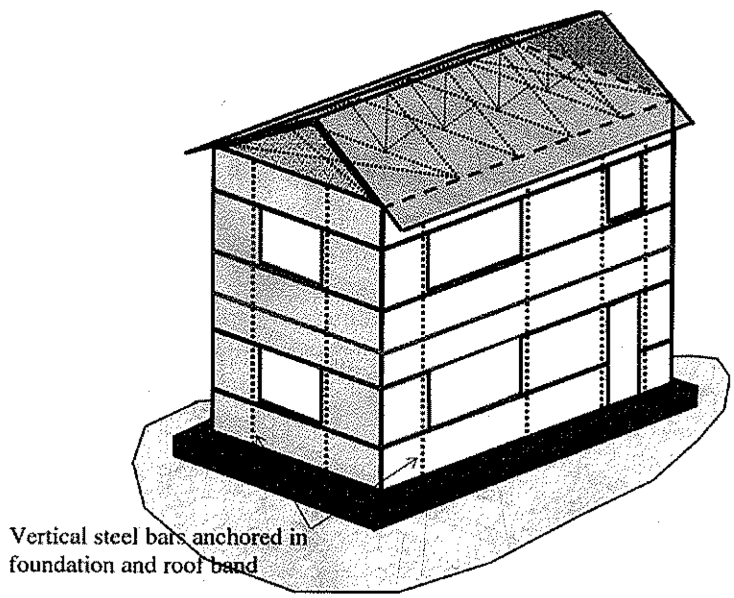


Figure 34 Vertical bars in a masonry building

Provision of Cross Walls or Buttresses

A wall is subjected to seismic forces not only in its own plane but also perpendicular to the surface of the wall (out-of-plane). The bending and shear resistances of a wall increase with increase in the wall thickness and with increase in compression due to gravity load. However, unless the wall is extremely thick and well bonded, it will lack the stiffness and the strength to resist the forces acting perpendicular to it. Such thin long walls will easily collapse under an earthquake, unless they are braced by cross walls or supported by buttresses (Figure 35). A "cross wall" resists the horizontal forces acting in its own plane. In summary, a masonry wall requires the assistance of cross walls to resist the forces acting perpendicular to it. However,

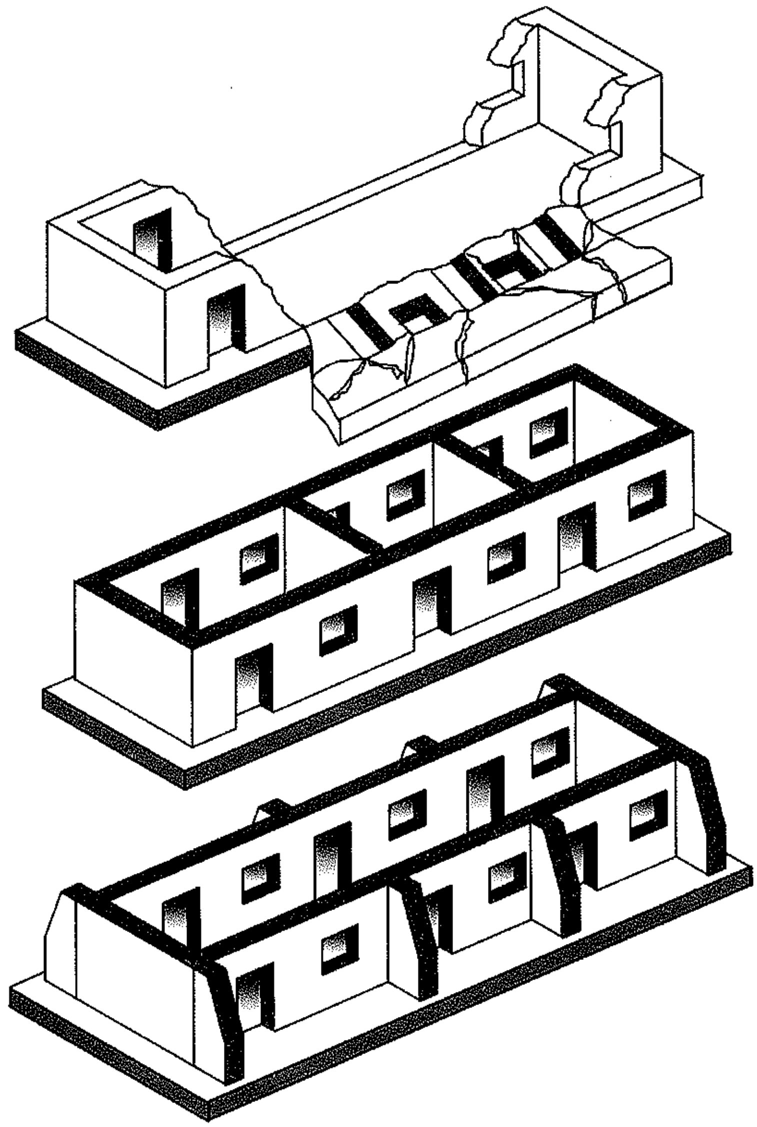


Figure 35 Cross walls or buttresses protect a long wall from falling out-of-plane

there should be enough number of cross walls and the connections between the walls should be proper.

In absence of the above essential features, vulnerability to seismic forces increases in a masonry building. Based on an assessment of the vulnerability, various retrofit means are possible, as described in subsequent sections.

ESSENTIALS OF SEISMIC DESIGN OF REINFORCED CONCRETE BUILDINGS

Transmission of Gravity Loads

The gravity loads from the weight of the floor slabs and the occupants are transferred to the beams supporting the slabs. The beams are supported by columns, which transfer the loads to the foundations. Finally, the loads are transmitted to the soil supporting the foundations. A foundation consists of individual footing slabs or a combined raft, which are designed based on the bearing capacity of the soil.

Transmission of Seismic Loads

The inertial forces generated in the floor slabs are resisted by the frames primarily due to bending of the columns (Figure 36). Although the framework in a building is three-dimensional, it is only the parallel frames aligned in one direction that resist the lateral loads acting in that direction. Hence, it is important to ensure that there is adequate number of frames in the two perpendicular directions in plan. The frames should be more-or-less symmetrically distributed to avoid twisting of the building. The floor slabs should be properly connected to the beams. Similarly, the beams, columns and the foundation slabs should have proper joints. The beam-column joints should be strong and very stiff (rigid) for a frame to transmit the inertial forces from the floor slabs to the foundation.

If shear walls are provided, they should be present in both the directions in plan and should be located close to the perimeter of the building, more-or-less symmetrically, in order to avoid twisting of the building.

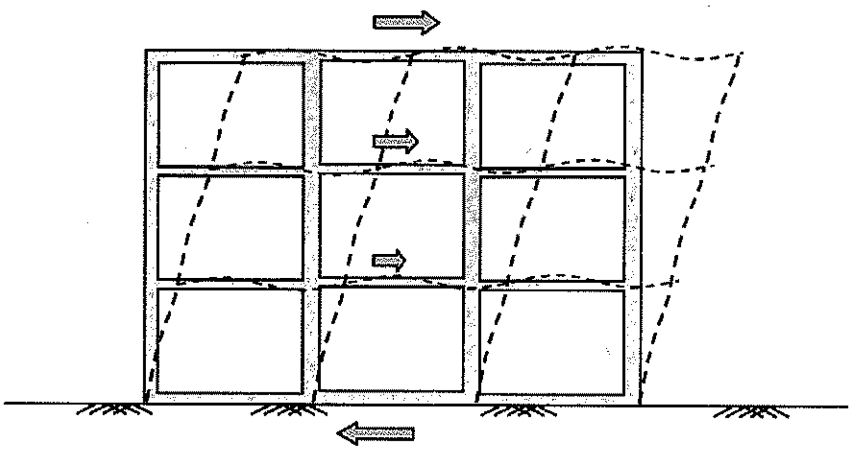


Figure 36 Transmission of seismic forces in a reinforced concrete building

Distress in RC Framed Buildings

Many low-rise and medium-rise framed buildings have been constructed in the recent past, without proper attention paid in their design for wind or earthquake loads. This serious shortcoming in structural design and detailing has been exposed by failures that have occurred in the recent earthquakes in various parts of the country.

It is the failure of the columns during an earthquake which is more severe than the failure of the slabs or beams. The failure of the columns can lead to collapse of the storeys one over the other (pancaking effect), as shown in Figure 37.

The columns can fail either in shear or in bending. Shear failures occur mainly because the column sizes provided are inadequate to resist the seismic loads and also because of inadequate lateral ties. A typical shear failure in a column, accompanied by wide diagonal cracking, is shown in Figure 38. The failure can occur at any location along the height of the column. Figure 39 shows how devastating such a failure can be, accompanied by crushing of concrete and buckling of reinforcement.

Bending (flexural) failures occur because of inadequate amount of steel bars provided vertically in the columns, particularly near the beam-column joints or column-foundation junctions, and may also occur due to poor quality of concrete. The failure initiates due to crushing of concrete in compression either before (which is rapid and hence undesirable), or after the yielding of the bars. The bars may buckle if the horizontal ties are widely spaced. Usually, cracking and crushing will appear on both sides because of the reversible nature of the seismic forces.

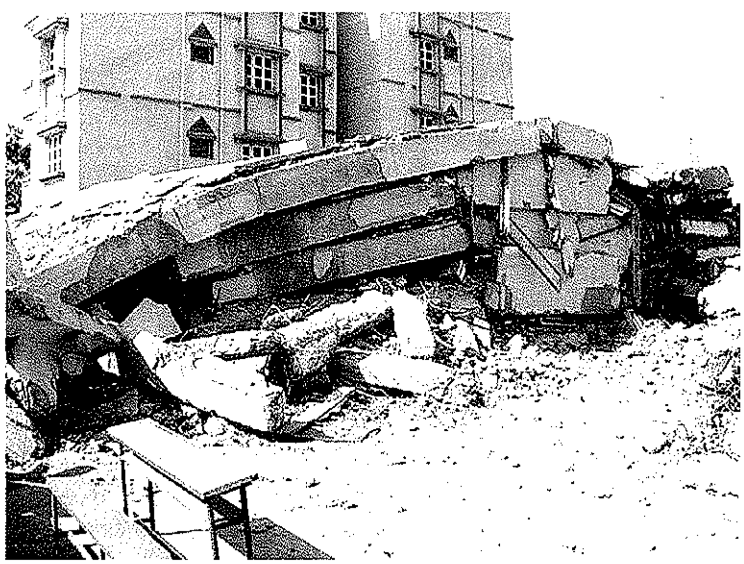


Figure 37 'Pancaking' collapse due to failure of the columns (after Bhuj earthquake, 2001) (Source: www.nicee.org)

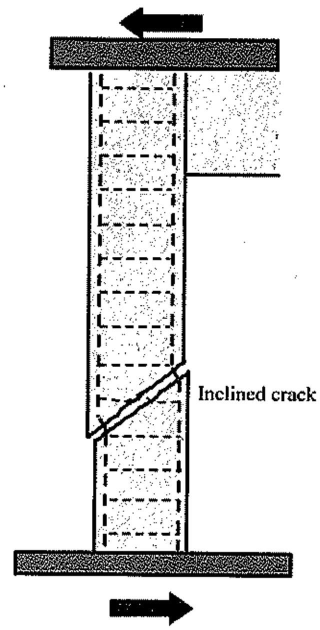


Figure 38 Schematic representation of shear failure in a column

Figure 39 A shear failure in a column
(after Bhuj earthquake, 2001) (Source: www.nicee.org)

Figure 40 Failures in beam and column (Andaman earthquake, 2004)

Beams may also fail either in shear or in bending. Shear failure is undesirable, as it limits the load resisting capacity and prevents the yielding of the longitudinal steel bars for ductile behaviour. Shear failures occur mainly because of inadequate vertical ties. Bending failures occur because of inadequate amount of horizontal steel bars, or inadequate anchorage of the bars, particularly at the bottom near the beam-column joints, or poor quality of concrete. The bottom bars tend to slip near the joints, leading to drop in the bending capacity. A typical bending failure in a beam and the failure of the supporting column are shown in Figure 40.

Provisions of Adequate Size, Reinforcement and Detailing

The Indian Standard IS 13920: 1993 gives recommendations on how the reinforcing bars in beams and columns need to be tied with closely spaced transverse bars, in order to avoid shear failure and provide ductility. In particular, it is necessary to provide ties for the column at the beam-column joint. Such detailing should be strictly followed in earthquake-resistant framed constructions, especially when they are designed for reduced seismic forces based on the assumed ductile behaviour. Also, splicing of the vertical bars in a column should be avoided near the floor levels, and should be within the middle half location of the column.

In order to avoid shear and bending failures, the columns should have adequate size and reinforcement, with proper detailing and closely spaced ties. The common practice of providing only 230 mm thick columns (no more than the thickness of a brick wall) is unsuitable for seismic resistance, especially in shear. The minimum size recommended is 300 mm in any direction. Ill proportioned columns (larger dimension in cross section greater than 2.5 times the shorter dimension) should be avoided.

The beams should also be carefully designed, with adequate horizontal bars at the top and bottom (to resist bending action) and well anchored into the columns (Figure 41). The vertical bars (to resist shear action) should be closely spaced near the supports and provided with proper end hooks. Under gravity loads, typically, the beams sag in the middle (requiring steel bars at the bottom) and hog near the column supports (requiring steel bars at the top). Under an earthquake, this hogging action increases at one end, but decreases and sometimes reverses to sagging at the other end. This possibility of reversal of bending of the beams near the supports must be accounted for in design and detailing.

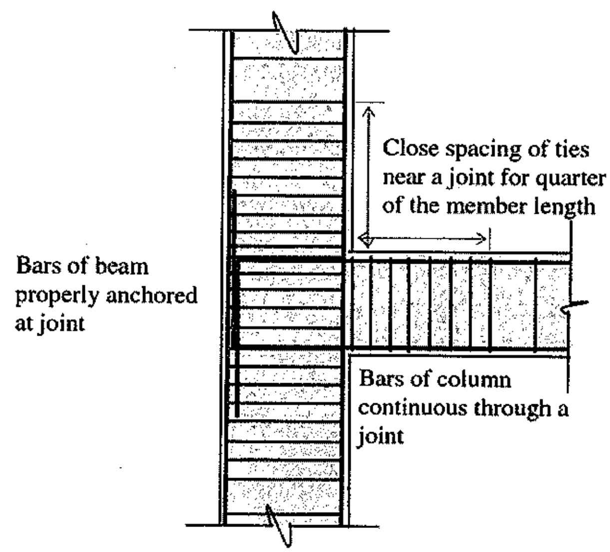


Figure 41 Detailing of reinforcing bars near a beam-column joint

Integration of Staircases

For staircases, the slabs should ideally be supported on inclined beams (stringer beams) which connect integrally with the main frame in the building (Figure 42). IS 4326: 1993 provides guidelines for the framing of the staircase. But the provisions are usually neglected by architects. Also, at least two staircases should be located symmetrically in a multi-storeyed building. Since structural safety is paramount, the owners or users of a building should insist on this provision.

Figure 42 Stairs with stringer beams connected to the building frame

Connections in Pre-cast Concrete Buildings

Pre-cast concrete is suitable for rapid and economic construction of buildings in a mass scale. Some of the components (columns, beams, slabs and wall panels) are cast elsewhere and installed at site. The rest of the components and some connections are cast at the site. Sometimes bolts and other fastening devices are used to provide connections.

In pre-cast concrete buildings, special attention should be given to the design and detailing of joints inter-connecting the various components. When the building undergoes severe shaking during an earthquake, all these connections will be put to test. If they fail, the building will simply fall apart (Figure 43).

HOW EARTHQUAKE-SAFE IS OUR BUILDING?

The photos of destruction of buildings shown in the previous sections should serve as a wake-up call to pose this important question:

How earthquake-safe is our building?

If we do not address this question, and take appropriate action to retrofit an unsafe building, we have only ourselves to blame, if things go wrong, when the next earthquake hits our region. We may face two different situations:

1. Safety of an existing building in which we live
2. Safety of a new building that we are planning to invest in.

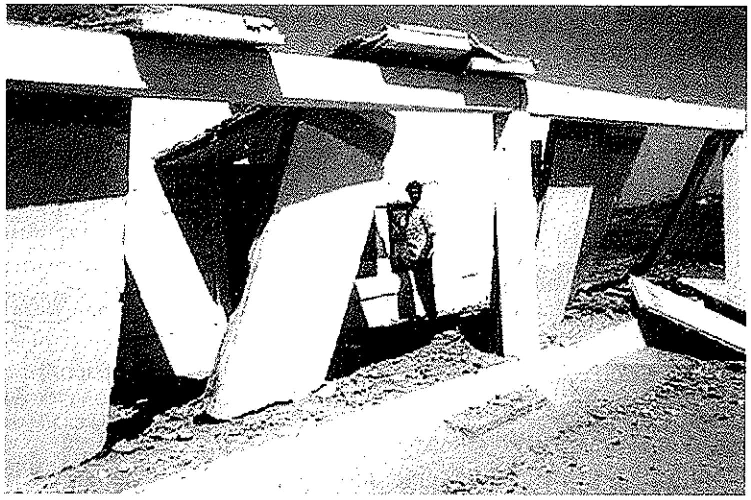


Figure 43 Lack of proper connection in a pre-cast building (after Bhuj earthquake, 2001) (Source: www.nicee.org)

These are discussed in the sections to follow. But before that, we need to understand that no building can ever be 100 percent safe against seismic forces, and get built economically. There is always some risk of failure involved, but the failure should not be fatal. Based on past experience and understanding of the structural behaviour of buildings, certain "acceptable" levels of risk in structural design have been recommended.

How Much Risk is "Acceptable"?

The risk involved depends on the "level" of the earthquake. The seismic zone and site characteristics will govern the prescribed maximum level of the earthquake. But the chance of such an extreme earthquake occurring during the life of the building can be very low. There are lower levels of earthquake that are more likely to occur.

Figure 44 illustrates an approximate relationship between expected damage and the earthquake level for ordinary buildings designed as per standard codes. We should expect the building to experience no damage when it is subjected to tremors that have a good chance of occurring during the "service life" of the building. The term, *serviceability earthquake*, is sometimes used to refer to an earthquake level that has only a 50% chance of being exceeded during a period of 50 years. For earthquake levels that are rare (with lower probability of occurrence), we can accept the risk of some damage. In an extreme event, called *maximum considered earthquake* (MCE), which has only a 2% chance of being exceeded in 50 years, we could even expect very serious damage to the building, but not complete collapse, so that lives are not lost.

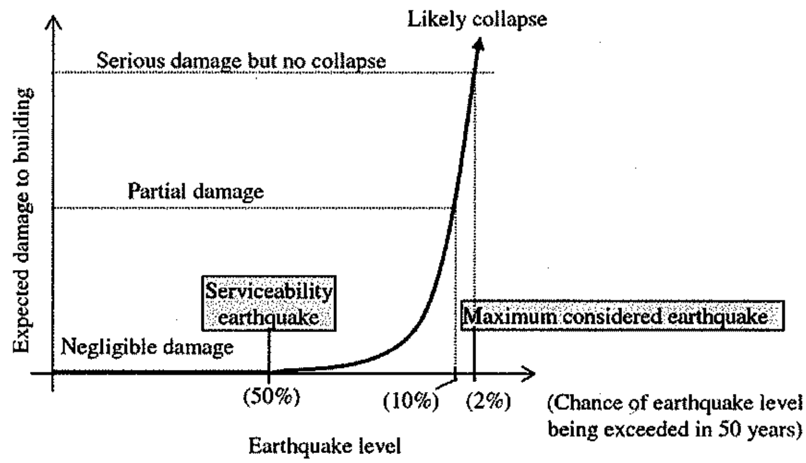


Figure 44 Relationship between expected damage to a building and the earthquake levels for ordinary buildings designed to accepted standards

Assessment of Existing Buildings

Existing buildings may not comply with requirements of the prevailing standards due to various reasons.

1) The buildings may not have been designed specifically to resist earthquake loads.
2) Even if designed, the seismic resistance provided may not measure up to the requirements of the current code (which is periodically upgraded). For example, many existing buildings in a certain seismic zone until 2002, are currently in a higher zone as per the new zone map of IS 1893: 2002.
3) The condition of the buildings may also have deteriorated (cracking, corrosion, etc.) over the years, in the absence of repair and maintenance.

It is possible today to have our building assessed properly to see whether or not they meet the acceptable seismic risk, and if they do not, to have the buildings retrofitted to the level required. The *Handbook on Seismic Retrofit of Buildings* provides information to facilitate not only the assessment of a building, but also various methods of retrofit in order to minimise the risk of failure.

There are a few steps involved in the evaluation of the seismic resistance of an existing building. First, a quick assessment can be carried out by a procedure called *rapid visual screening*. This procedure helps the inspectors to identify and inventory the vulnerable buildings. When a building is identified as vulnerable and prioritised for retrofit, relevant data is acquired by filling up the data collection forms. Next, the *preliminary evaluation* is conducted. It involves a set of initial calculations to identify the potential weaknesses in the building and a check list for code compliance. If the preliminary evaluation indicates the need, a more detailed structural evaluation is carried out by a structural engineer to quantify the extent of inadequacy, with respect to the design codes. For a detailed structural evaluation, it is necessary to have an assessment of the existing condition of the materials (*condition assessment*).

After the evaluation, a decision has to be taken on whether or not to retrofit. Some guidelines are given in the following sections on the desired level of retrofit and the various options of retrofit (retrofit strategies). The decision to retrofit and selection of a retrofit scheme (combination of retrofit strategies), of course, will be governed by the importance of the building, estimated cost of retrofit, disruption to the use of building and available technology. If the cost is affordable and the other considerations are viable, then it would be wise to implement the retrofit scheme immediately. If the existing building is found to be very unsafe, and the cost of retrofit is prohibitively high, retrofit may not be a viable option. Of course, continued occupancy of the building should not be encouraged. In the interest of safety to human lives, such buildings should be abandoned, if not demolished and rebuilt.

Making New Buildings Earthquake-Safe

We have no excuse when it comes to new buildings that we plan to invest in. We simply must ensure that they are properly designed and constructed, meeting the requirements of the prevailing codes of seismic analysis and design. How do we ensure this? We must demand this from the builder. Indeed, this is our legal right as consumers, and the responsibility of the builder. Builders usually give all kinds of assurances about safety, as do advertisements for some building materials, such as bricks and cements that are claimed to be "earthquake-proof". The reality is that materials by themselves cannot be safe against earthquakes. If a building is not properly designed, detailed and built then the building may collapse during an earthquake when the strength of the critical components are exceeded.

In this introductory information, proper architectural layout, structural design and detailing for earthquake resistance have been highlighted. The users will do well to verify that these features have been incorporated in the building. If not, they must not hesitate to ask the builder pointed questions on these aspects. It is always desirable to have proper documentation of drawings and design calculations, and the designer must be asked to furnish these. In the case of multi-storeyed buildings, it is also desirable to have the structural design proof-checked by a competent third party for code compliance. Finally, abundant care must be taken at the time of construction to ensure that the detailing is implemented as indicated in the drawings, that the materials used are of good quality, and that all the construction activities are carried out under competent supervision.

INTRODUCTION TO SEISMIC RETROFIT

It is important to distinguish between the terms *retrofit*, *repair* and *rehabilitation* of a building. All three terms refer to modifications carried out on a building, but in different contexts. 'Repair' is loosely used to describe any intervention. But in the context of strengthening for seismic forces, it is used to refer to minor interventions that are non-structural in nature.

On the other hand, both 'retrofit' and 'rehabilitation' refer to structural interventions aimed at strengthening the building. The difference between the two terms is subtle. Rehabilitation aims to regain the original strength of a building, which may have been damaged or deteriorated. Retrofit aims to strengthen a building to satisfy the requirements of the current codes for seismic design. The building may not be damaged or deteriorated.

To Retrofit or Not?

The purpose of seismic retrofitting a building is to enhance the structural capacities (lateral strength, lateral stiffness, ductility, stability and integrity), so that the building can withstand the design level of earthquake. A decision on whether or not to retrofit an unsafe building depends on many factors. Lifeline buildings[1] must necessarily be retrofitted, in view of their extreme importance. Otherwise, they may meet the tragic fate of the Bhuj District Hospital complex (Figure 45). Important buildings should also be retrofitted.

It is likely that many ordinary buildings will be found seismically unsafe. Retrofitting all such buildings is a major task that many building corporations and government have to grapple with. The financial implication of such a mammoth task can be mind boggling. Who will bear the cost?

Usually, in the case of private buildings, the owners of the building will have to bear the cost of seismic retrofit. This cost must be weighed against the cost of not retrofitting. What is the risk involved? Studies have shown that the risk of collapse of an existing building whose strength is less than that of a new building (designed to current standard) can be correlated to that of the new building.

As illustrated in Figure 46, if the seismic strength of an existing building (or structural component) is only 33% of that required by the current standard for a new building, the risk involved is as high as about 20 times that of the new building. If the strength is two-thirds that required by the current standard, the risk reduces to three times the standard risk: this level of risk is generally considered as the limit of acceptable risk. Hence, it is recommended that

[1]Life line buildings include hospitals, fire stations, power stations, telephone exchanges, television stations, radio stations, railway stations, stations for rapid transit system, air ports. Service and community buildings such as schools, cinema halls, multiplexes, marriage and other assembly halls are important buildings.

Figure 45 Ruins of the Bhuj District Hospital (after Bhuj earthquake, 2001) (Source: www.nicee.org)

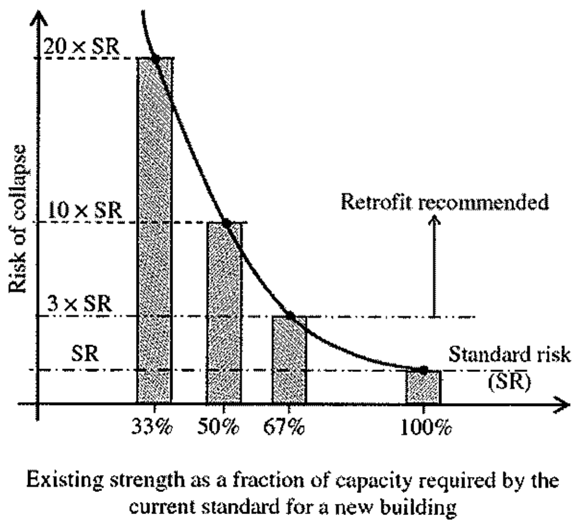


Figure 46 Seismic load capacity versus risk of building collapse

seismic retrofit be necessarily undertaken when the strength of an existing building (in term of the total seismic load that it can resist without collapsing) drops below about 70% of the capacity required by the current standard.

If it is not viable to carry out seismic retrofit for financial reasons or other considerations, then we must accept and live with the risk involved. When the risk is too high (more than 10 times the standard risk), building authorities should prohibit human occupancy of the building in the interest of public safety. The building should be demolished and reconstructed when financial resources become available.

Extent of Seismic Retrofit

Should the aim of retrofit be to raise this capacity to 100 percent (that is, equal to that required by the current standard)?

The answer to this question depends on the importance of the building. For lifeline buildings, the capacity should be raised to 100 percent. For other buildings, it can be decided based on the expected remaining usable life of a building, expressed in terms of the original design life of the building. As indicated in Figure 47, if the building is relatively old and has lived more than 50 percent of its design life, it should be retrofitted to resist at least 70 percent of the total design seismic load as per the current standards. This minimum level of retrofit should be raised to at least 77, 84, 89 and 94 percents of the total design seismic load if the remaining usable life is 60, 70, 80 and 90 percents of the original design life, respectively.

The expected design life of any building depends on its type and quality of construction and can vary from about 10 years for some types of non-engineered construction to about 100 years for high quality engineered construction. For a typical reinforced concrete building, the design life may be taken as 50 to 60 years.

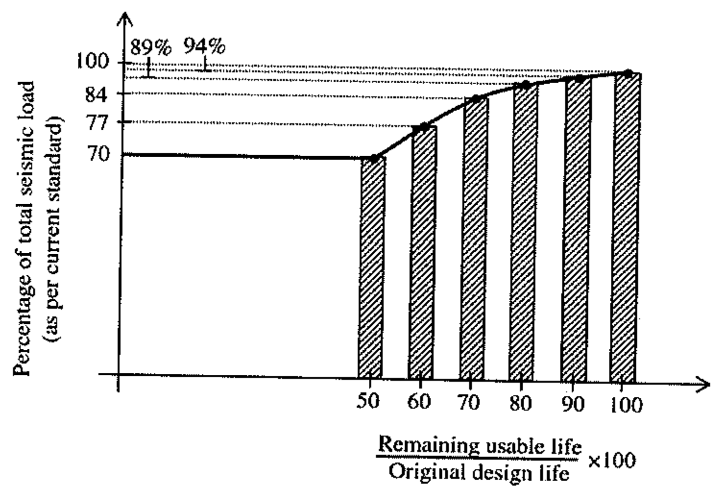


Figure 47 Design seismic load as a function of remaining usable life

Local versus Global Retrofit

A 'retrofit strategy' or 'retrofit technique' refers to any option of increasing the lateral strength, stiffness and/or ductility of the members or of the whole building. Some of the strategies target the building as a whole. These strategies are referred to as global retrofit strategies. The strategies that aim to avoid failure of the components are referred to as local retrofit strategies.

There can be more than one combination of local and global retrofit strategies for a building, having different cost implications. The structural engineer must work out an appropriate, practically viable and economical solution. The *Handbook on Seismic Retrofit of Buildings* provides guidelines on the various retrofit strategies, as applicable to non-engineered buildings, masonry buildings, historical and heritage structures, reinforced concrete buildings and steel buildings.

Some of the important strategies relevant to non-engineered buildings, masonry buildings and reinforced concrete buildings are highlighted in the following two sections. More details are provided in the respective chapters of the Handbook.

RETROFIT OF NON-ENGINEERED AND MASONRY BUILDINGS

Non-engineered buildings are those, which are not formally designed, but built using traditional techniques. This is in comparison to the engineered buildings which are properly designed based on calculations, at least for gravity loads. The retrofit strategies for non-engineered buildings are prescriptive in nature. Their benefit is based on engineering judgment or verified by tests. Engineering calculations are not required for their application. On the other hand, the retrofit strategies for engineered buildings are quantitative in nature. Their amount is determined based on design calculations. The presentation in this booklet illustrates the strategies, without any methodology for calculations.

Strengthening of Walls, Floors and Roofs

The seismic resistance of the walls of small buildings such as dwelling units can be enhanced by providing containment reinforcement as shown in Figure 48. Horizontal, vertical and cross bars are inserted in grooves which are subsequently covered by mortar. Perpendicular walls can be stitched to enhance the integrity. Figure 49 shows the stitching by steel bars inserted at an angle of 45°. The drilled holes are subsequently filled with cement grout. The span of long

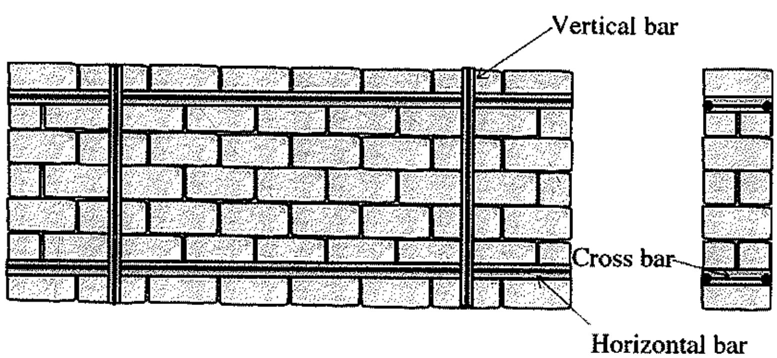


Figure 48 Containment reinforcement for strengthening a masonry wall

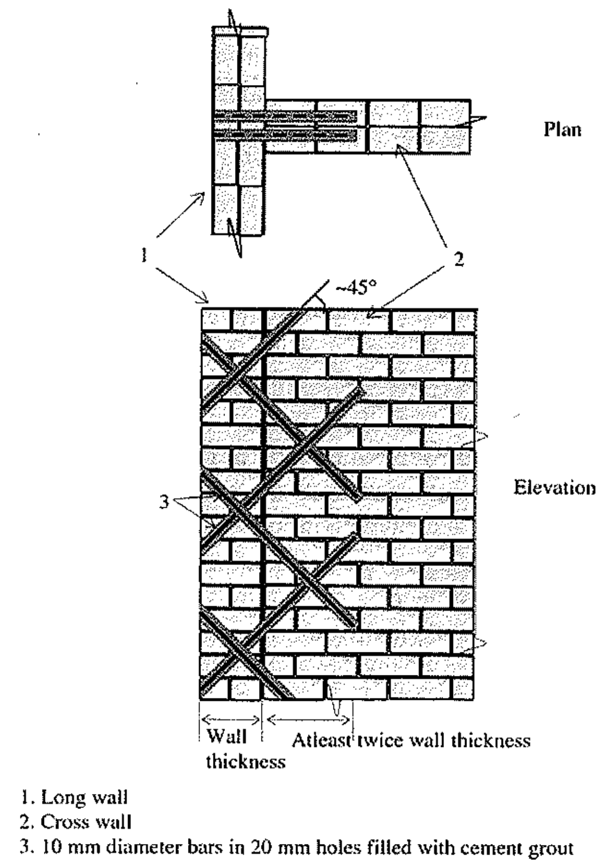


Figure 49 Connecting perpendicular walls with inclined bars (IS 13935)

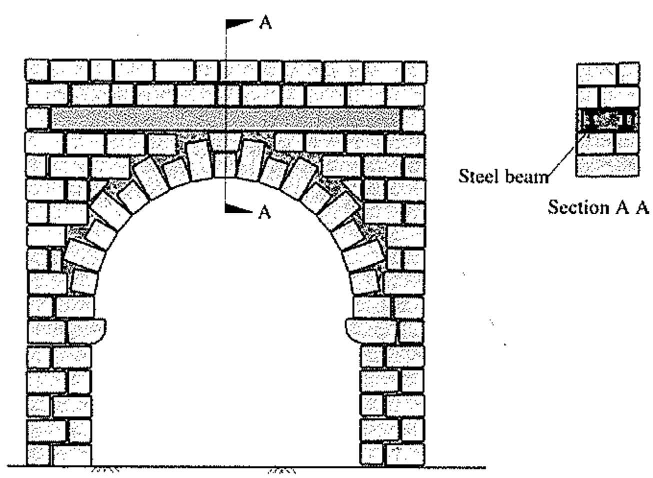
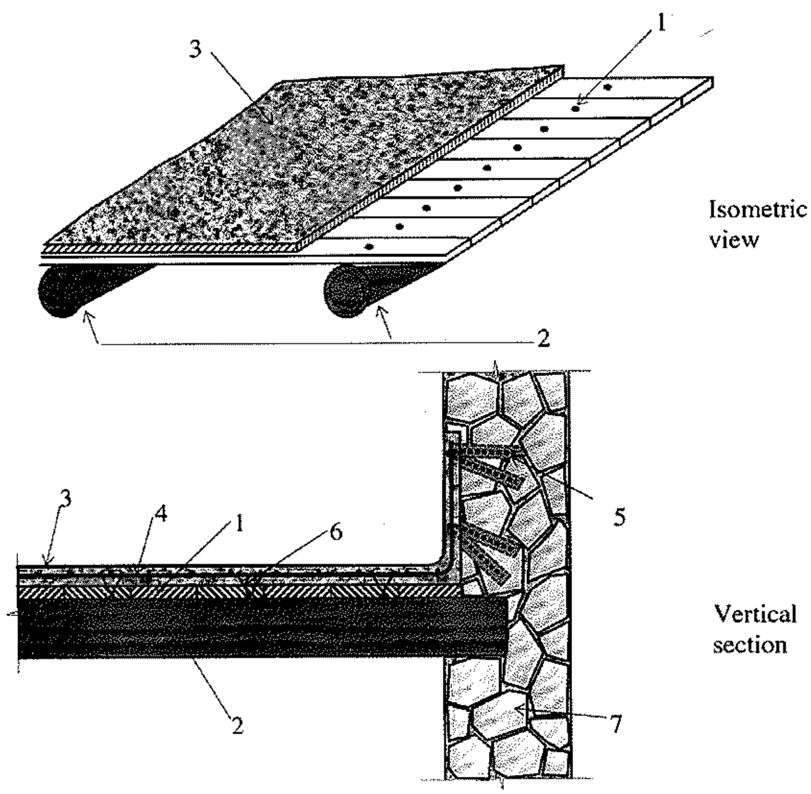


Figure 50 Stress relieving of arch by inserting lintel (IS 13935)

walls can be reduced by introducing cross walls or buttresses (Figure 35). An arch can be relieved of the compressive stress by inserting steel beams above it, as shown in Figure 50.

The connection of an intermediate wooden floor or roof with the wall can be strengthened to enhance the integrity (Figure 51). A concrete overlay with mesh reinforcement is cast on the wooden floor. The overlay is extended as a skirting on the wall, where the mesh is anchored. Nails are provided to attach the mesh with the wooden floor. An alternative strategy of strengthening the connection is shown in Figure 52. Steel flats are nailed on the existing rafters and anchored to the wall.



1. Existing wooden planks
2. Existing wooden rafters
3. New concrete topping
4. Steel mesh reinforcement
5. Steel anchors grouted in drilled holes
6. Nails
7. Existing wall

Figure 51 Strengthening of wooden floor
(Guidelines for Earthquake Resistant Non-engineered Construction, 2004)

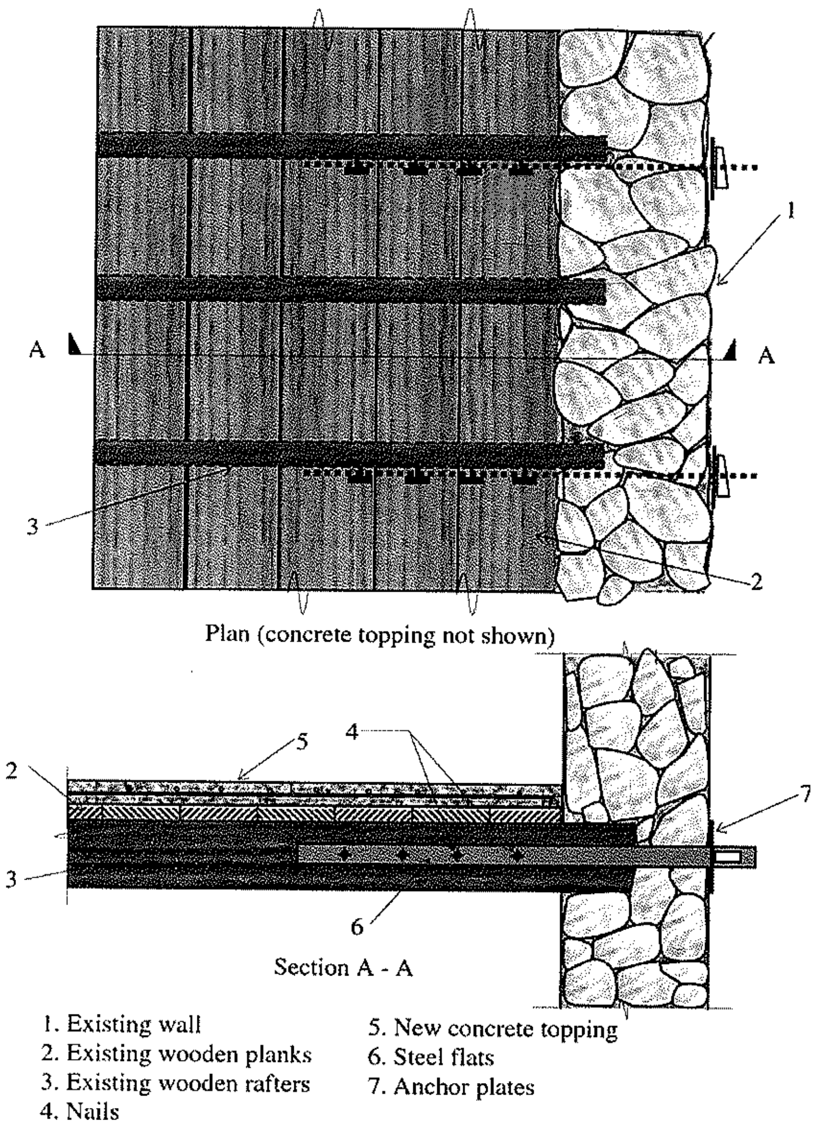


Figure 52 Strengthening of wooden floor (alternate)
(Guidelines for Earthquake Resistant Non-engineered Construction, 2004)

Techniques for Global Strengthening

The layout and configuration of a masonry building can be improved by introducing joints between perpendicular blocks, similar to that shown in Figure 20. For huts, the lateral strength can be significantly improved by providing cross braces (Figure 53).

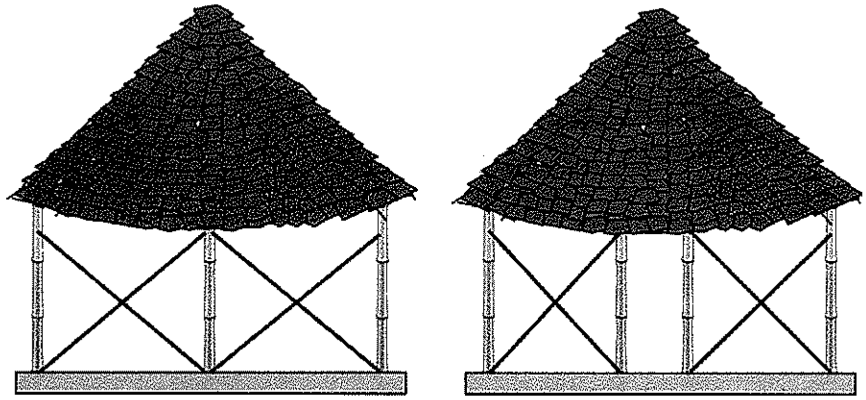


Figure 53 Introduction of braces in a hut

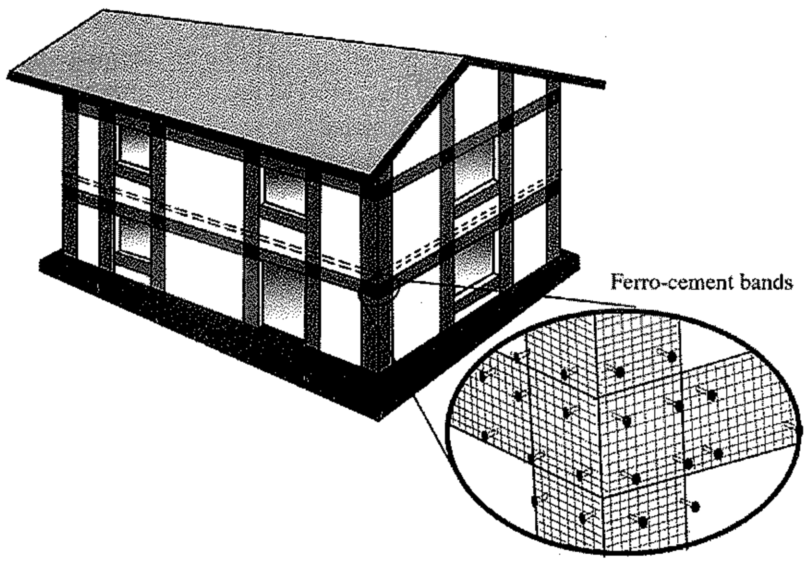


Figure 54 Splint and bandage strengthening technique (IS 13935)

For integrity of a masonry building, the provision of bands at plinth, sill, lintel or roof levels is illustrated in Figure 33. The requirement of vertical steel bars at the corners of the building and adjacent to the openings is shown in Figure 34. Similar provisions can be introduced in an existing building by the "splint and bandage strengthening technique". Strips of steel mesh are attached to the exterior surfaces of the walls and subsequently covered by mortar (Figure 54). The vertical and horizontal strips are termed as splints and bandages, respectively. There should be continuity of the horizontal strips at the corners.

RETROFIT OF REINFORCED CONCRETE BUILDINGS

Global Retrofit Strategies

When a building is severely deficient under the design seismic forces, the first step of seismic retrofit is to strengthen and stiffen the structure by providing additional lateral load resisting elements. Additions of infill walls, shear walls or braces are grouped under global retrofit strategies. A reduction of an irregularity or of the mass of a building can also be considered under global retrofit strategies.

Addition of infill walls in the ground storey is a viable option to retrofit buildings with open ground storeys. In absence of plinth beam, the new foundation of the infill wall should be tied to the existing footings of the adjacent columns (Figure 55).

Shear walls can be introduced in buildings with frames or in buildings with flat slabs. In the latter type of buildings, there are no conventional frames and the slabs are supported by columns. The lateral strength and stiffness of such buildings can be substantially inadequate in absence of shear walls. For a new shear wall, there should be an adequate foundation. The reinforcing bars of the wall should be properly anchored to the bounding frame (Figure 56) or slabs and columns in case of buildings with flat slabs.

Steel braces can be inserted in a frame to provide lateral stiffness, strength, ductility, energy dissipation, or any combination of these (Figure 57). The braces can be added at the exterior frames with least disruption of the building use. For an open ground storey, the braces can be placed in appropriate bays to retain the functional use of the storey. The connection between the braces and the existing frame is an important consideration. One

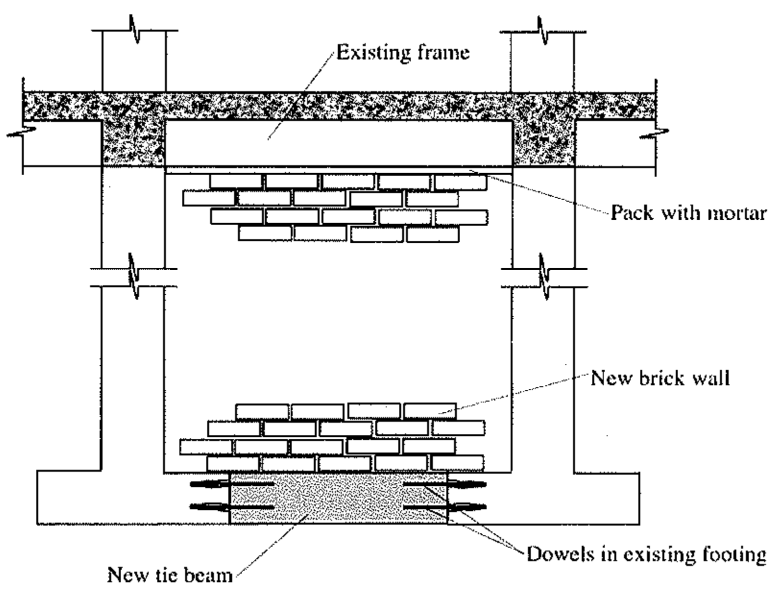


Figure 55 Addition of a masonry infill wall

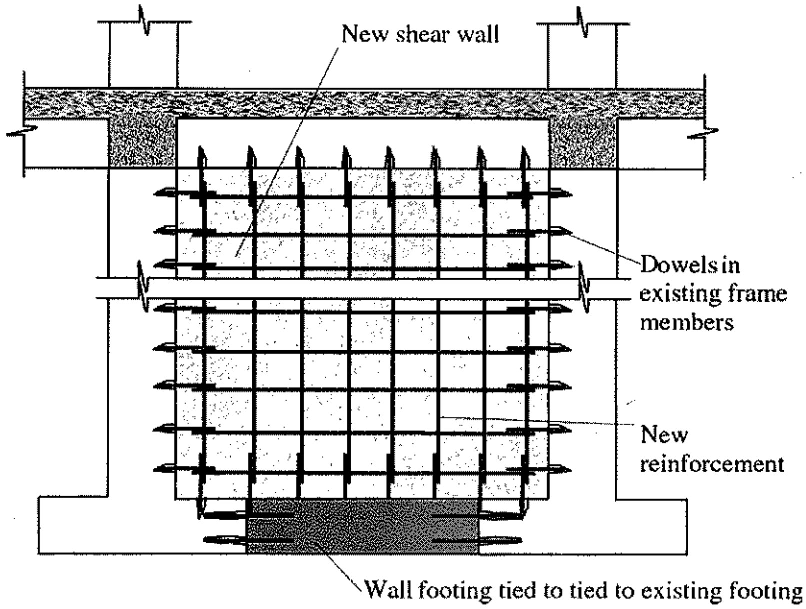


Figure 56 Addition of a shear wall (Jain, 2001)

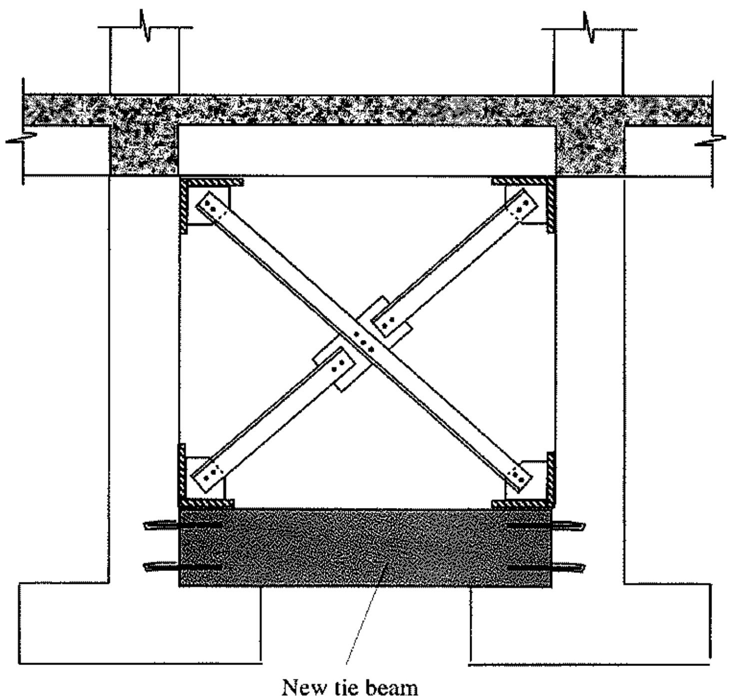


Figure 57 Addition of steel braces

technique of installing braces is to provide a steel frame within the designated bay. Else, the braces can be connected directly to the frame with plates and bolts.

Local Retrofit Strategies

Local retrofit strategies refer to retrofitting of columns, beams, joints, slabs, walls and foundations. The local retrofit strategies fall under three types: concrete jacketing, steel jacketing (or use of steel plates) and fibre-reinforced polymer (FRP) sheet wrapping.

Concrete jacketing involves addition of longitudinal bars, closely spaced ties and a layer of concrete (Figures 58 and 59). The jacket increases both the flexural strength and shear strength of the column or beam. The suitability of the scheme of jacketing depends on the constraints. If there is a wall above a beam that cannot be knocked down, then a jacket cannot be provided all around the beam.

Steel jacketing of column refers to encasing the column with steel plates and filling the gap

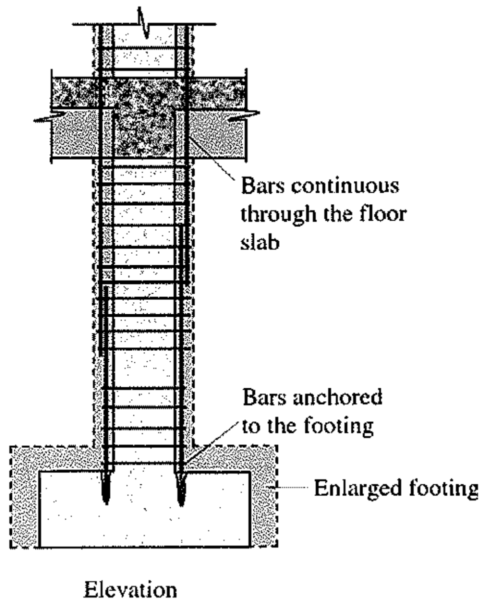


Figure 58 Concrete jacketing of a column

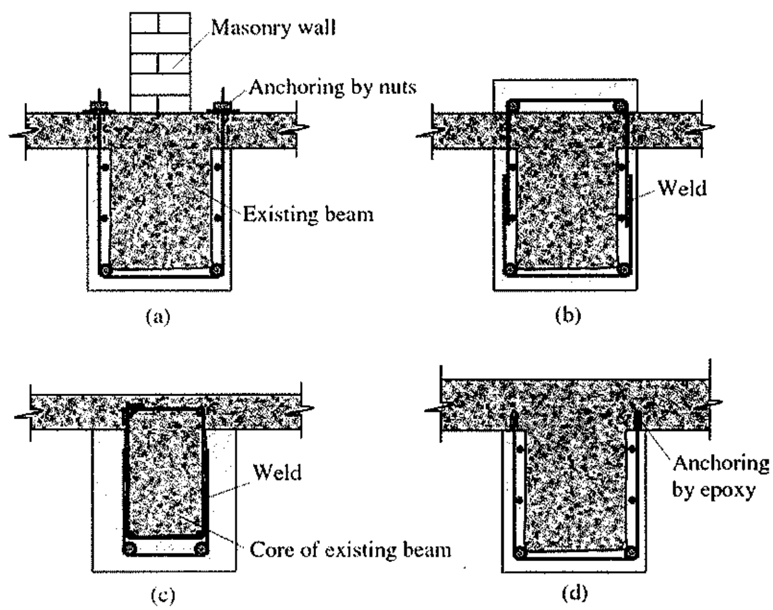


Figure 59 Concrete jacketing of beams

with non-shrink grout. The jacket is effective to remedy inadequate shear strength and provide confinement to the column. Since the plates cannot be anchored to the foundation and made continuous through the floor slab, steel jacketing is not suitable for the enhancement of flexural strength. As a temporary measure after an earthquake, a steel jacket can be placed before an engineered scheme is implemented. Different types of steel jacketing are illustrated in Figure 60.

Steel sheets are used in beams to enhance their flexural or shear strengths. The enhancement of flexural strength is possible for the sagging behaviour at the central region of a beam under gravity loads. A steel sheet is bonded or bolted at the bottom face of the beam. For seismic load, the shear strength can be enhanced by bonding or bolting sheets on the side faces near the two ends of the beam (Figure 61).

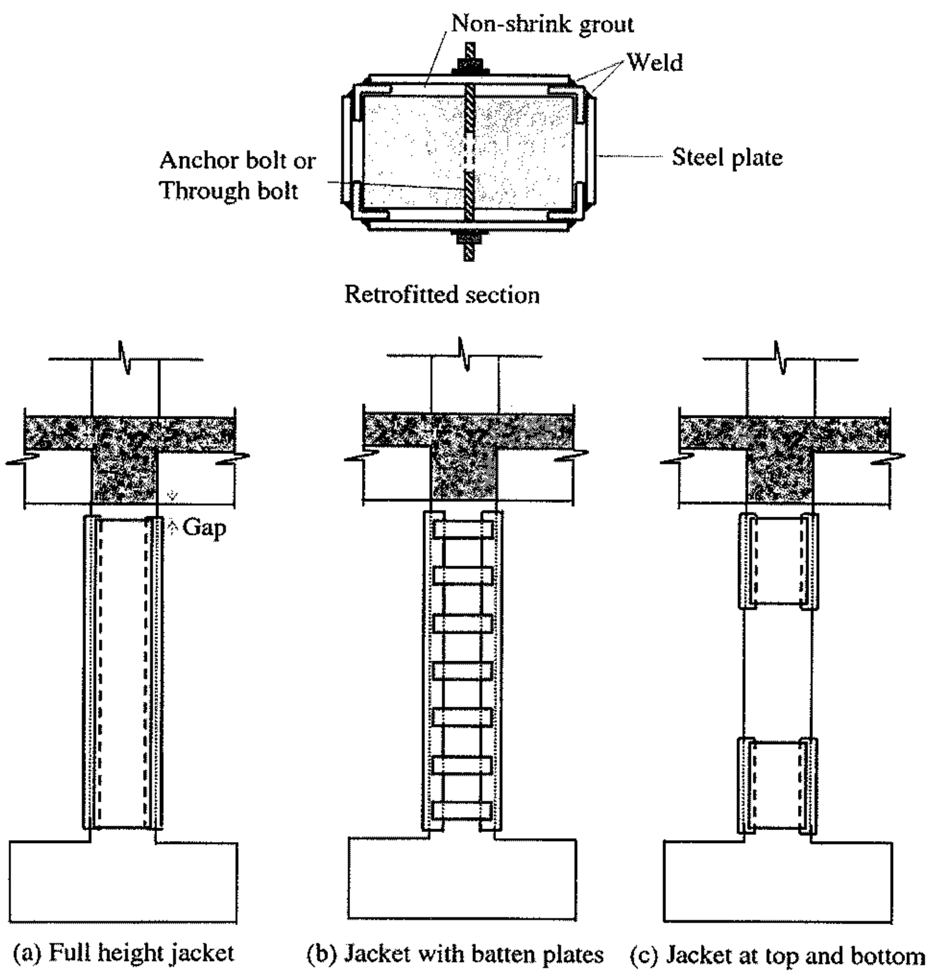


Figure 60 Steel jacketing of columns

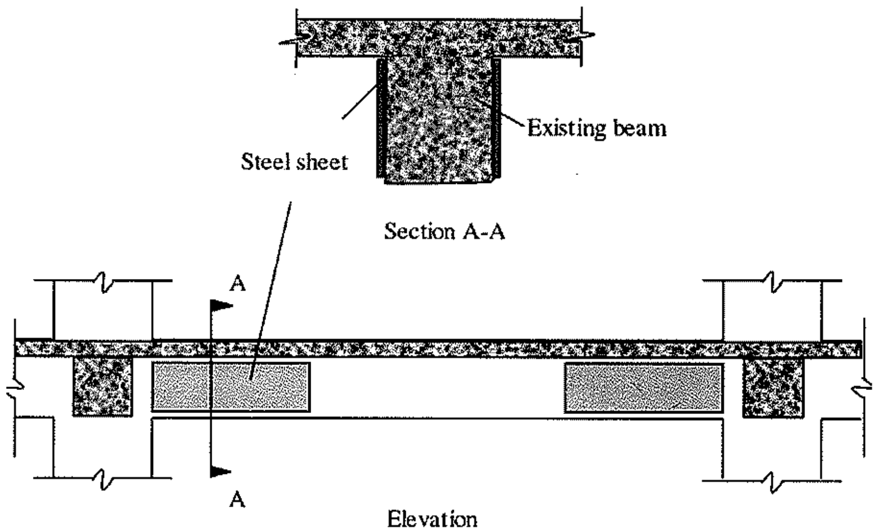


Figure 61 Use of steel sheets in beams

Fibre reinforced polymer (FRP) sheets are used in a similar manner to steel plates or sheets. The shear strength of a column can be enhanced by wrapping FRP sheets around it. The wrapping enhances the behaviour marginally under flexure due to the confinement of the concrete. The confinement refers to the enclosing of concrete which has a beneficial effect in terms of increase in compressive strength and ductility. For a beam, the sheets cannot be wrapped all around if there is a slab. Nevertheless, the shear strength can be increased by bonding sheets at the sides.

SUMMARY

Some of the key points identified in this introductory information on earthquakes, design for seismic forces and seismic retrofit are summarised below.

General

- Earthquakes do not kill; unsafe buildings do.
- Earthquakes are natural phenomena. But when and where exactly the next earthquake will occur cannot be predicted as of date.
- The Indian sub-continent has been divided into four seismic zones (Zones II, III, IV and V), Zone V being the most hazardous.
- The important aspects of a building for resisting seismic forces are reduced mass, adequate lateral strength, stiffness, ductility and integrity among the components. Low-rise buildings with light-weight materials are best suited in high seismic zone areas.

- Under severe earthquakes, damage is expected in ordinary buildings (other than lifeline and important buildings); otherwise the buildings would not be financially viable. If a building has been properly designed and constructed in accordance to the prevailing codes of practice, it is expected to survive the expected design earthquake.
- Most buildings (including the so-called "engineered" buildings) in India, however, are vulnerable, as revealed by the devastating earthquakes of the recent past.
- Get your building assessed for its seismic vulnerability. If the building is found unsafe, get it suitably retrofitted. Prevention is better than cure.
- If you are planning to invest in a new building, make sure that the building layout and configuration are simple both in plan and elevation, especially if the building is located in a high seismic zone.
- Avoid filled up areas for construction. Insist on soil investigation.
- Restrain heavy and costly equipments, such as television set, computer, water heater, air-conditioning unit etc. to avoid their fall. Place hazardous materials such as chemicals, in closed cup-boards; else provide restrainers/stoppers in open storage racks.

Non-engineered and Masonry Buildings

- The walls in a masonry building should be provided with reinforced concrete bands at plinth, sill, lintel and roof levels (for sloping roofs). Vertical steel bars should be provided at the edges of wall segments, ensuring that they are well anchored to the foundation and roof bands.
- Long walls are weak against the forces that act in a direction perpendicular to their length. To prevent possible collapse, adequate cross walls or buttresses need to be provided, with proper bonding at the junctions.
- The floor slabs and roof need to be properly connected to the supporting walls for effective transfer of seismic forces.
- The splint and bandage strengthening technique can be adopted to retrofit a masonry building. For huts especially with heavy roof, adequate braces should be provided.

Reinforced Concrete Buildings

- For proper transfer of loads, the foundations must be stronger than the columns, and the columns must be stronger than the beams. The columns should have adequate cross-sectional size and reinforcing bars (both vertical bars and closely spaced horizontal ties). The common practice of 230 mm thick columns is unsuitable for providing seismic resistance, especially under shear. The minimum size recommanded is 300 mm in any direction.
- The columns in an open ground storey are particularly vulnerable under an earthquake, unless they have been properly designed for the additional stresses.

- The beams should have adequate reinforcing bars at the top and bottom, which are well anchored at the beam-column joints. Closely spaced vertical stirrups are also required, with proper hooks.
- Any shear wall should be well connected to the frame of the building.
- Ensure that the staircases are well framed to avoid collapse during the earthquake.
- Avoid large overhanging projections and eccentric water tanks.
- In the case of multi-storeyed buildings, the design should be proof-checked by a competent structural engineer to ensure that the design is code compliant.
- The options for retrofitting a building can be broadly divided into global and local strategies. Introducing walls or braces in an open ground storey are example of global strategies. The local strategies include jacketing of columns and beams by concrete or steel and the use of fibre reinforced polymer wraps.

This introductory information will have served its purpose if it has sensitised the reader on the vital importance of making his/her building safe against earthquakes. More detailed technical information is provided in the *Handbook on Seismic Retrofit of Buildings*.

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MAKING BUILDINGS SAFE AGAINST EARTHQUAKES

A PRIMER

Making Buildings Safe Against Earthquakes introduces the reader to how earthquakes damage buildings and how such damage can be minimised through retrofit. The material is presented in easily readable style, with neat sketches. A summary and a list of important and popular references are also included. The important statements are highlighted for easy understanding. This includes advice regarding safety of existing buildings and tips for prospective owners of new buildings.

KEY FEATURES:

- Simple Language
- Explanatory illustrations for easy understanding
- Coverage of masonry and reinforced concrete buildings
- List of do's and don'ts
- Information from various design standards
- References to websites for disaster management

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