2.1. INTRODUCTION

The traditionally built constructions of India include small structures constructed in brick, stone, mud or a combination thereof. The masonary buildings which are brittle structure have proved to be the most vulnerable to strong seismic forces. This construction system generally built by local masons, without guidance from professional experts is termed as non-engineered construction. These traditionally built structures have suffered extensive damage during earthquakes. The main cause of their failure may be attributed to the negligible tensile strength of materials used and their heavy mass. There is general lack of strong and ductile connections between masonry walls, roof components and foundation system in masonry construction. More than 90 percent of Indian population prefers to live in such houses as the masonry construction is flexible enough to accomodate itself according to the requirements of owners and prevailing environmental conditions. But the recent earthquakes have demonstrated that seismic efficiency of such constructions is very low and the large scale collapse of traditionally built houses is the single largest factor contributing to the heavy losses and major casualities which occurred during earthquakes, such as Bhuj earthquake of 2001. Thus it is very important to improve the seismic behaviour of such traditionally built constructions by introducing number of earthquake resistant features. The strengthening of masonry buildings have been dealt in detail in the Indian Seismic Code IS : 4326. This chapter deals with seismic performance of masonry constructions during earthquakes and describes various modes of failure.

2.2. SEISMIC PERFORMANCE OF MASONRY BUILDINGS

Study of some of the significant past earthquakes in the recent years [**Bhuj** (*Gujrat*)-2001, **Chamoli** (*Uttaranchal*)-1999, **Jabalpur** (*Madhya Pradesh*)-1997, **Latur** (*Maharashtra*)-1993] have clearly demonstrated that the seismic response of traditionally built structures is very poor. The main cause of large scale devastation is the improper seismic design of such buildings. Some of the important factors contributing towards low seismic efficiency of masonry building ... described below :

1. Failure of connection between walls : The walls, which are the weakest ... masonry buildings must be tied together properly like a box to ensure good seismic perform...

2. Absence of proper bonding between perpendicular walls at the junction : A ... interlocking of brick courses at the corner junctions should be ensured.

3. Large size of openings : The sizes of door and window openings must be kept sma... to increase the resistance of wall to seismic shocks.

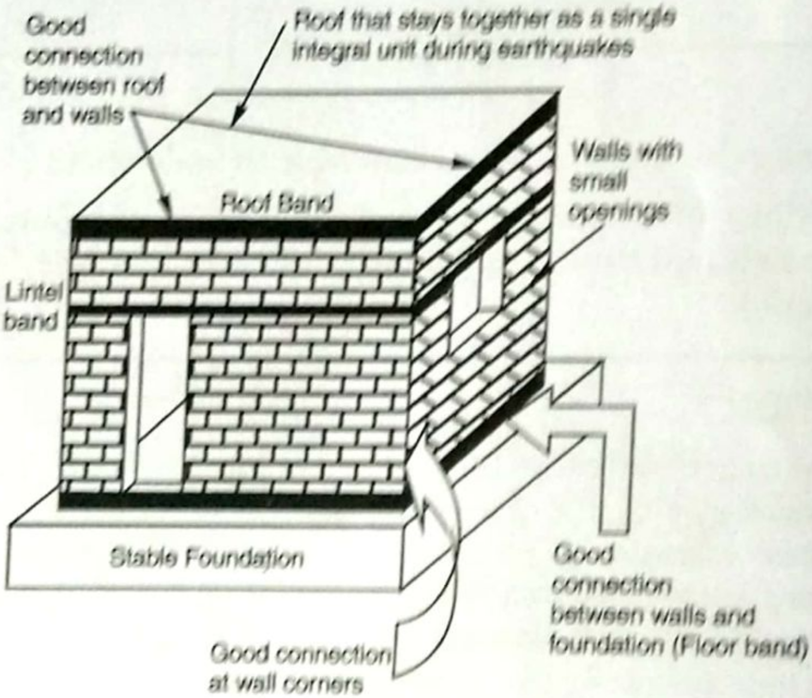


Fig. 2.1 (*a*)

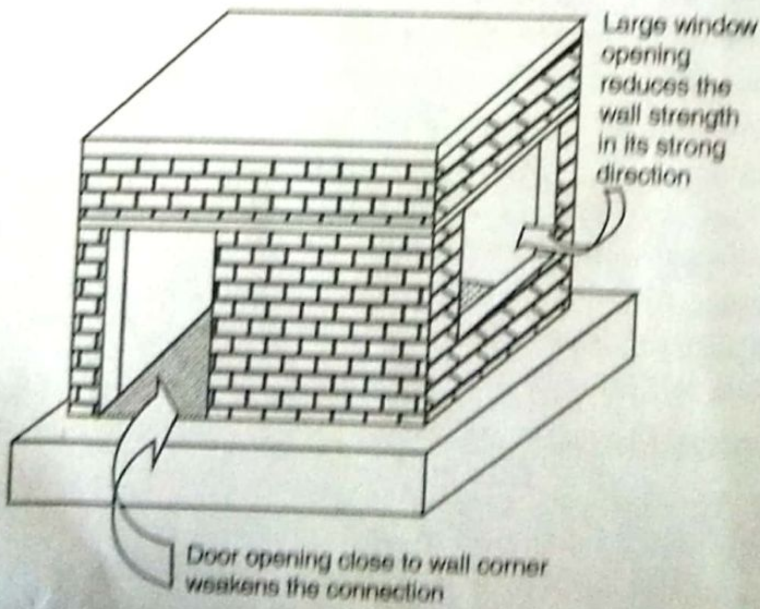


Fig. 2.1 (*b*)

4. **Too long walls (greater length) and too tall walls (*more height*) are vulnerable to ground shaking :** The length to thickness and height to thickness ratio of walls must be according to the specified seismic design codes.

5. **Excessive porosity and poor tensile strength of bricks,** which is the major construction material : The seismic behaviour of masonry walls depends upon the relative strength of bricks and mortar. It is important to note that both masonry and concrete can carry compressive loads safely but their behaviour in tension is very poor. Standard recommended bricks and specified grades of mortars must be used in the construction of masonry buildings situated in a particular seismic zone (*As per seismic zone map*).

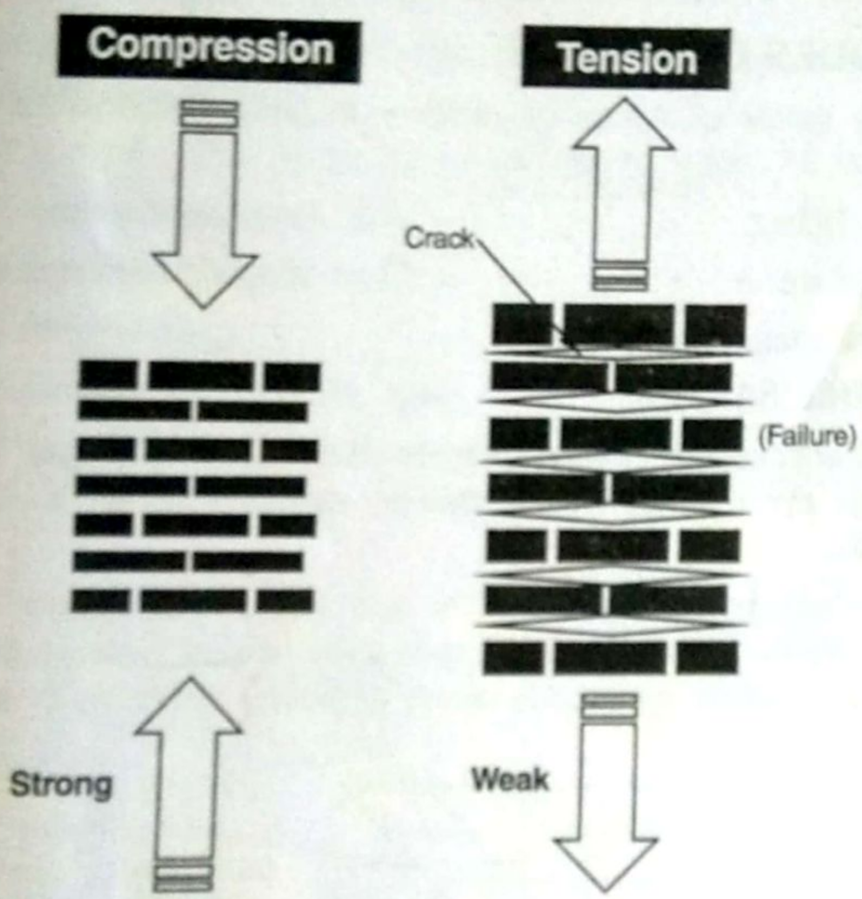


Fig. 2.2

6. **Large scale construction of non-structural components in the building like parapets, ...bles, unanchored walls, projections etc. :** The collapse of these improperly tied non-structural ...mponents during earthquake is one of the major cause of loss of lives. The loss of lives could ... minimized by constructing lesser number of such elements and that too by giving proper design ...nsiderations *i.e.* proper anchoring etc.

7. **Irregular or asymetric plans of masonry buildings :** The rectangular buildings suffer ...s damage during earthquakes as compared to irregular buildings. An irregular building may ... defined as building that lacks symmetry and has discontinuity in mass and geometry. It may ... noted that concentration of large mass at one place attracts large horizontal or torsional forces ...ring ground shaking. So a building must be designed by adopting appropriate structural ...nfiguration with overall distribution of mass.

2.3. MODE OF FAILURE OF MASONRY BUILDINGS

It is not always possible to replace or rebuilt the majority of earthquake damaged buildings due to economic or other considerations. The only solution is to 'retrofit' the seismically deficient buildings so that they become safe for future use. ***'Retrofitting' of a structure may be simply defined as improving the strength and structural capacity of seismically deficient building by adopting suitable means for its possible future use to withstand safely the effects of earthquake.***

For adopting suitable retrofitting methods, it is important to study the failure mode of traditional masonry structures. It has been observed by proper survey that modes of failure of masonry buildings resulted by seismic activity is generally common, although the type and technique of construction is different in different regions.

2.4. COMMON MODES OF FAILURE

The most common modes of failure of masonry buildings subjected to seismic motion are given below :

1. Out of plane failure
2. In-plane failure
3. Diaphragm failure
4. Connection failure
5. Non-structural components failure

2.4.1. OUT-OF PLANE FAILURE

It is one of the most common modes of failure of masonry buildings. It may be understood that the walls, which are the main sub-units in masonry structures behave as discrete or independent units during earthquakes.

The out-of-plane failure is the type of failure in which structural walls situated perpendicular to the ground seismic motion are subjected to out-of-plane bending causing development of vertical cracks or fissures at the corners and at the centre of walls. These walls are termed as flexural walls.

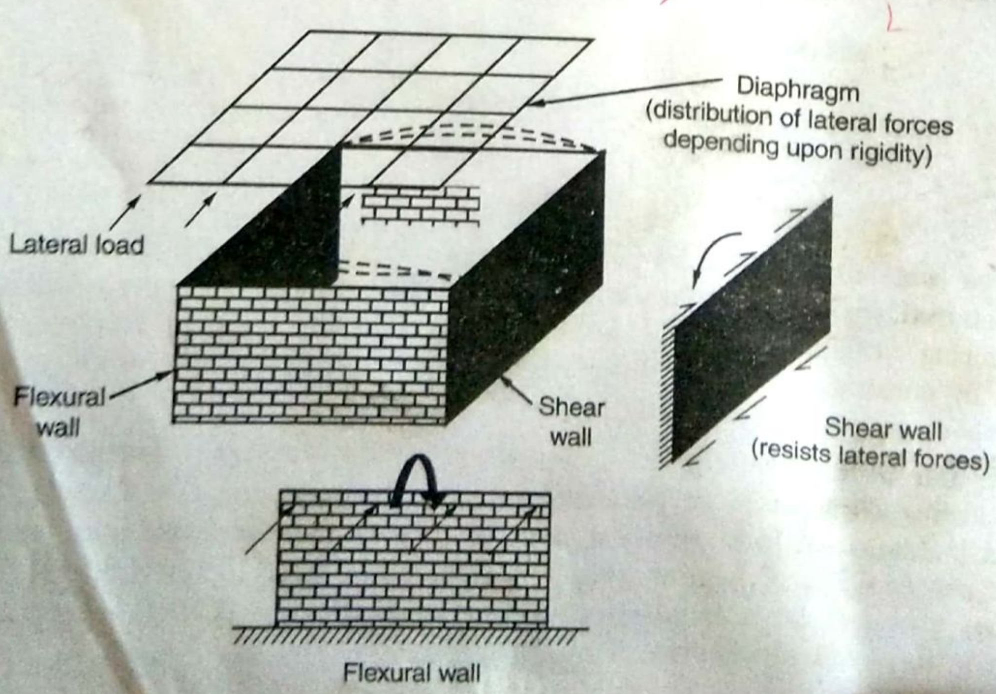


Fig. 2.3

2.4.1.1. Causes of out-of-plane failure : The main causes of out-of-plane failure of walls in unreinforced traditional masonry structures are given below :

(*a*) Inadequate or improper joining of vertical walls with the roof structure.

(*b*) Poor and limited tensile strength of masonry units and mortar. The common masonry units used in the country are burnt and unburnt bricks, solid and hollow blocks and stone blocks etc.

(*c*) Construction of long span diaphragms (*horizontal resisting elements such as roof slab and floors etc.*). These horizontal diaphragms result in out of plane failure due to excessive horizontal flexure. The increase in flexural stress leads to ruputre of component parts followed by collapse of building.

2.4.1.2. Characterization of out-of-plane failure : The out-of-plane failure is characterised by observing the following developments.

(*i*) Formation of vertical cracks in the corner and in the middle of the walls.

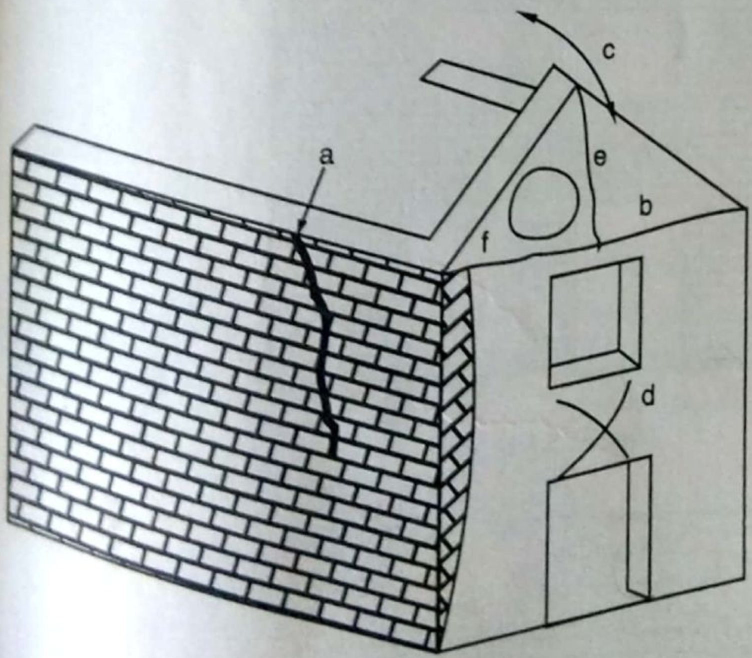
(*ii*) Formation of cracks at the lintel level.

(*iii*) Formation of cracks at the roof level.

(*iv*) Rupture of exterior walls.

(*v*) Ejection of masonry units from the walls.

(*vi*) Formation of horizotnal cracks along the facade (Front of a building).



a vertical cracks in the corner and/or T walls
b Horizontal cracks along the facade
c Partial collapse of an exterior wall
d Cracks at lintel and top of slender piers
e Cracks at the level of the roof
f Masonry ejection

Fig. 2.4

2.4.2. IN-PLANE FAILURE

In-plane failure of structural walls in traditionally built constructions of India is also one of the major modes of failure but is quiet less common as compared to out-of-plane failure.

It is a type of failure in which structural walls situated parallel to earthquake motion are subjected to bending and shear forces causing development of horizontal and diagonal cracks in the walls.

These walls are termed as shear walls. (See fig. 2.3)

2.4.2.1. Causes of In-plane failure : The main causes of in-plane failure are :

(*i*) Excessive bending

(*ii*) Excessive shear

(*iii*) Repeated load reversal

2.4.2.2. Characterisation of In-plane failure : In-plane failure in structural walls of unreinforced masonry structures is characterised by the following features shown in fig. 2.5 (*a*).

(*a*) Vertical cracks above the openings.

(*b*) Diagonal cracks or shear cracks on parapets

(*c*) Diagonal shear cracks in doors and window lintels. The diagonal cracking is also known as X-Cracking (Fig. 2.5 (*b*).

(*d*) Diagonal cracks in wall portion situated between openings. It is termed as ***'Wall pier masonry'***

(*e*) Crushing of wall corners.

(*f*) Horizontal bending cracks on top and bottom of wall pier masonry.

(*g*) Vertical cracks near wall junctions.

(*h*) Spalling of material at floor beam level.

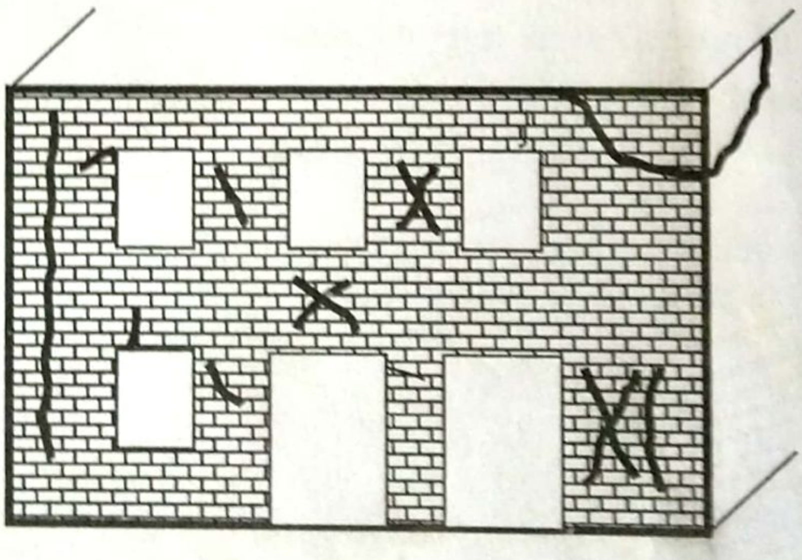
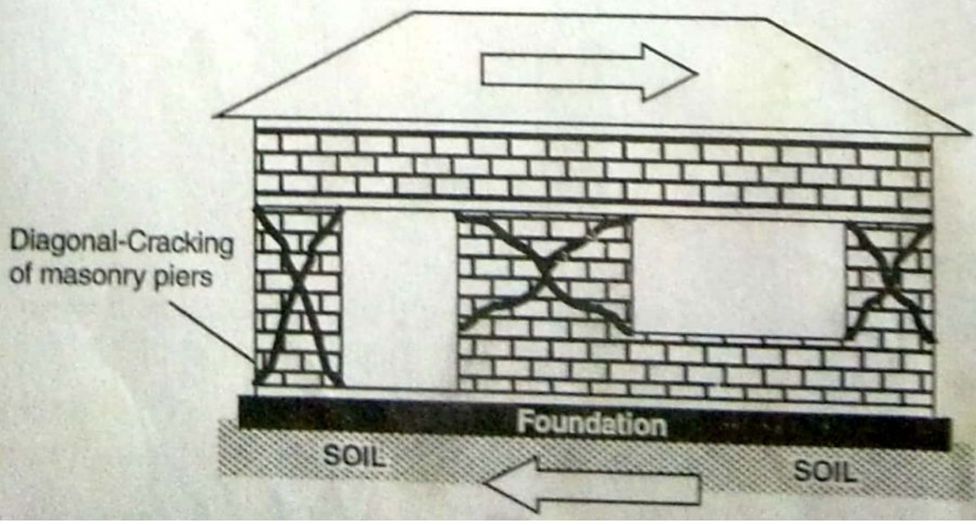


Fig. 2.5 (*a*)



2.4.3 DIAPHRAGM FAILURE

This type of failure occurs rarely during earthquakes. *Diaphragms are horizontal resisting elements serving as horizontal link with the vertical components of buildings such as columns and walls.* For example, roof slab (*roof diaphragm*), first floor diaphragm etc. These horizontal diaphragms are important structural elements, which must possess adequate strength and stiffness. These transfer the delivered earthquake forces to the vertical components like coloumns, shear walls, frames etc. which ultimately transfer the seismic forces into the foundation.

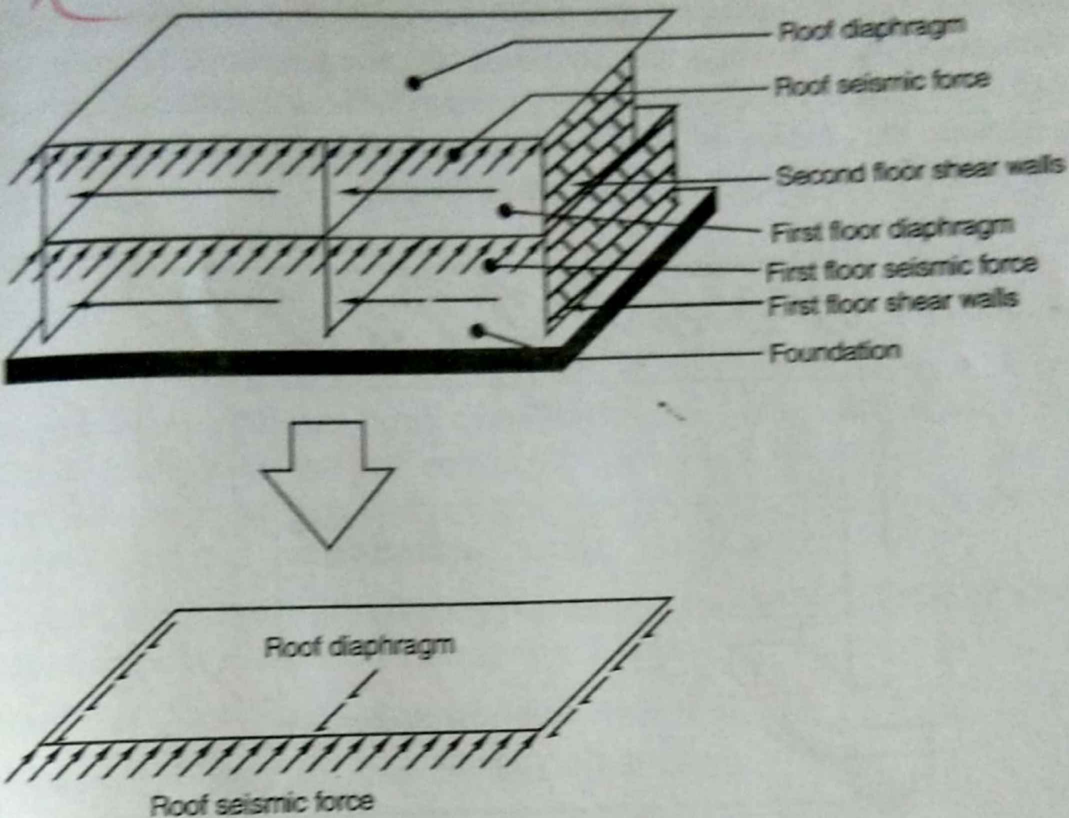
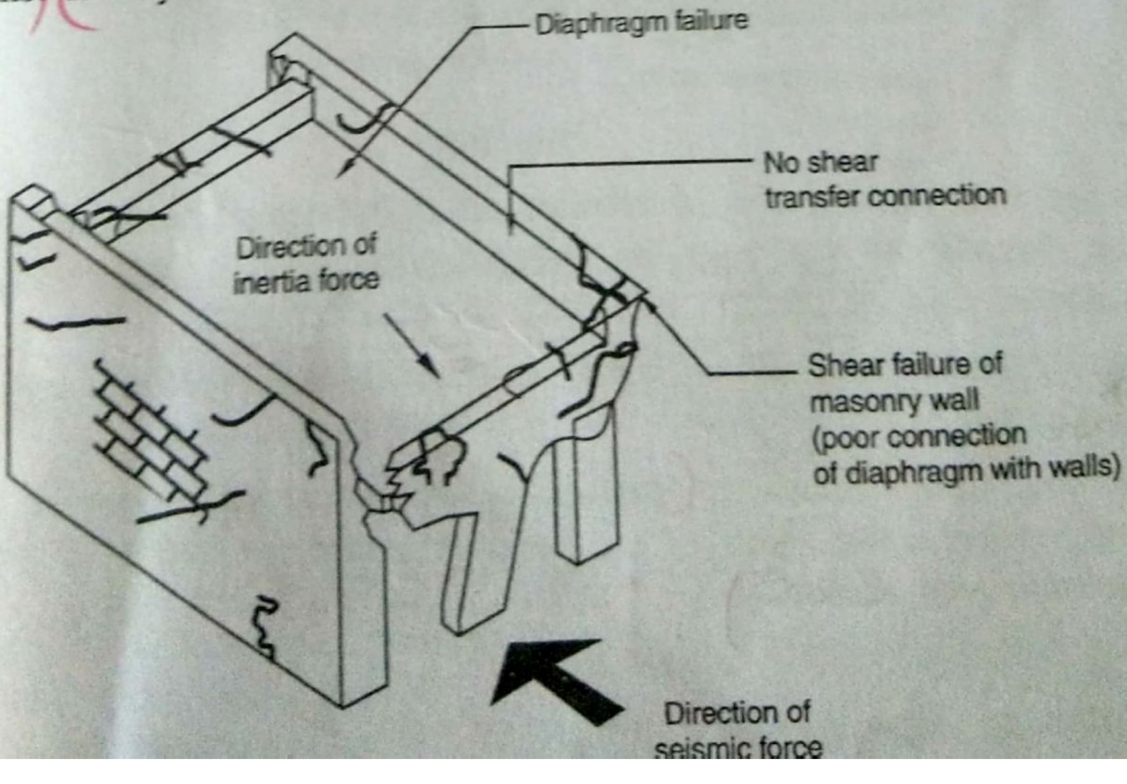


Fig. 2.6

The diaphragm failure is a type of failure in which it losses its capability of good shea[r] transfer to the walls. It may be understood that diaphragm failure only leads to shear failure o[f]



masonry walls, resulting from excessive diaphragm flexibility. Damage at the corners of the walls is generally observed in the absence of no shear transfer connection. Diaphragm failure in any case does not mean that it will lose its gravity load carrying capacity. In properly strengthened and anchored buildings, the problem of diaphragm failure remains non existent. This type of failure can be prevented by adequantely anchoring the diaphragm with the reaction walls by use of shear bolts.

2.4.4 CONNECTION FAILURE

During earthquake, seismic inertia forces are generated in all elements of the building. These inertial forces are initially delivered to the horizontal diaphragms such as floor slab. These lateral forces are further distributed by the floor slab to the vertical elements like walls and columns which in turn transfer the forces to the foundations. Ultimately the lateral inertia forces are transferred to the soil system lying below the foundations.

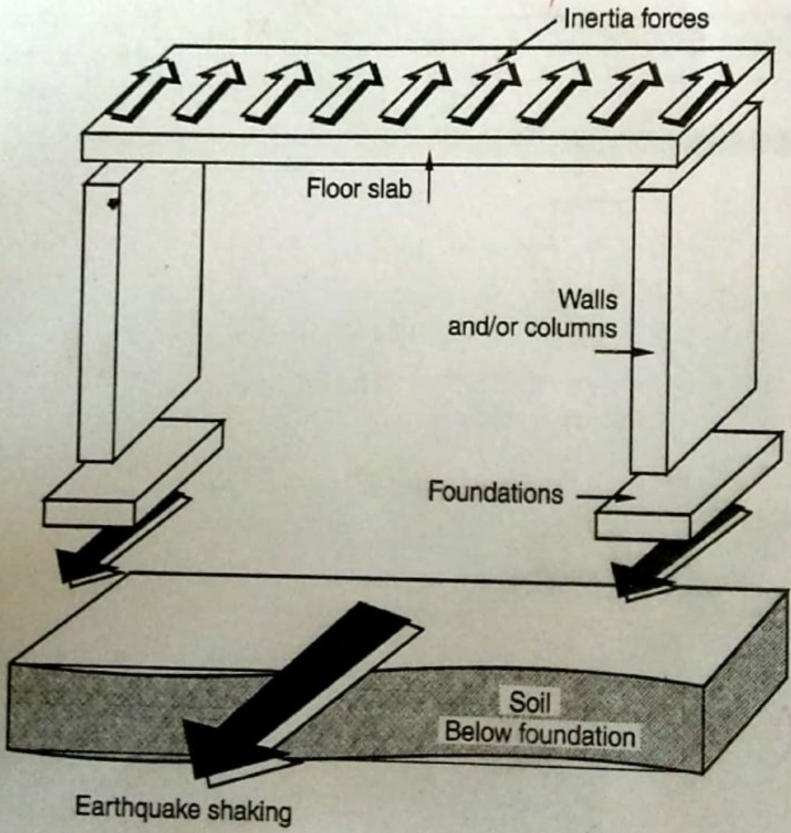


Fig. 2.8

Thus we see that the connections between all the structural elements such as floor slabs, walls, columns, foundations etc. must be designed adequately so that seismic forces of inertia are safely distributed through them.

In traditionally built constructions, walls are generally made of masonry and are improperly connected to floor slabs.

The connection failure refers to "*Inadequate and improper connection between horizontal diaphragms and vertical components of the building leading to failure of masonry walls under the attack of seismic ground motion*".

This type of failure is typically characterised by ;

(*i*) Formation of diagonal cracks on masonry walls.

(*ii*) Collapse of corner zones.

2.4.4.1 Main causes of connection failure : The principal causes of connection failure is traditionally built constructions are ;

1. Increased size and number of wall openings.
2. Inadequately strengthened openings near the edges of masonry walls.
3. Insufficient connection of floors with the external walls.
4. Due to relative small thickness of walls and use of brittle material like masonry.

2.4.5 NON-STRUCTURAL COMPONENTS FAILURE

The components of building which are not designed and detailed by structural engineer like the other load bearing elements (*columns, beams, slabs etc.*) are termed as non-structural components. The non-structural components include :

(*i*) Parapet walls
(*ii*) Partition walls
(*iii*) Mumty
(*iv*) Water tanks
(*v*) Cornices
(*vi*) Canopies
(*vii*) Stair case
(*viii*) Projections etc.

The above mentioned non-structural components are damaged generally when subjected to earthquake forces because these are not structurally safe and are also not a part of initial building design. Some of the non-structural components like partition walls, projections and water tanks etc. are often added after the initial building design is approved.

2.4.5.1 Causes of failure of non-structural components : Some of the important causes of failure of non-structural components are given below :

(*i*) Improper and inadequate design to resist lateral force.
(*ii*) Poor connection with the main structural elements.
(*iii*) Non-bracing or poor restraining of these structural elements.

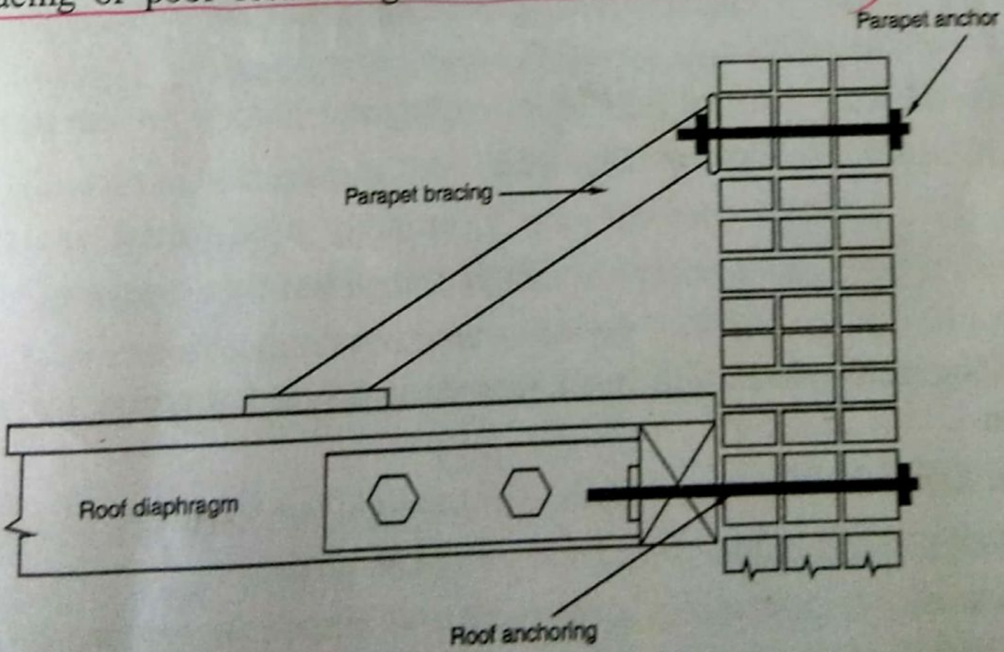


Fig. 2.9

In the absence of anchoring or bracing these components behave like cantilevers and are subjected to greater amplification becoming prone to damged during earthquakes. In the figure 2.9 shown above, the vulnerable parapets are properly braced with the roof diaphragm to reduce damages. The roof diaphragms can also be connected to masonry walls through roof anchors.