

STRUCTURAL PERFORMANCE DURING EARTHQUAKES

2.1 INTRODUCTION

Earthquakes are natural hazards under which disasters are mainly caused by damage to or collapse of buildings and other man-made structures. Experience has shown that for new constructions, establishing earthquake resistant regulations and their implementation is the critical safeguard against earthquake-induced damage. As regards existing structures, it is necessary to evaluate and strengthen them based on evaluation criteria before an earthquake.

Earthquake damage depends on many parameters, including intensity, duration and frequency content of ground motion, geologic and soil condition, quality of construction, etc. Building design must be such as to ensure that the building has adequate strength, high ductility, and will remain as one unit, even while subjected to very large deformation.

Sociologic factors are also important, such as density of population, time of day of the earthquake occurrence and commu-

nity preparedness for the possibility of such an event.

Up to now we can do little to diminish direct earthquake effects. However we can do much to reduce risks and thereby reduce disasters provided we design and build or strengthen the buildings so as to minimize the losses based on the knowledge of the earthquake performance of different building types during an earthquake.

Observation of structural performance of buildings during an earthquake can clearly identify the strong and weak aspects of the design, as well as the desirable qualities of materials and techniques of construction, and site selection. The study of damage therefore provides an important step in the evolution of strengthening measures for different types of buildings.

This Chapter discusses earthquake performance of structures during earthquake intensity, ground shaking effects on structures, site condition effects on building damage, other factors affecting damage,

failure mechanisms of structures, earthquake damage and damage categories.

Typical patterns of damage for specific types of construction are discussed in the respective chapters.

2.2 EARTHQUAKE EFFECTS

There are four basic causes of earthquake-induced damage: ground shaking, ground failure, tsunamis and fire.

2.2.1 Ground shaking

The principal cause of earthquake-induced damage is ground shaking. As the earth vibrates, all buildings on the ground surface will respond to that vibration in varying degrees. Earthquake induced accelerations, velocities and displacements can damage or destroy a building unless it has been designed and constructed or strengthened to be earthquake resistant. Therefore, the effect of ground shaking on buildings is a principal area of consideration in the design of earthquake resistant buildings. Seismic design loads are extremely difficult to determine due to the random nature of earthquake motions. However, experiences from past strong earthquakes have shown that reasonable and prudent practices can keep a building safe during an earthquake.

2.2.2 Ground failure

Earthquake-induced ground failure has been observed in the form of ground rupture along the fault zone, landslides, settlement and soil liquefaction.

Ground rupture along a fault zone may be very limited or may extend over hundreds of kilometers. Ground displacement along the fault may be horizontal, vertical

or both, and can be measured in centimeters or even metres. Obviously, a building directly astride such a rupture will be severely damaged or collapsed.

While landslide can destroy a building, the settlement may only damage the building.

Soil liquefaction can occur in low density saturated sands of relatively uniform size. The phenomenon of liquefaction is particularly important for dams, bridges, underground pipelines, and buildings standing on such ground.

2.2.3 Tsunamis

Tsunamis or seismic sea waves are generally produced by a sudden movement of the ocean floor. As the water waves approach land, their velocity decreases and their height increases from 5 to 8 m, or even more. Obviously, tsunamis can be devastating for buildings built in coastal areas.

2.2.4 Fire

When the fire following an earthquake starts, it becomes difficult to extinguish it, since a strong earthquake is accompanied by the loss of water supply and traffic jams. Therefore, the earthquake damage increases with the earthquake-induced fire in addition to the damage to buildings directly due to earthquakes. In the case of the 1923 Kanto earthquake 50% of Tokyo and 70% of the total number of houses were burnt and more than 100,000 people were killed by the fire.

2.3 GROUND SHAKING EFFECT ON STRUCTURES

2.3.1 Inertia forces

Buildings are fixed to the ground as shown in *Fig 2.1(a)*. As the base of a building moves

the superstructure including its contents tends to shake and vibrate from the position of rest, in a very irregular manner due to the inertia of the masses.

When the base of the building suddenly moves to the right, the building moves to the left relative the base, *Fig 2.1(b)*, as if it was being pushed to the left by an unseen force which we call "Inertia Force". Actually, there is no push at all but, because of its mass, the building resists any motion. The process is much more complex because the ground moves simultaneously in three mutually perpendicular directions during an earthquake as shown in *Fig 2.1 (b), (c), and (d)*.

2.3.2 Seismic load

The resultant lateral force or seismic load is represented by the force *F* as shown in

Fig 2.1(e). The force *F* is distinctly different from the dead, live, snow, wind, and impact loads. The horizontal ground motion action is similar to the effect of a horizontal force acting on the building, hence the term "Seismic Load". As the base of the building moves in an extremely complicated manner, inertia forces are created throughout the mass of the building and its contents. It is these reversible forces that cause the building to move and sustain damage or collapse.

Additional vertical load effect is caused on beams and columns due to vertical vibrations. Being reversible, at certain instants of time the effective load is increased, at others it is decreased.

The earthquake loads are dynamic and impossible to predict precisely in advance,

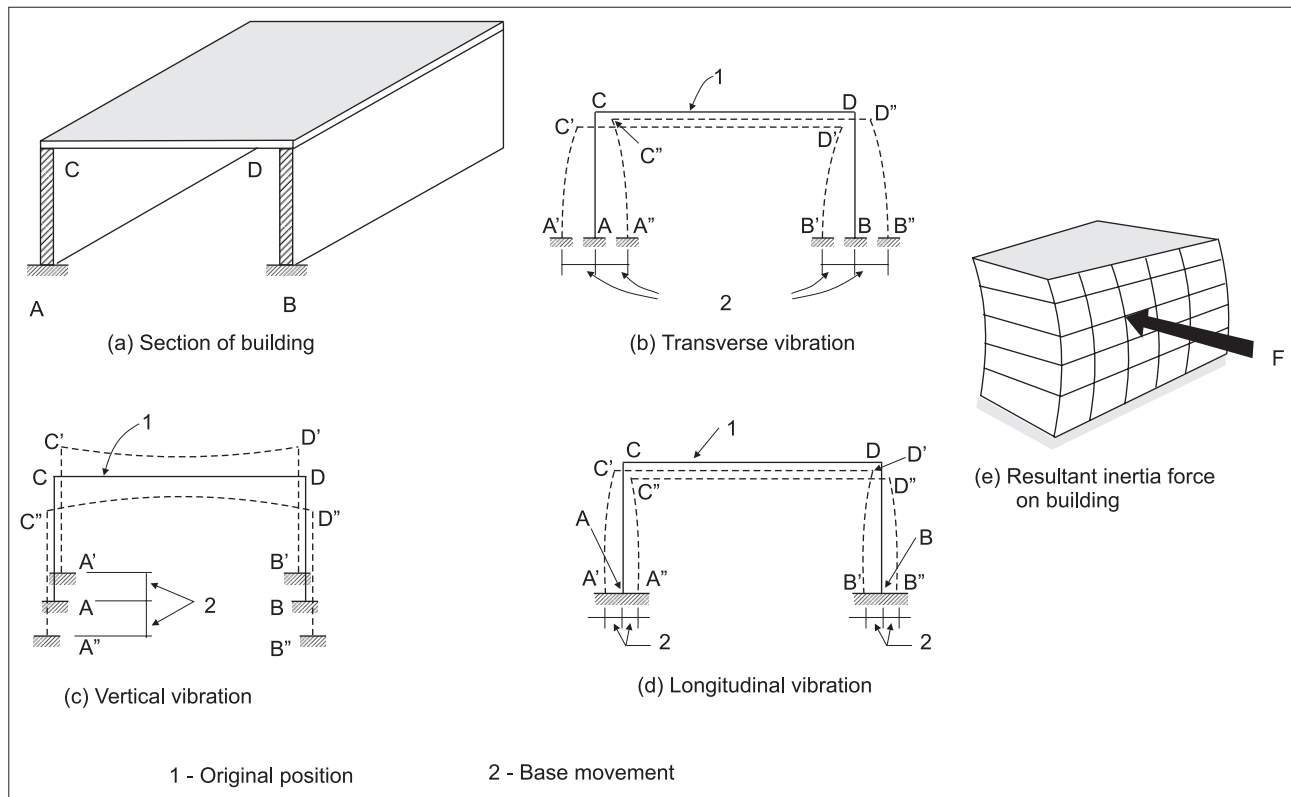


Fig 2.1 Seismic vibrations of a building and resultant earthquake force

since every earthquake exhibits different characteristics. The following equivalent minimum total lateral force is, used for seismic design:

$$F = S \cdot F_s \cdot I \cdot C \cdot W$$

Where S , F_s , I , C and W are the factors affecting seismic load, which will be explained in the following section.

2.3.3 Factors affecting seismic load

The earthquake zone factor S depends upon the ground intensity of the earthquake. The value of S usually is plotted on maps in terms of seismic intensity isolines or maximum acceleration isolines. Obviously, the higher the intensity or acceleration, the larger will be the seismic force.

The soil-foundation factor F_s depends upon the ratio of fundamental elastic period of vibration of a building in the direction under consideration and the characteristic site period. Therefore, F_s is a numerical coefficient for site-building resonance.

The occupancy importance or hazard factor I depends upon the usage of the building. The higher the importance or larger the hazard caused by the failure of the building, the greater the value of the factor I .

The C is a factor depending on the stiffness and damping of the structure. Larger the stiffness for given mass, shorter the fundamental period of vibration of the structure and larger the value of C . Damping is the energy dissipation property of the building; larger the damping, smaller the value of C .

The W is the total weight of the superstructure of a building including its contents. The inertia forces are proportional to the mass of the building and only that part of the loading action that possesses mass will give rise to seismic force on the building. Therefore, the lighter the material, the smaller will be the seismic force.

2.3.4 Nature of seismic stresses

The horizontal seismic forces are reversible in direction. The structural elements such as walls, beams and columns that were bearing only vertical loads before the earthquake, have now to carry horizontal bending and shearing effects as well. When the bending tension due to earthquake exceeds the vertical compression, net tensile stress will occur. If the building material is weak in tension such as brick or stone masonry, cracking occurs which reduces the effective area for resisting bending moment, as shown in Fig 2.2. It follows that the strength in tension and shear is important for earthquake resistance.

2.3.5 Important parameters in seismic design

It follows that the following properties and parameters are most important from the point of view of the seismic design.

(i) Building material properties

- Strength in compression, tension and shear, including dynamic effects
- Unit weight
- Modulus of elasticity

(ii) Dynamic characteristics of the building system, including periods, modes and dampings.

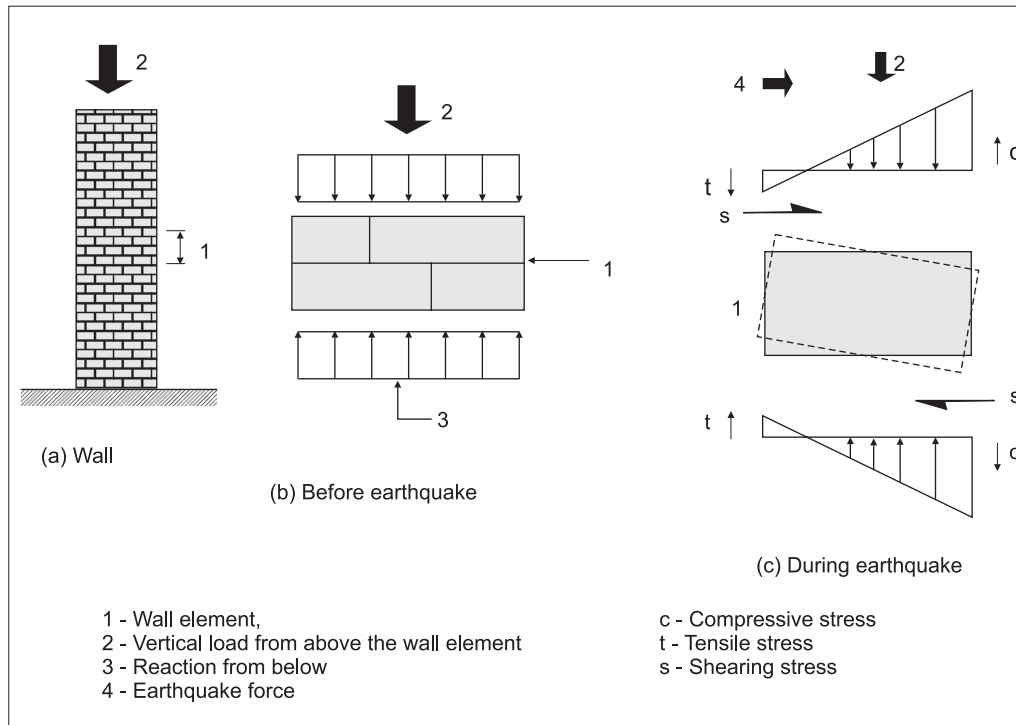


Fig 2.2 Stress condition in a wall element

(iii) Load-deflection characteristics of building components.

2.4 Effect of site conditions on building damage

Past earthquakes show that site condition significantly affects the building damage. Earthquake studies have almost invariably shown that the intensity of a shock is directly related to the type of soil layers supporting the building. Structures built on solid rock and firm soil frequently fares better than buildings on soft ground. This was dramatically demonstrated in the 1985 Mexico City earthquake, where the damage on soft soils in Mexico City, at an epicentral distance of 400 km, was substantially higher than at closer locations.

From studies of the July 28, 1957 earthquake in Mexico City, it was already known for example that the damage on the soft soils

in the center of the city could be 5 to 50 times higher than on firmer soils in the surrounding area. Another example occurred in the 1976 Tangshan, China earthquake, in which 50% of the buildings on thick soil sites were razed to the ground, while only 12% of the buildings on the rock subsoil near the mountain areas totally collapsed. Rigid masonry buildings resting on rock may on the contrary show more severe damage than when built on soil during a near earthquake as in Koyna (India) earthquake of 1967 and North Yemen earthquake of 1980.

Lessons learned from recent earthquake show that the topography of a building site can also have an effect on damage. Buildings built on sites with open and even topography are usually less damaged in an earthquake than buildings on strip-shaped hill ridges, separated high hills, and steep

slopes.

2.5 OTHER FACTORS AFFECTING DAMAGE

The extent of damage to a building depends much on the strength, ductility, and integrity of a building and the stiffness of ground beneath it in a given intensity of the earthquake motions.

Almost any building can be designed to be earthquake resistant provided its site is suitable. Buildings suffer during an earthquake primarily because horizontal forces are exerted on a structure that often meant to contend only with vertical stresses. The principal factors that influence damage to buildings and other man-made structures are listed below:

2.5.1 Building configuration

An important feature is regularity and symmetry in the overall shape of a building. A building shaped like a box, as rectangular both in plan and elevation, is inherently stronger than one that is L-shaped or U-shaped, such as a building with wings. An irregularly shaped building will twist as it shakes, increasing the damage.

2.5.2 Opening size

In general, openings in walls of a building tend to weaken the walls, and fewer the openings less the damage it will suffer during an earthquake. If it is necessary to have large openings through a building, or if an open first floor is desired, then special provisions should be made to ensure structural integrity.

2.5.3 Rigidity distribution

The rigidity of a building along the vertical direction should be distributed uniformly.

Therefore, changes in the structural system of a building from one floor to the next will increase the potential for damage, and should be avoided. Columns or shear walls should run continuously from foundation to the roof, without interruptions or changes in material.

2.5.4 Ductility

By ductility is meant the ability of the building to bend, sway, and deform by large amounts without collapse. The opposite condition in a building is called brittleness arising both from the use of materials that are inherently brittle and from the wrong design of structures using otherwise ductile materials. Brittle materials crack under load; some examples are adobe, brick and concrete blocks. It is not surprising that most of the damage during the past earthquakes was to unreinforced masonry structures constructed of brittle materials, poorly tied together. The addition of steel reinforcements can add ductility to brittle materials. Reinforced concrete, for example, can be made ductile by proper use of reinforcing steel and closely spaced steel ties.

2.5.5 Foundation

Buildings, which are structurally strong to withstand earthquakes sometimes fail due to inadequate foundation design. Tilting, cracking and failure of superstructures may result from soil liquefaction and differential settlement of footing.

Certain types of foundations are more susceptible to damage than others. For example, isolated footings of columns are likely to be subjected to differential settlement particularly where the supporting ground consists of different or soft types of soil. Mixed types of foundations within the

same building may also lead to damage due to differential settlement.

Very shallow foundations deteriorate because of weathering, particularly when exposed to freezing and thawing in the regions of cold climate.

2.5.6 Construction quality

In many instances the failure of buildings in an earthquake has been attributed to poor quality of construction, substandard materials, poor workmanship, e. g., inadequate skill in bonding, absence of “through stones” or bonding units, and improper and inadequate construction.

2.6 FAILURE MECHANISMS OF EARTHQUAKES

2.6.1 Free standing masonry wall

Consider the free standing masonry walls shown in Fig 2.3. In Fig 2.3(a), the ground motion is acting transverse to a free standing wall A. The force acting on the mass of the wall tends to overturn it. The seismic resistance of the wall is by virtue of its weight and tensile strength of mortar and it is obviously very small. This wall will collapse by overturning under the ground motion.

The free standing wall B fixed on the ground in Fig 2.3(b) is subjected to ground motion in its own plane. In this case, the wall will offer much greater resistance because of its large depth in the plane of bending. Such a wall is termed a shear wall. The damage modes of an unreinforced shear wall depend on the length-to-width ratio of the wall. A wall with small length-to-depth ratio will generally develop a horizontal crack due to bending tension and

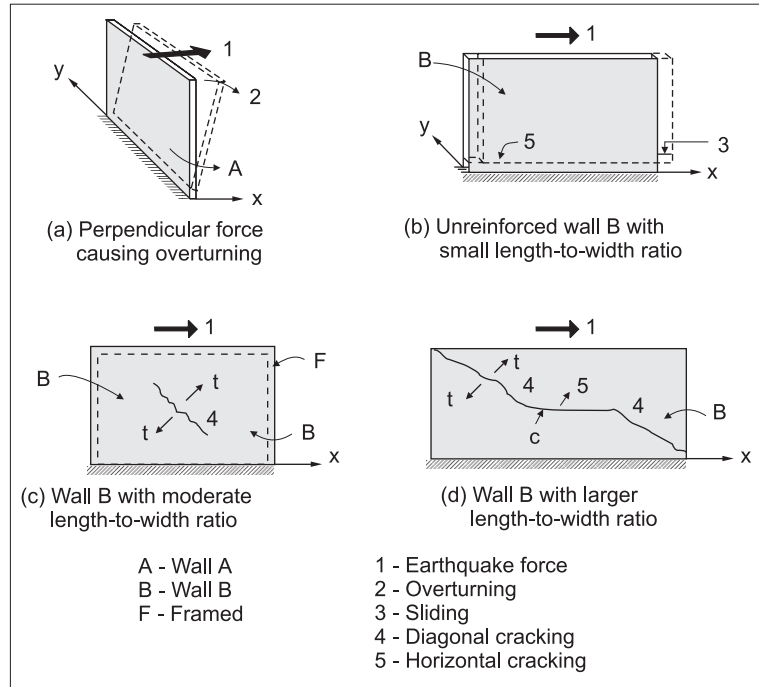


Fig 2.3 Failure mechanism of free standing walls

then slide due to shearing. A wall with moderate length-to-width ratio and bounding frame diagonally cracks due to shearing as shown at Fig 2.3 (c).

A wall with large length-to-width ratio, on the other hand, may develop diagonal tension cracks at both sides and horizontal cracks at the middle as shown at Fig 2.3 (d).

2.6.2 Wall enclosure without roof

Now consider the combination of walls A and B as an enclosure shown in Fig 2.4. For the X direction of force as shown, walls B act as shear walls and, besides taking their own inertia, they offer resistance against the collapse of wall A as well. As a result walls A now act as vertical slabs supported on two vertical sides and the bottom plinth. The walls A are subjected to the inertia force on their own mass. Near the vertical edges, the wall will carry reversible bending mo-

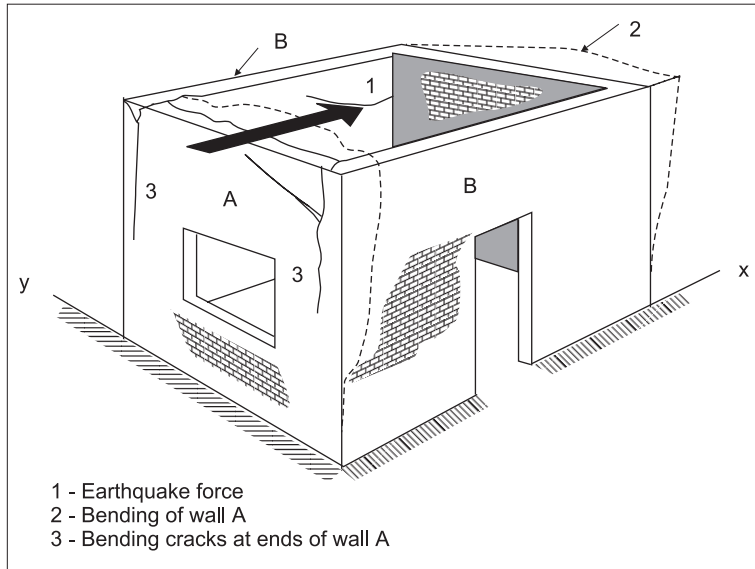


Fig 2.4 Failure mechanism of wall enclosure without roof

ments in the horizontal plane for which the masonry has little strength. Consequently cracking and separation of the walls may occur along these edges shown in the figure.

It can be seen that in the action of walls *B* as shear walls, the walls *A* will act as flanges connected to the walls *B* acting as web. Thus if the connection between walls *A* and *B* is not lost due to their bonding ac-

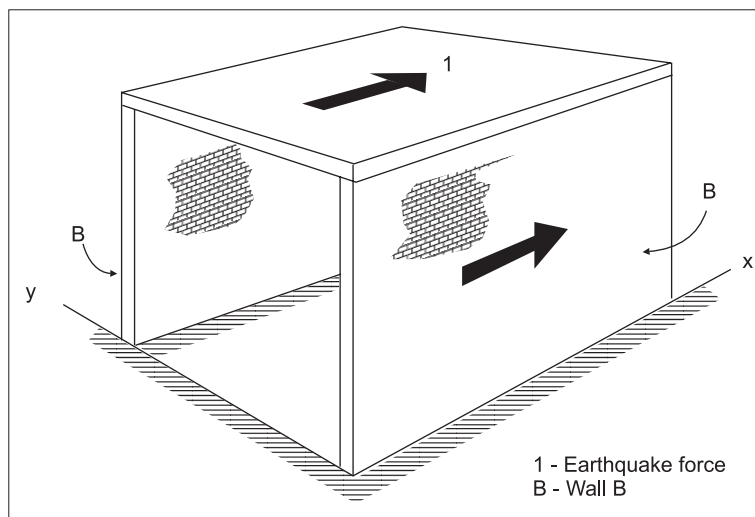


Fig 2.5 Roof on two walls

tion as plates, the building will tend to act as a box and its resistance to horizontal loads will be much larger than that of walls *B* acting separately. Most unreinforced masonry enclosures, however, have very weak vertical joints between walls meeting at right angles due to the construction procedure involving toothed joint that is generally not properly filled with mortar. Consequently the corners fail and lead to collapse of the walls. It may also be easily imagined that the longer the walls in plan, the smaller will be the support to them from the cross walls and the lesser will be the box effect.

2.6.3 Roof on two walls

In *Fig 2.5 (a)* roof slab is shown to be resting on two parallel walls *B* and the earthquake force is acting in the plane of the walls. Assuming that there is enough adhesion between the slab and the walls, the slab will transfer its inertia force at the top of walls *B*, causing shearing and overturning action in them. To be able to transfer its inertia force to the two end walls, the slab must have enough strength in bending in the horizontal plane. This action of slab is known as diaphragm action. Reinforced concrete or reinforced brick slabs have such strength inherently and act as rigid diaphragms. However, other types of roofs or floors such as timber or reinforced concrete joists with brick tile covering will be very flexible. The joists will have to be connected together and fixed to the walls suitably so that they are able to transfer their inertia force to the walls. At the same time, the walls *B* must have enough strength as shear walls to withstand the force from the roof and its own inertia force. Obviously, the structure shown in *Fig 2.5*, when subjected to ground motion perpendicular to its plane, will col-

lapse very easily because walls B have little bending resistance in the plane perpendicular to it. In long barrack type buildings without intermediate walls, the end walls will be too far to offer much support to the long walls and the situation will be similar to the one just mentioned above.

2.6.4 Roof on wall enclosure

Now consider a complete wall enclosure with a roof on the top subjected to earthquake force acting along X-axis as shown in Fig 2.6. If the roof is rigid and acts as a horizontal diaphragm, its inertia will be distributed to the four walls in proportion to their stiffness. The inertia of roof will almost entirely go to walls B since the stiffness of the walls B is much greater than the walls A in X direction. In this case, the plate action of walls A will be restrained by the roof at the top and horizontal bending of wall A will be reduced. On the other hand, if the roof is flexible the roof inertia will go to the wall on which it is supported and the support provided to plate action of walls A will also be little or zero. Again the enclosure will act as a box for resisting the lateral loads, this action decreasing in value as the plan dimensions of the enclosures increase.

2.6.5 Roofs and floors

The earthquake-induced inertia force can be distributed to the vertical structural elements in proportion to their stiffness, provided the roofs and floors are rigid to act as horizontal diaphragms. Otherwise, the roof and floor inertia will only go to the vertical elements on which they are supported. Therefore, the stiffness and integrity of roofs and floors are important for earthquake resistance.

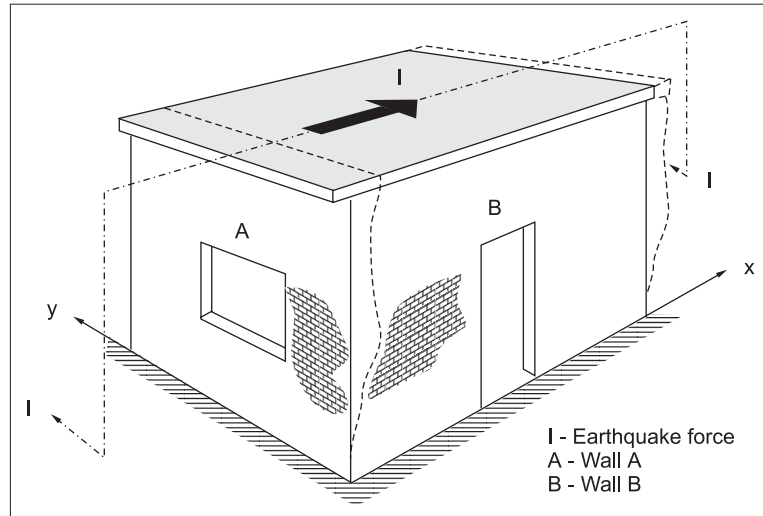


Fig 2.6 Roof on wall enclosure

The roofs and floors, which are rigid and flat and are bonded or tied to the masonry, have a positive effect on the wall, such as the slab or slab and beam construction be directly cast over the walls or jack arch floors or roofs provided with horizontal ties and laid over the masonry walls through good quality mortar. Others that simply rest on the masonry walls will offer resistance to relative motion only through friction, which may or may not be adequate depending on the earthquake intensity. In the case of a floor consisting of timber joists placed at center to center spacing of 20 to 25 cm with brick tiles placed in directly over the joists and covered with clayey earth, the brick tiles have no binding effect on the

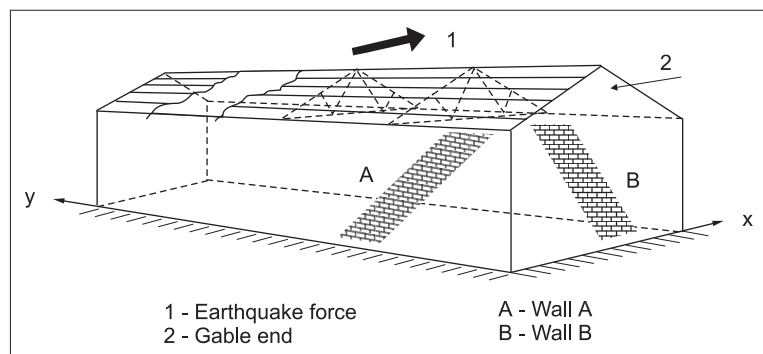


Fig 2.7 Long building with roof trusses

joists. Therefore, relative displacement of the joists is quite likely to occur during an earthquake, which could easily bring down the tiles, damaging property and causing injury to people. Similar behaviour may be visualized with the floor consisting of precast reinforced concrete elements not adequately tied together. In this case, relative displacement of the supporting walls could bring down the slabs.

2.6.6 Long building with roof trusses

Consider a long building with a single span and roof trusses as shown in Fig 2.7. The trusses rest on the walls A. The walls B are gabled to receive the purlins of the end bays. Assuming that the ground motion is along the X-axis, the inertia forces will be transmitted from sheeting to purlins to trusses and from trusses to wall A.

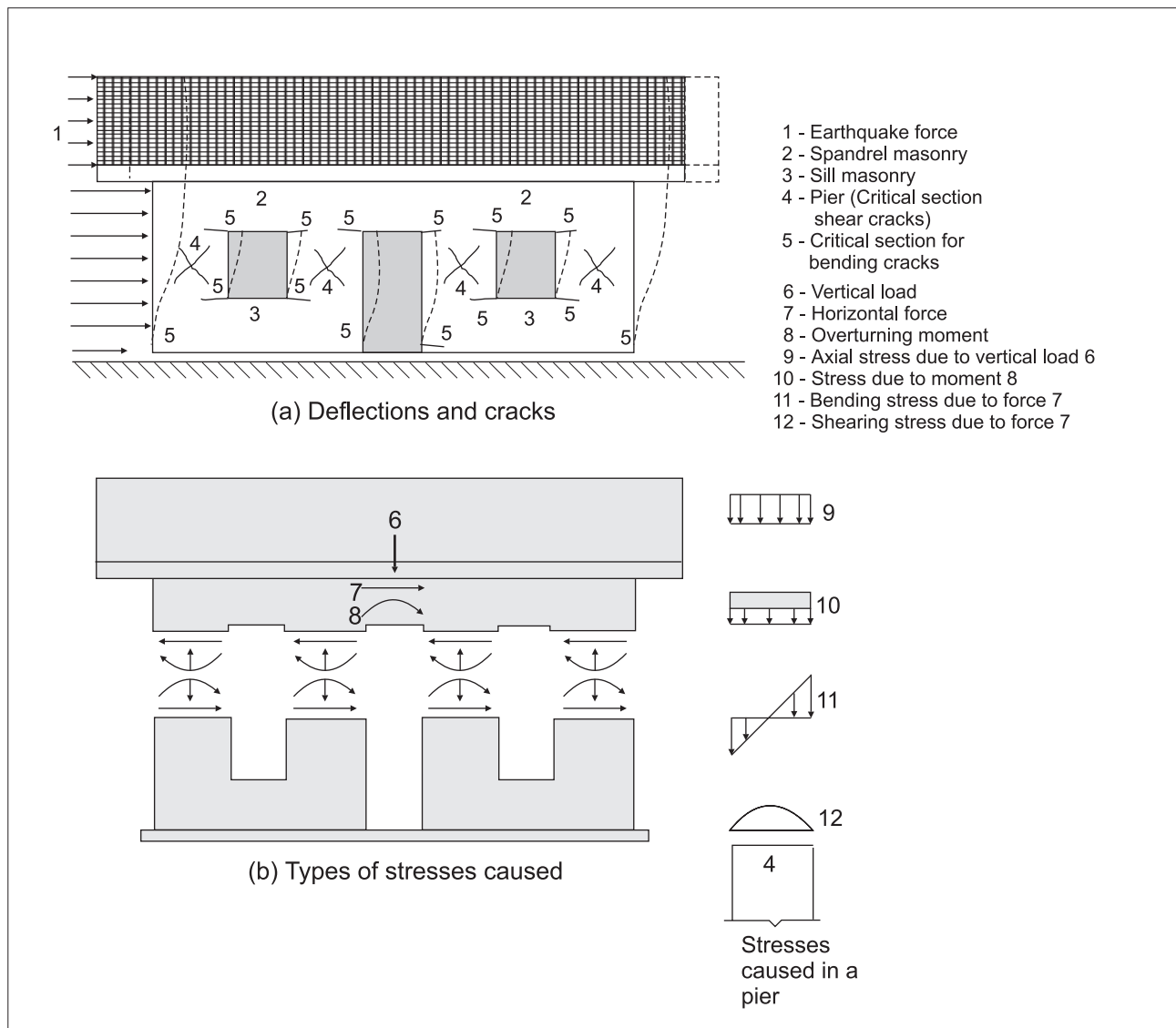


Fig 2.8 Deformation of a shear wall with openings.

Table 2.1 Categories of damage

<i>Damage category</i>	<i>Extent of damage in general</i>	<i>Suggested post- earthquake actions</i>
0 No damage	No damage	No action required
I Slightly non-structural damage	Thin cracks in plaster, falling of plaster bits in limited parts.	Building need not be vacated. Only architectural repairs needed.
II Slight Structural Damage	Small cracks in walls, failing of plaster in large bits over large areas; damage to non-structural parts like chimneys, projecting cornices, etc. The load carrying capacity of the structure is not reduced appreciably.	Building need not be vacated. Architectural repairs required to achieve durability.
III Moderate structural damage	Large and deep cracks in walls; widespread cracking of walls, columns, piers and tilting or failing of chimneys. The load carrying capacity of the structure is partially reduced.	Building needs to be vacated, to be reoccupied after restoration and strengthening. Structural restoration and seismic strengthening are necessary after which architectural treatment may be carried out.
IV Severe structural damage	Gaps occur in walls; inner and outer walls collapse; failure of ties to separate parts of buildings. Approx. 50 % of the main structural elements fail. The building takes dangerous state.	Building has to be vacated. Either the building has to be demolished or extensive restoration and strengthening work has to be carried out before reoccupation.
V Collapse	A large part or whole of the building collapses.	Clearing the site and reconstruction.

The end purlins will transmit some force directly to gable ends. Under the seismic force the trusses may slide on the walls unless anchored into them by bolts. Also, the wall *A*, which does, not get much support from the walls *B* in this case, may overturn unless made strong enough in the vertical bending as a cantilever or other suitable arrangement, such as adding horizontal bracings between the trusses, is made to transmit the force horizontally to end walls *B*.

When the ground motion is along *Y* direction, walls *A* will be in a position to act as shear walls and all forces may be trans-

mitted to them. In this case, the purlins act as ties and struts and transfer the inertia force of roof to the gable ends.

As a result the gable ends may fail. When the gable triangles are very weak in stability, they may fail even in small earthquakes. Also, if there is insufficient bracing in the roof trusses, they may overturn even when the walls are intact.

2.6.7 Shear wall with openings

Shear walls are the main lateral earthquake resistant elements in many buildings. For understanding their action, let us consider a shear wall with three openings shown in

Fig 2.8. Obviously, the piers between the openings are more flexible than the portion of wall below (sill masonry) or above (spandrel masonry) the openings. The deflected form under horizontal seismic force is also sketched in the figure.

The sections at the level of the top and bottom of opening are found to be the worst stressed in tension as well as in compression and those near the mid-height of piers carry the maximum shears. Under reversed direction of horizontal loading the sections carrying tensile and compressive stresses

are also reversed. Thus it is seen that tension occurs in the jambs of openings and at the corners of the walls.

2.7 EARTHQUAKE DAMAGE CATEGORIES

In this section, an outline of damage categories is simply described in *Table 2.1* on the basis of past earthquake experience. Therein the appropriate post-earthquake action for each category of damage is also suggested.

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