the joists. Relative displacement of the joists is quite likely to occur during an earthquake, which could easily bring down the tiles. Similar behavior may be visualized with other types of joists.

Long Building with Roof Trusses

Consider the long barrack type structure carrying roof trusses shown in Figure 5.1-5. The trusses rest on walls A. The walls B are gabled and support the purlins of the end bays. The ground motion is along the x-axis. The inertia forces will be transmitted from sheeting to purlins to trusses and from trusses to walls A. The end purlins will transmit some force directly to gable ends. Under the earthquake force, the following could happen:

1. The trusses may move over the walls unless anchored into them by holding down bolts.
2. Walls A, which do not get much support from walls B in this case, may overturn unless they are made strong in resisting vertical bending with a cantilever to transmit the horizontal force to end walls B, which are strong enough to resist the force.

Now if ground motion is along the y-direction, walls A will be in a position to act as shear walls and all forces may be transmitted to them. In this case, the purlins act as ties and struts, and transfer the inertia force from the roof to the gable ends. As a result the gable ends may fail. Gable trian gles are often very weak and may even fail in small earthquakes.

Shear Wall with Openings

As stated above, the shear walls are the main lateral load resisting members in load bearing wall buildings. Their action can be physically understood with reference to Figure 5.1-6 wherein a shear wall with three openings is shown under the action of horizontal load from left to right. The wall sections between the openings are more flexible than the wall below or above the openings. The deflected form is approximately sketched.

The wall sections above and under openings are heavily stressed in tension and in compression and the mid-sections of piers carry maximum shears. Thus it is seen that tension occurs in the jambs of openings and at the corners of the walls.

The magnitude of these tensile stresses in a shear wall dependent on the value of seismic forces and increases rapidly since the total stress is made up of three parts Po, Pb and Pt as defined below.

Po = compressive stress due to vertical load

P_b = local bending stress caused due to double curvature bending of piers between openings, proportional to the

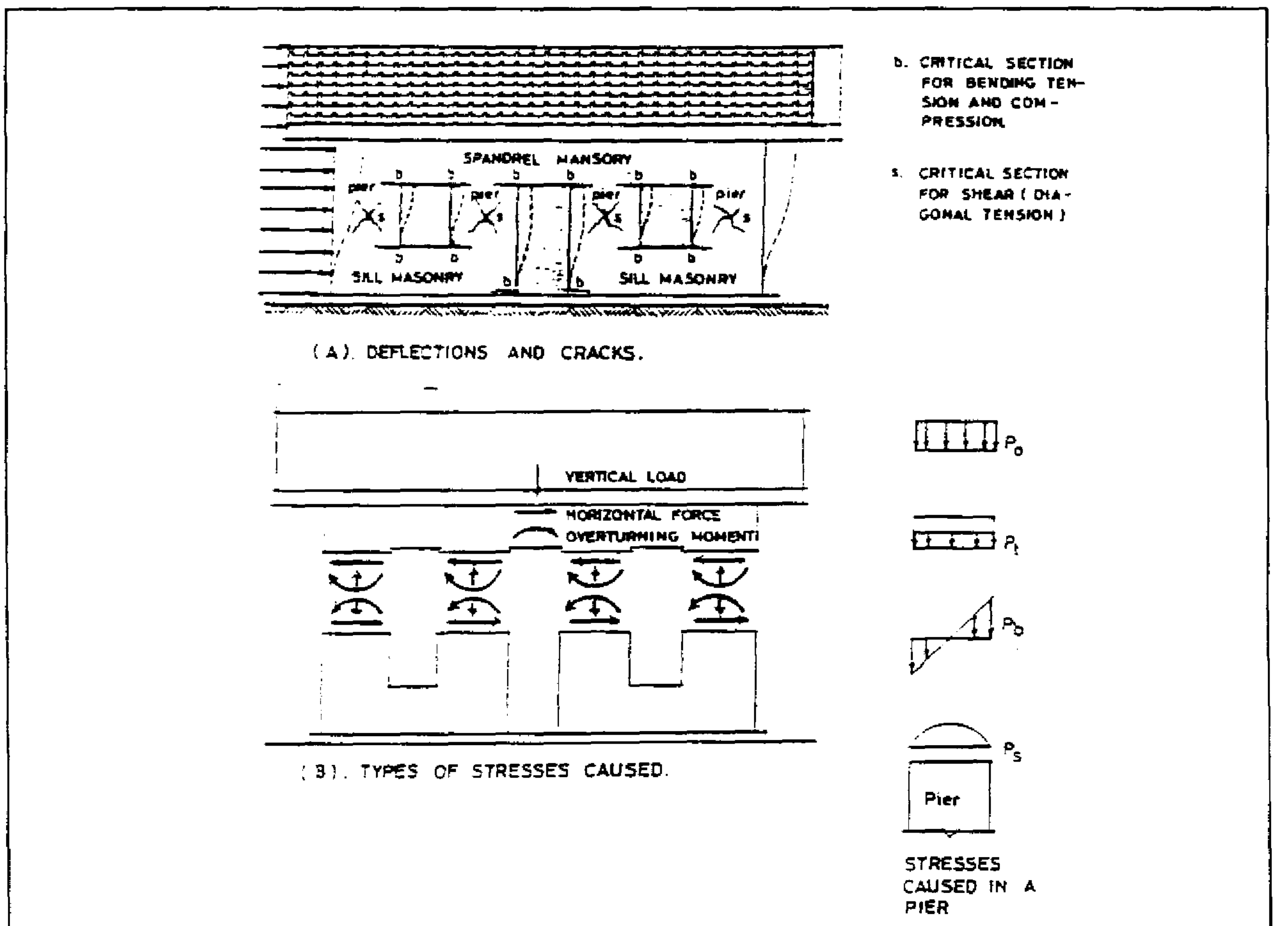

Figure 5.1-6 Deformation of a Shear Wall [1]

value of horizontal force

Pt = uniform bending stress due to overturning moments, caused by horizontal forces, (depends on the force as well as the height of the building). The stress could therefore remain compressive for small seismic forces where Po > (Pb + Pt), but for larger seismic forces, Po becomes less than (Pb + Pt), and tension occurs. Therefore cracks are seen to occur at corners of openings in the walls and diagonal cracks at centers of wider piers. These cracks are frequently joined together and then the masonry between the openings fails, bringing down the spandrel masonry and the roof.

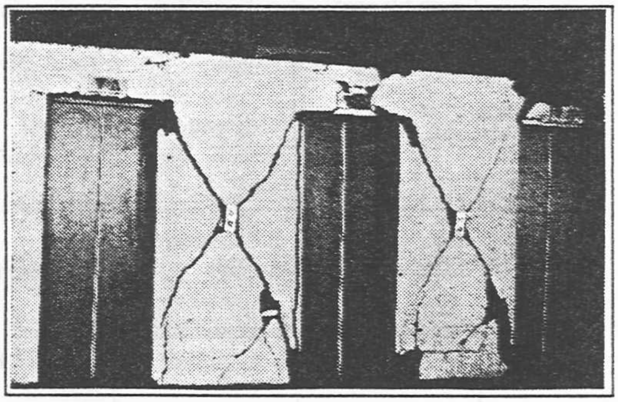

Figure 5.1-7 Typical X-type failure on the fill-in walls of an elevator shaft in a building damaged during the Mexican earthquake of 1979.

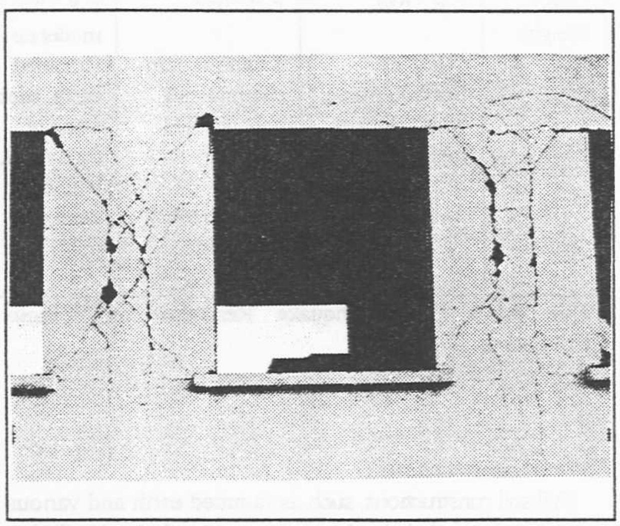

Figure 5.1-8 Typical cracks at window level due to reduced stiffness of the building in this region. This type of damage is mitigated or avoided if buildings have strong internal walls, in particular of the shear type.

? a. Which types of failures have occurred in your country ?

b. Which buildings in your city are vulnerable to these failures ?

seismic failure, wall, roof, truss.

SESSION 6: EARTHQUAKE BEHAVIOR OF LOW COST CONSTRUCTIONS

Topic 6.1: Earthquake Behavior of Low Cost Construction

The weight of construction is extremely important in earthquake engineering, because it determines the lateral forces. The mass is also important as a climatological and comfort factor. Generally, we can say that the large majority of low cost constructions in hot arid areas has a heavy mass, in hot humid areas a light mass, and in temperate areas an intermediate mass. Classification according to mass is therefore useful from the geographic and earthquake point of view.

We can classify walls into:
1. *Heavy walls:* rammed earth and various types of thick masonry
2. *Light walls:* frames with a light cladding
3. *Intermediate walls:* frames with infill and thin masonry.

And roofs can be classified into:
1. *Heavy roofs:* thick soil roofs
2. *Light roofs:* leaves or grass, sheets
3. *Intermediate roofs:* tiles; thick thatch, some light vaults.

The earthquake resistance of various types of low-cost constructions is shown in Table 6.1-1.

The earthquake behavior of heavy walls

As heavy walls can be considered:
- full soil constructions
- stone masonry
- adobe masonry
- brick masonry.

Heavy walls may be damaged or collapse due to:
1. shear, caused by forces parallel to the wall, and result in diagonal cracks at points with high stresses, such as corners, openings, and intersections,
2. bending out of plane, by forces perpendicular to the wall,
3. combination of both.

Wall Roof	Light Weight	Medium Weight	Heavy Weight
Light Weight	E.R.: Good Wood or bamboo frame, with tile roof	E.R.: moderate to good Taquezal,quin-chamud and pole, infilled frame or hollow concrete block wall, with leaf, grass or sheet roof	E.R.: moderate to bad Rammed earth, adobe stone or brick wall, with leaf, grass or sheet roof
Medium Weight	E.R.: moderate to good Wood or bamboo frame, with tile roof	E.R.: moderate to good Taquezal,quin c-hamud and pole, infilled frame or hollow concrete block wall, with tile roof	E.R.: moderate to bad Rammed earth, adobe stone or brick wall, with tile roof
Heavy Weight	E.R.: bad Wood or bamboo frame, with tick earth roof	E.R.: bad Taquezal,quin-chamud and pole, infilled frame or hollow concrete block wall, with thick earth roof	E.R.: bad to moderate Rammed earth, adobe stone or brick wall, with tick earth roof

Table 6.1-1 The Earthquake Resistance of Various Constructions.

Full soil constructions

Full soil constructions, such as rammed earth and various forms of kneaded clay have shown poor behavior during earthquakes. They hardly withstand heavy earthquakes. Wall made out of cobs or clay-balls have very little tensile strength. They generally behave poorly during earthquakes. However, rammed earth constructions, if properly built, can certainly withstand small earthquakes.

Stone masonry

Soil masonry is usually made out of round stones or rubble in a mud mortar or with no mortar at all. These walls disintegrate very easily during earthquakes and therefore are generally considered the worst type of construction. Sometimes wooden tie beams and the use of lime mortar help to restrict the damage.

The poor bond in stone masonry, plus the practice of building a wall with 2 stone faces and a rubble infill in between, were the main reason for the poor performance during earthquakes.

In Kinnaur, Pakistan (1975) it was noticed that houses made out of rubble without mortar were severely damaged, whereas houses made out of dressed natural stones laid in cement mortar were not damaged. In Iraq, stone masonry with flat slates is considered to have a considerable earthquake resistance.

Adobe masonry

Adobe masonry is very common in the third world. Adobes are soil blocks made in various sizes, according to local tradition, by hand molding or sometimes in a press machine. The mortar used in adobe masonry is usually the same soil as used for the block production. The cohesion and tensile strength of an adobe wall is often insufficient during earthquakes. Walls shear apart in high-stress areas such as corners or intersections, and are pushed outward by the roof. The performance of adobe constructions has been rather poor, and led to large damage and casualties

From many examples we may conclude that adobe masonry behaves poorly due to the poor quality of the material, poor mortar and bond, poor workmanship, design errors, advanced age, weathering, and heavy roof load. Wooden tie beams or bracing frames helps to perform better.

Brick masonry

Brick masonry usually shows a better performance than adobe due to the higher quality of materials used. Yet, damage to brick houses sometimes is also heavy, particularly during strong earthquakes and when the masonry is unreinforced. As in the case of adobe, poor quality of materials and poor workmanship, as well as design errors, contribute to a poor performance of brick masonry during some earthquakes. Nevertheless, its performance is usually better than that of adobe, although far from the performance of light frame-light roof constructions. One mistake sometimes made is that brick-walls, because they are considered better, are constructed too thin to behave well in earthquake.

Earthquake behavior of heavy roofs

Houses with heavy roofs collapse earlier than those with light roofs. The mass of the roof is important in determining earthquake resistance of structures

Heavy roofs (and floors) often collapse due to:

- insufficient strength of the roof or floor
- failure of roof-wall connections
- rupture of supporting structure.

Heavy roofs cause big lateral forces on the walls, which are often not designed to resist those. Flat earth roofs are already heavy when built, but during repairs mud is often added, and the roof may thus reach a thickness of 40-50 cm and get very heavy. The roof beams are often insufficiently connected to the walls.

Vaults may produce lighter and stronger roofs. But vaults cause a lateral thrust and need transverse walls or ties to absorb this. During an earthquake, these supporting walls may shift and the vault may collapse.

Domes have a double curve, and are therefore stronger and perform better during earthquakes. Collapses as caused by the absence of a tie-beam, to keep the supporting walls together.

Houses with heavy walls and heavy roofs

Traditional heavy roofs are dangerous even if supported by heavy walls, because such walls lack cohesion and tensile strength. They move during an earthquake, and the roof, often poorly connected to the walls, can collapse

The earthquake behavior of houses with heavy walls and light roofs

As has been noticed in several earthquakes, the performance of such houses is better than that of those with heavy roofs, mainly due to the lesser lateral thrust at roof level. Yet, the walls have a large mass and often lack strength to withstand lateral forces. Collapse is therefore not uncommon, although often less dangerous for the inhabitants due to the lesser weight of the roof. A good roof should also perform as a diaphragm keeping the walls together; it therefore should have sufficient strength and rigidity and needs to be anchored to the walls. With light roofs, this is often not the case.

The earthquake behavior of light wall constructions

Contrary to heavy walls, light walls are good construction choices. But again, human imperfection may lead to failures, caused by:

- poor workmanship
- poor connection of the frame to the foundations and of the various members of the frame
- poor quality of material (unseasoned or untreated timber)
- poor maintenance
- design errors, such as irregular shape
- use of brittle infills or irregularly distributed infills in plan and elevation
- use of heavy roof

The earthquake behavior of light walls with heavy roofs

The lateral force of a heavy roof cause great shear and bending forces on the walls or columns. It is not advisable to build heavy roofs on light frame constructions, particularly when slender walls and columns are used. If circumstances make such a roof unavoidable, the wood sizes of the frame should be considerably increased, and the length of the vertical supports reduced. Bracing should also be increased

The earthquake behavior of some intermediate constructions

Intermediate constructions are those between heavy full constructions and light frames. The walls often consist of a frame, with an infill of a heavier material, whereas roofs can be of moderately heavy materials such as tiles or thatch, or somewhat lighter sheets, supported by wooden beams.

The following behavior was noticed for a variety of such constructions:

1. Mud and pole (or wattle and daub) constructions are used extensively in many parts of the third world. They are built by erecting vertical poles at distances of 40-60 cm., which are connected with horizontal branches, reeds, bamboos or other vegetable material. Metal ties are occasionally nailed, but more often are made with vegetable materials such as creepers, plant stems or even worse banana leaves. Walls are then filled in with mud, often incorporating stones, and given a mud plaster, sometimes even finished with a lime mortar coating.

   During past earthquakes many people were killed in mud and pole houses. However, round mud and pole houses performed better than rectangular ones, due to their regular shape and distribution of forces. Failures were due to:

   - improperly tied corners
   - lack of bracing
   - the use of very weak, vegetable ties, that get increasingly brittle over time
   - inner walls that were not connected to the roofs and weakened by doors
   - termites affecting the poles.

2. *Taquezal* is the name of a somewhat different structure that occurs often in Central America, where it has been subjected to many destructive earthquakes. The structure is made out of square timber parts, of about 10x10 cm., spaced at about 60 cm. intervals, and connected on both sides by wooden laths, of approximately 1.2 x 5 cm. at 20 cm. intervals. This structure is filled up and plastered with mud, and can easily reach a wall thickness of 20 cm. In the Managua (Nicaragua) earthquake, many such houses collapsed. (Figure 6.1-1)

3. *Quincha* is a typical structure for Peru, consisting of vertical posts at about 200 cm distances, braced by horizontal beams at the bottom, in the middle and at the top

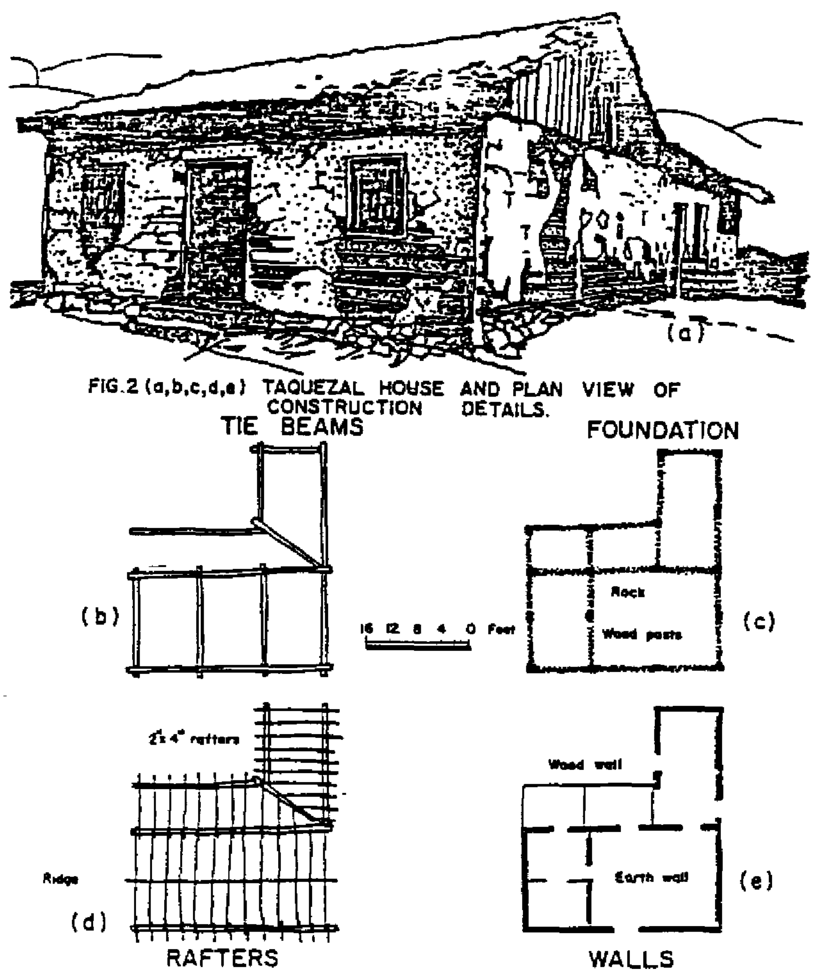

FIG.2 (a,b,c,d,e) TAQUEZAL HOUSE AND PLAN VIEW OF CONSTRUCTION DETAILS.

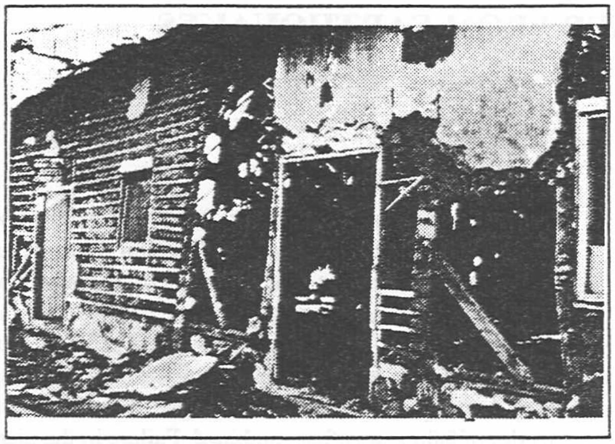

Figure 6.1-2 Damage to taquezal (wattle and daub) buildings in the central part of Managua devastated by the earthquake of December, 1972.

of the wall. Canes are woven vertically along these poles and form the basis for a plaster applied on both sides. Since this structure has no infill, it has less mass and more flexibility than the foregoing examples. In addition, roofs are usually light, with a corrugated iron sheet or grass covering. *Quincha* structures are probably more comparable to lightly clad frames than to infilled frames. Their performance during earthquakes in Peru was considerably better than that of adobe walls.

4. Reinforced adobe walls have been built, incorporating vertical and horizontal wood, bamboo or reed reinforcement. The inclusion of horizontal timber has proved useful. Braced wooden frames have also been incorporated in Chile, and in Guatemala after the 1976 earthquake.

5. In infilled frames the frame takes over the structural functions, and adobe, bricks, stone or mud are merely used as an infill.

   These constructions are quite common in some countries. They do not behave as well as framed buildings with light cladding. The weight and brittleness of the infills, their irregular distribution and poor connections to the frame certainly negatively affect the performance of infill frames.

6. Hollow concrete block masonry, with some vertical reinforcement, may be considered another form of intermediate construction. Its walls are of moderate weight, due to the voids, and the reinforcement provides a kind of frame. The frame can consist of concrete columns or of steel rods incorporated in some of the hollow blocks, that are subsequently filled with mortar. A ring beam is usually provided on top of the wall. The performance of such constructions is usually good.

As could be expected, the intermediate types of constructions perform better than the heavy types, but do not attain the performance of light frames with light roofs.

Figure 6.1-3 A substantial percentage of the population of Chimaltenango, Guatemala, died in their heavy-walled adobe buildings. East Anatolian and Iranian adobe buildings are even deadlier, because of their heavy roofs of tree trunks or rafters topped with a thick earth cover.

? a. Classify the different types of low cost constructions according to their earthquake performance.

earthquake behavior, low cost constructions, quincha, taquezal,
Peru, Central-America.

SESSION 7: LESSONS LEARNED FROM EARTHQUAKES

Topic 7.1: Lessons Learned from Earthquakes

Overstressing produces different types of damage to the various elements of a building. The typical damage and modes of failure are described.

The study of structural behavior and failure of various building elements during earthquakes identifies the critical sections which lead to collapse. The study of past-earthquake failures together with theoretical analysis and laboratory testing of buildings, serve as the basis for the design and construction of earthquake-resistant structures.

Typical Damage and Failure of Buildings and Elements

The typical damages and modes of failure of various buildings and elements are briefly described below.

Failure of Bearing Walls

The common modes of failure of load bearing walls are the following:

1 Random rubble masonry walls completely shatter away and pile up in a heap of stone. Main reasons are weak mortar, lack of through stones from outer to inner face of wall, and incomplete filling of mortar into the space between outer and inner leaf of stones.

2 Failure due to shear is characterized by diagonal cracks. Such failure may run through the pattern of masonry joints diagonally through a wall. These cracks start around openings and sometimes at center. This kind of failure can cause partial or complete collapse of the structure (Figure 7.1-1)

3 A wall can fail by bending forces - due to seismic inertia forces on the mass of the wall itself - in a direction transverse to the plane of the wall. Tension cracks occur vertically at the center, ends or corners of walls. The longer the wall and openings the more prominent is the damage (Figure 7.1-1). Since earthquake effects occur along both axes of a building simultaneously, bending and shearing effects occur often together and the two modes of failure are often combined. Failure in the piers occurs due to combined action of bending and shear

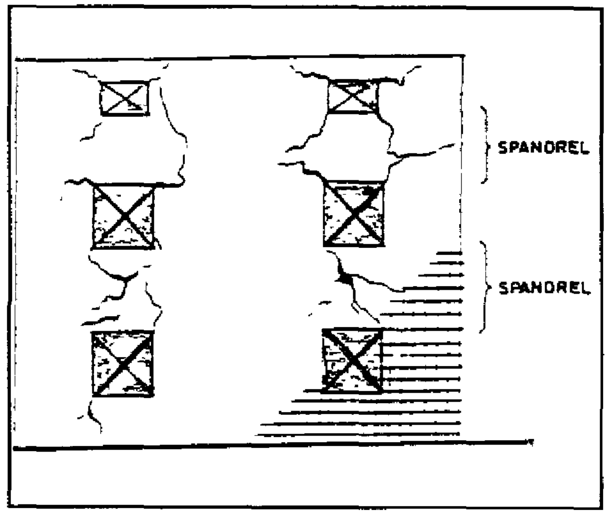

Figure 7.1-2 Cracking of Sprandel Wall between opening

4. Unreinforced gable end masonry walls are very unstable and the strutting action of purlins imposes additional forces which can cause their failure

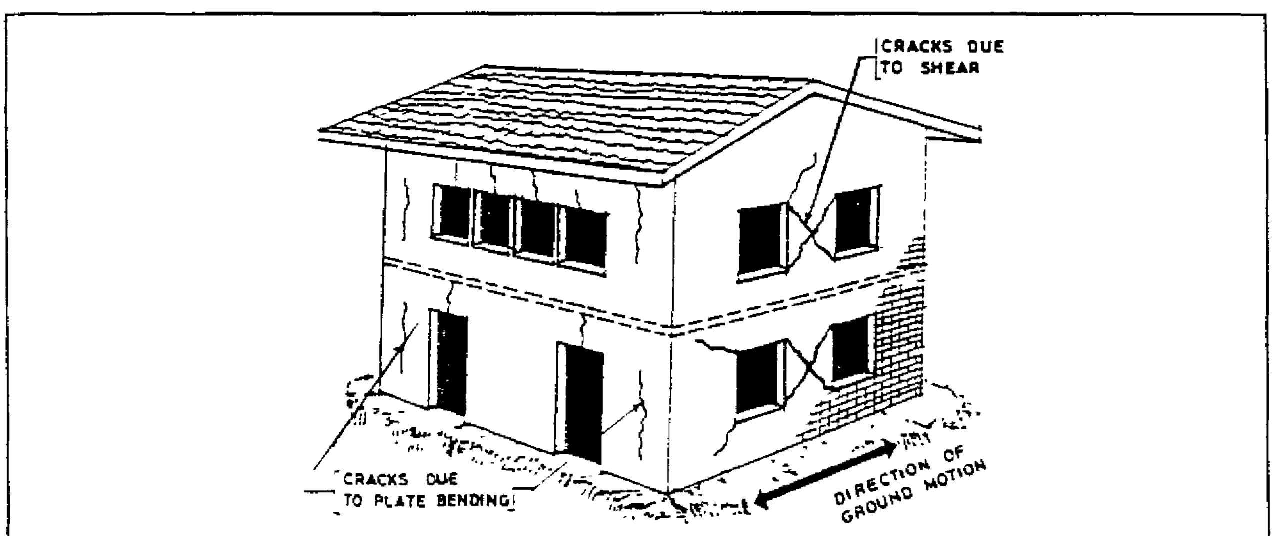

Figure 7.1-1 Cracking in Bearing Wall Building due to Bending and Shear