

EARTHEN BUILDINGS

7.1 INTRODUCTION

Earthen construction has been, is and will continue to be a reality. Recent statistics show that the percentage of earthen housing in the next 15 years will be higher than 50%.

Even though this material has clear advantages of costs, aesthetics, acoustics and heat insulation and low energy consumption, it also has some disadvantages such as being weak under earthquake forces and water action. However, the technology developed to date has allowed a reduction in its disadvantages, stressing its most valuable advantages.

Earthen constructions are, in general, spontaneous and a great difficulty is the dissemination of knowledge about its adequate use.

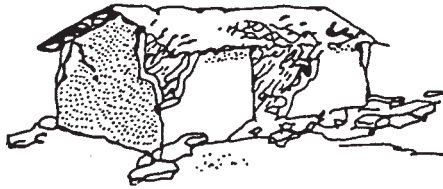
The recommendations presented herein are applicable to earthen constructions in general, but they are especially oriented to popular housing, aiming to enhance the quality of the spontaneous, informal or

massive constructions which are the ones causing the greatest loss of life and damage during seismic events.

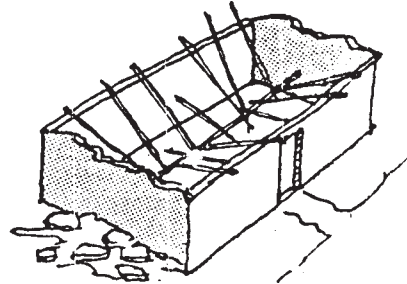
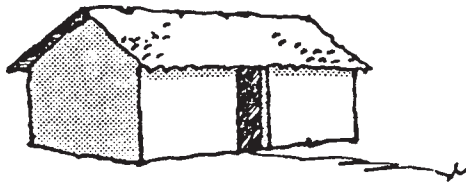
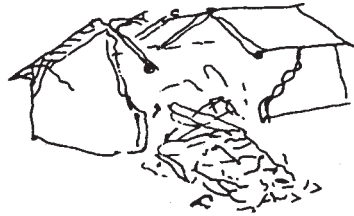
Therefore, it does not include solutions involving the use of stabilizers (cement, lime, asphalt, etc.) to improve the strength or durability. Also for making the strengthening very economical, minimum use of the expensive materials (concrete, steel, wood, etc.) has been indicated to enhance the dynamic behaviour of the structure.

7.2 TYPICAL DAMAGE AND COLLAPSE OF EARTHEN BUILDINGS

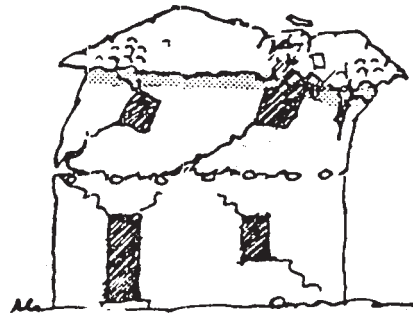
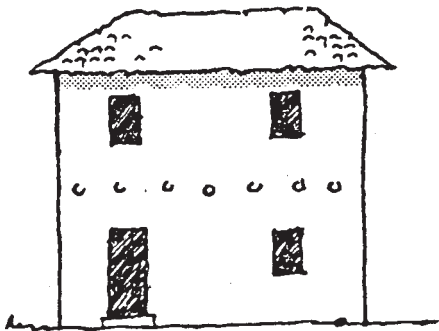
Earthquake experience shows that earthen buildings may be cracked at MSK Intensity VI, wide cracks and even partial collapse may occur at MSK VII and collapses are widespread under MSK VIII. Damage is always much more severe in two storeyed buildings than in one storeyed ones. Some typical damages are sketched in *Fig 7.1*. However, single storeyed houses with flat roofs constructed in good clay have been found to be undamaged in Intensity VIII



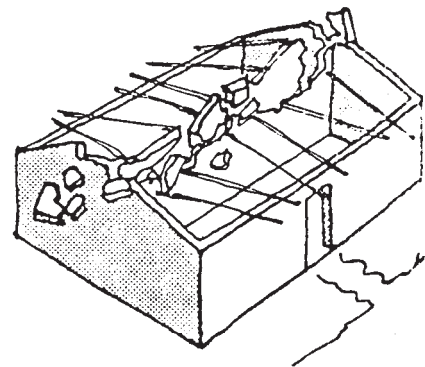
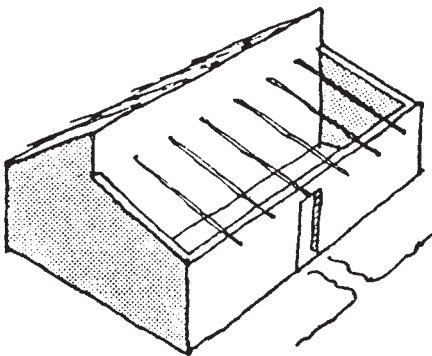
(a) Corner failure and out of plane collapse of walls



(b) Gables

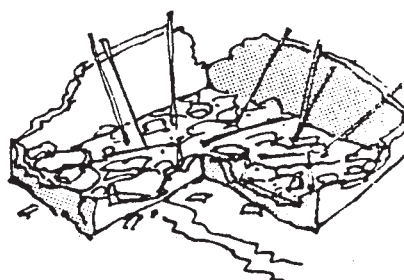
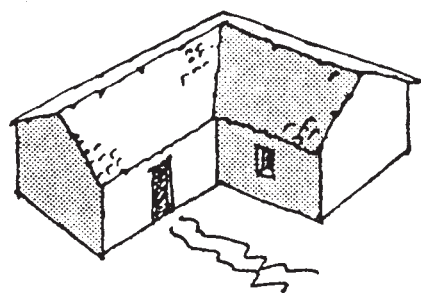


(c) Two storey house damage / collapse

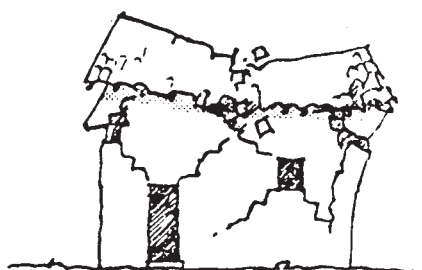
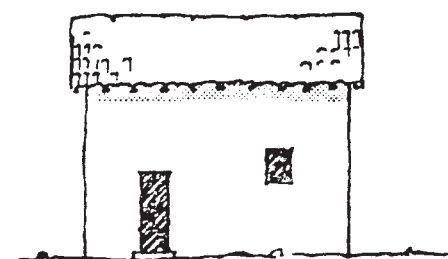


(d) Split level roof

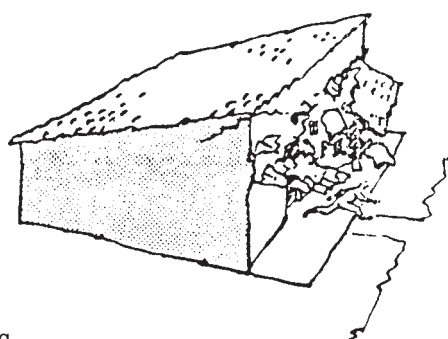
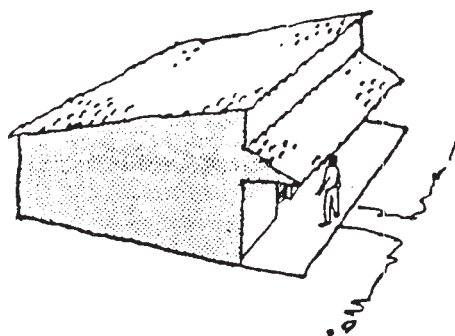
Fig 7.1 Typical damages and collapse of earthen buildings (continued on next page)



(e) L shaped buildings



(f) High walled houses



(g) Awning

Fig 7.1 Typical damages and collapse of earthen buildings (continued from previous page)

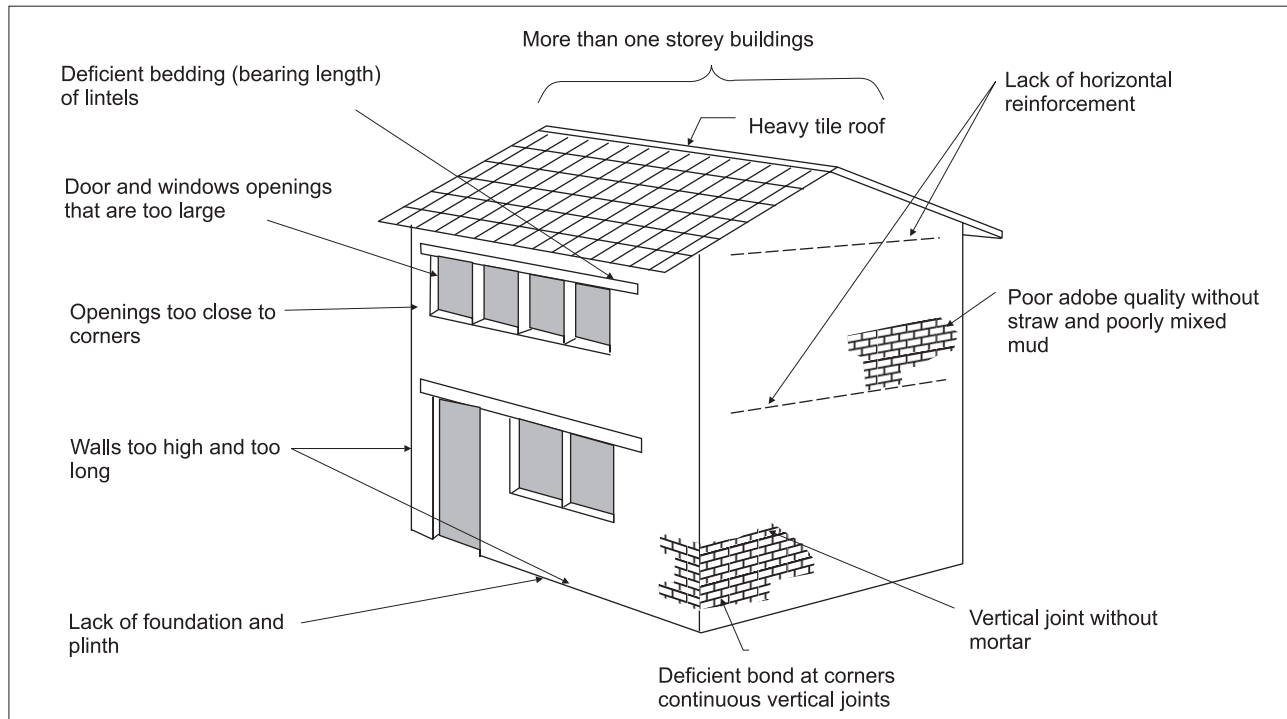


Fig 7.2 Graphic summary of causes of failure

zone whereas at the same location two storeyed houses were completely ruined. The main courses of failure of earthen buildings in earthquakes are graphically summarised in Fig 7.2.

7.3 CLASSIFICATION OF WALLS AND MATERIAL PROPERTIES

In earthen construction, the walls are the basic elements hence it can be classified according to the wall type as follows:

7.3.1 Classification of earthen constructions

- a. Hand-formed by layers
 - a.1 Simple forming
 - a.2 Earth balls, thrown and moulded as wall
- b. Adobe or blocks
 - b.1 Cut from hardened soil
 - b.2 Formed in mould

b.3 Moulded and compacted

c. Tapial or pise (rammed earth)

c.1 Compacted by hand blows

c.2 Mechanized or vibrating compaction

d. Wood or cane structure, with wood or cane mesh enclosures plastered with mud

d.1 Continuous

d.2 Pre-fabricated panels

Whereas systems (a), (b) and (c) depend for stability on the strength of earthen walls, the system d behaves like a wood frame and its construction will be dealt with separately.

7.3.2 Suitability of soil

The quality of materials, particularly clay content of the soil may vary somewhat for the type of construction. But in general the following qualitative tests are sufficient for

determining the suitability of a soil for earthen construction:

a. Dry strength test

Five or Six small balls of soil of approximately 2 cm in diameter are made. Once they are dry (after 48 hours), each ball is crushed between the forefinger and the thumb. If they are strong enough that none of them breaks, the soil has enough clay to be used in the adobe construction, provided that some control over the mortar microfissures caused by the drying process is exercised, Fig 7.3(a)

If some of the balls break, the soil is not considered to be adequate, because it does not have enough clay and should be discarded.

b. Fissuring control test

At least eight sandwich units are manufactured with mortars made with mixtures in different proportions of soil and coarse sand. It is recommended that the proportion of soil to coarse sand vary between 1:0 and 1:3 in volume. The sandwich having the least content of coarse sand which, when opened after 48 hours, does not show visible fissures in the mortar, will indicate the most adequate proportion of soil/sand for adobe constructions, giving the highest strength.

7.3.3 Strength test of adobe

The strength of adobe can be qualitatively ascertained as follows: After 4 weeks of sun drying the adobe should be strong enough to support in bending the weight of a man, Fig 7.3 (b). If it breaks, more clay and fibrous material is to be added. Quantitatively, the compressive strength may be determined by testing 10 cm cubes of clay

after completely drying them. A minimum value of 1.2 N/mm^2 will be desirable.

7.4 CONSTRUCTIONS OF WALLS

In general, the strength of walls is a function of clay content, and its activation by humidity (promoted by wetting or compaction procedures) and the control of fissuring.

The positive effect of a traditional practice, namely 'sleeping' the mud (storing it at least for one day but better for more days) before the fabrication of adobe bricks or mortar was confirmed. It seems that this procedure allows for a better dispersion and thus for a more uniform action of the clay particles.

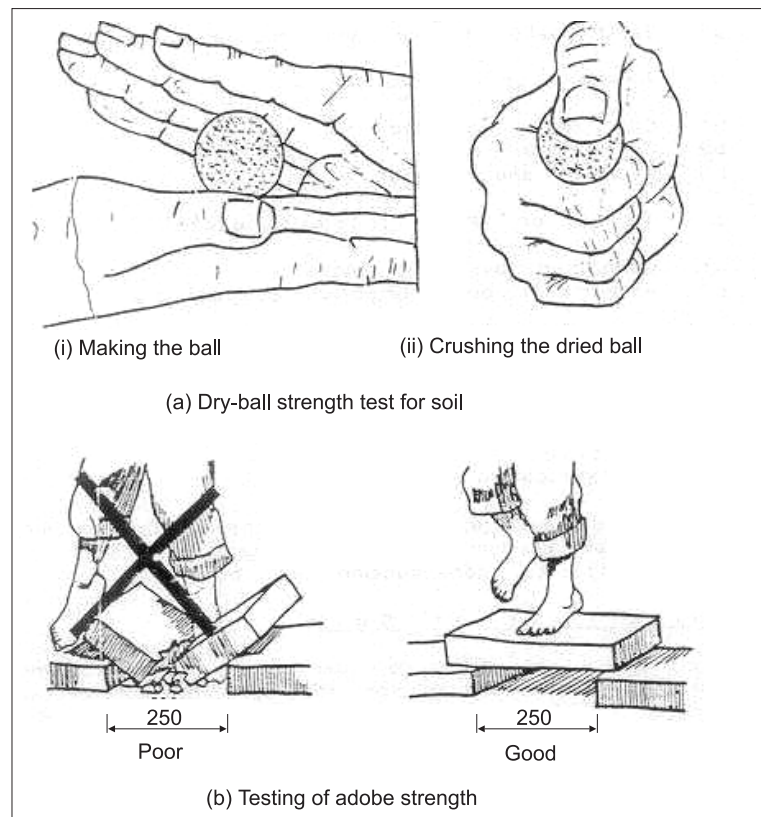


Fig 7.3 Field testing of strength of soil and adobe

If the soils are clayey, stronger constructions could be built, provided an adequate technology is used to control the typical fissures caused by drying from high moisture content. The most economical and simple form to control such fissures is by adding coarse sand to diminish the clay contraction or by adding dry straw to the mud to control the micro-fissures.

In general, there are no “recommended” mixing ratios for the soil to be used in earthen constructions. The different percentages of clay, lime, fine sand and coarse sand will be defined by the most abundantly available nearby soil, its clay content (see dry strength test), the type of constructions required according to the classification and the amount of coarse sand needed to control or avoid the visible fissures and attain a monolithic behaviour.

It may be concluded that:

- (i) Soils with low clay content should not be used (see dry strength test).
- (ii) Coarse sand needs be added to avoid fissures and straw to control them.

7.4.1 Hand-moulded layered construction

These are the most primitive and weakest type of constructions because of the low percentage of moisture employed to make the hand-moulding and the poor level of compaction attained. For these reasons, all the clay is not activated, either by moisture, or by compaction.

Even though a small amount of moisture is used (depending on the soil), some horizontal and also vertical fissures nor-

mally appear. These should be controlled by adding straw as much as possible to attain a reasonable workability of the mixture. If this is not possible, coarse sand could be used as additive, in the smallest experimental proportion able to achieve the disappearance of visible fissures (try with increasing proportions and wait a few days to check the results). An excess of coarse sand will inevitably reduce the wall strength.

Generally, it will be necessary to moisten the area of the lower layer which will be in contact with the mud, in order to avoid sudden drying of the contact zone, which produces the fissures.

7.4.2 Adobe or block construction

In the case of cut as well as moulded blocks, the strongest units correspond to plastic or clayey soils. However, the block strength plays a secondary role in the masonry strength, since the joints between blocks become critical. The blocks used should be well dried in order to avoid future retractions. Blocks are made in different sizes in various countries.

It may be stated that the dimensions of the blocks, nor the way these are placed, have a serious effect on their strength.

Traditional practices obtain an adequate block without important fissures, either by mixing sandy and clayey soils or by looking after the block so it dries without restrictions, thus eliminating the fissures. The soil to be used should be verified with the dry strength test, *Fig 7.3*, to ensure a minimum strength.

The mud used to fill the space between blocks (the so called “mortar”) requires special attention.

To guarantee the bond between blocks and mortar, the micro-fissures of the latter should be avoided. The conditions of the mortar drying are very severe because of the fact that the mortar gets in contact with blocks which readily absorb moisture and also they restrict the drying contraction. This produces the above-mentioned micro-fissures, which consequently weaken the masonry.

The joint mud should normally be the same as used to manufacture the block. If it is found to fissure, some straw (nearly 1:1 by volume) should be added to the mortar until an acceptable degree of workability is attained. Some coarse sand could also be added, the adequate proportion being given by the fissuring control test, 7.3.2 (b).

For clayey soils, the adobe blocks should be moistened for a few minutes before placing them. Also it will be useful to moisten the previous layer of blocks before placing the joint mortar. For sandy soils, it will be enough only to moisten the preceding layer of blocks.

The usual good principles of bonds in masonry should be adopted for construction of adobe walls, that is,

- (i) All courses should be laid level.
- (ii) The vertical joints should be broken between two consecutive courses by overlap of adobe and must be carefully filled with mortar.

- (iii) The right angle joints between walls should be made in such manner that the walls are properly joined together and a through vertical joint is avoided.

7.4.3 Tapial or pise construction

Tapial or pise constructions are rammed earth constructions in which moist soil is poured in wooden forms of the walls and compacted to achieve the desired density.

Whilst adobe constructions acquire their strength by activation of the clay through moisture contained in the soil, tapial constructions owe it to compaction, using small percentages of moisture in the soil.

High strength is obtained by humidity and compaction when clay is present. There are however, practical limitations to restrict the moisture, such as the feasibility to pound and compact the soil, the excessive deformation occurring when the forms are removed and the fissuring problem.

The use of low moisture content (such as the optimum in the Proctor test or lower) and the control of the amount of clay by adding coarse sand to the soils are required to control the shrinkage fissures on drying. If the amount of coarse sand is excessive, the strength diminishes dangerously. It is recommended to make wall tests with increasing percentage of sand, until fissuring is reasonably under control.

The compaction or number of blows applied to the wall is a function of the weight and shape of the tool used for this purpose. Higher strengths are obtained

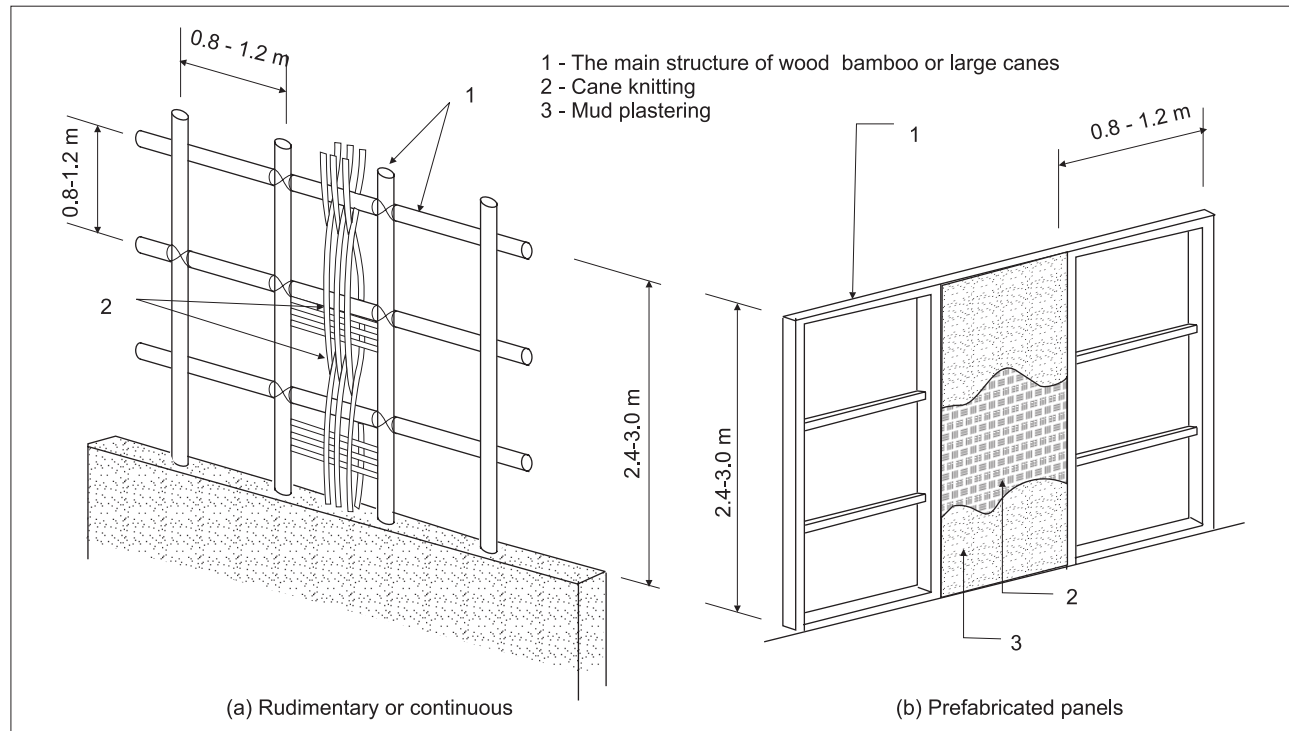


Fig 7.4 Earthen constructions with wood or cane structures

under higher compaction, but there is a point at which this is not true any more. A normal compaction is recommended and this will be the one under which no mud remains stuck to the form when this is removed.

Fifty strokes per 1000 cm² of wall area, applied with a mallet of about 8 to 10 kg weight is the recommended practice. The required height for the blocks varies between 50 and 80 cm, but it is very important that the compacted layers in the blocks do not exceed 10 cm each.

The best way to ensure the monolithic structure of the tapial walls is to sufficient quantity of water at the sub joints at every 10 cm. Likewise, between the tapial layers, every 50 to 80 cm, it is necessary to pour plenty of water on the layer before compacting further material. The placing of straw

between the tapial layers is not necessary.

The use of excessive amounts of straw in the mud mixture, more than 1:1/4 in volume is selfdefeating, because it causes a strength reduction.

7.4.4 Earthen construction with wood or cane structure

The scheme of earthen construction using structural framework of wood or cane is shown in Fig 7.4. It consist of vertical posts and horizontal blocking members of wood or cane or bamboo, the panels being filled with cane or bamboo, or some kind of reed matting plastered over both sides with mud. The construction could be done in the rudimentary way, building element by element or by using prefabricated panels.

The behaviour of this type of construction could be very good, as long as the fol-

Following fundamental rules are observed:

- Good connections between the wood or cane elements, so as to ensure an integral behaviour of the structure. The connections are normally fixed with nails. Their number and dimensions should be enough but not excessive as to split the elements. The connections can be also tied with wires, ropes, leather straps, etc.

— Preservation of the wood or cane elements by charring the surface or painting by coal tar, especially in the part embedded in the foundation,

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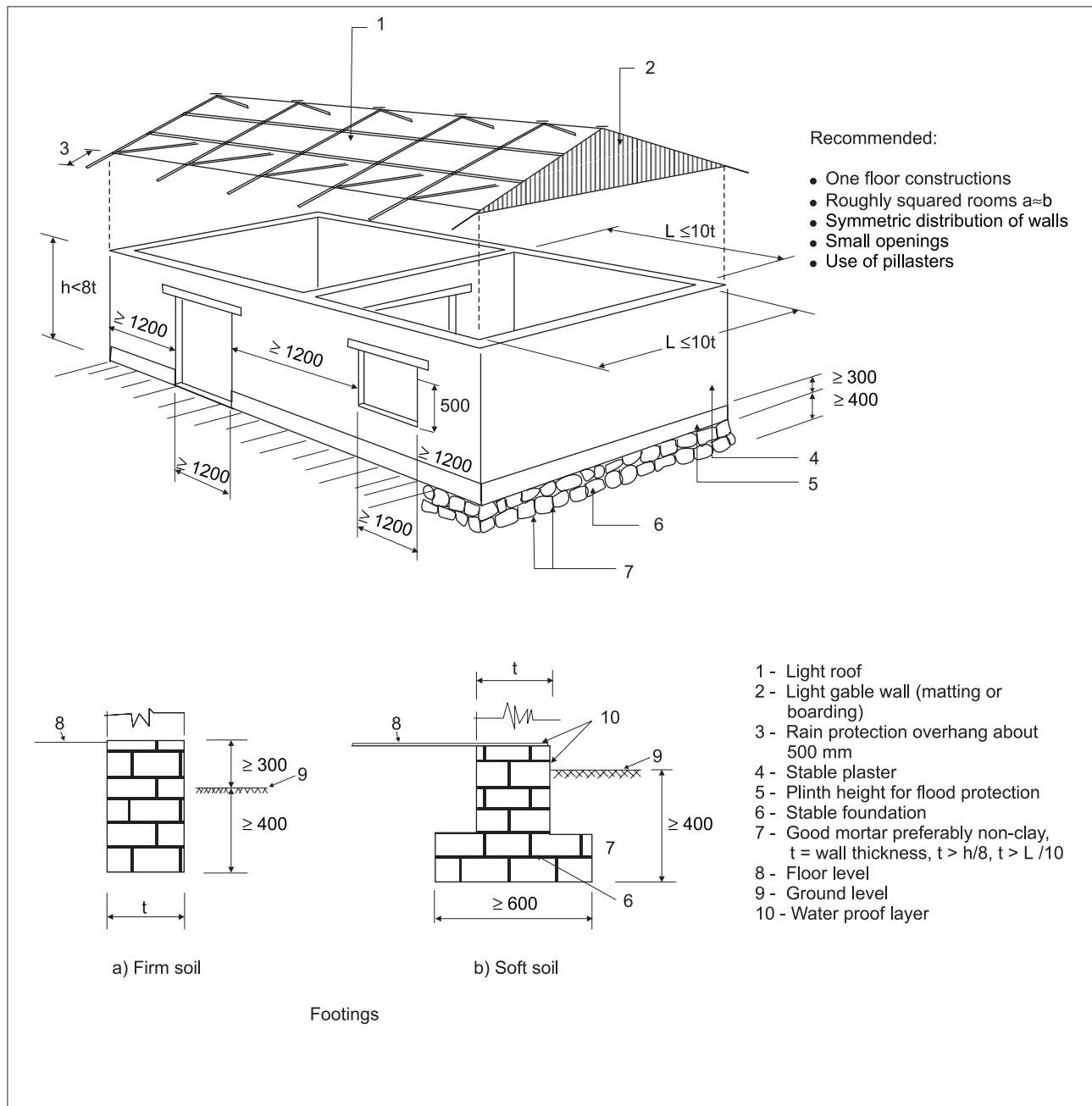


Figure 7.5 :: Adequate Configuration

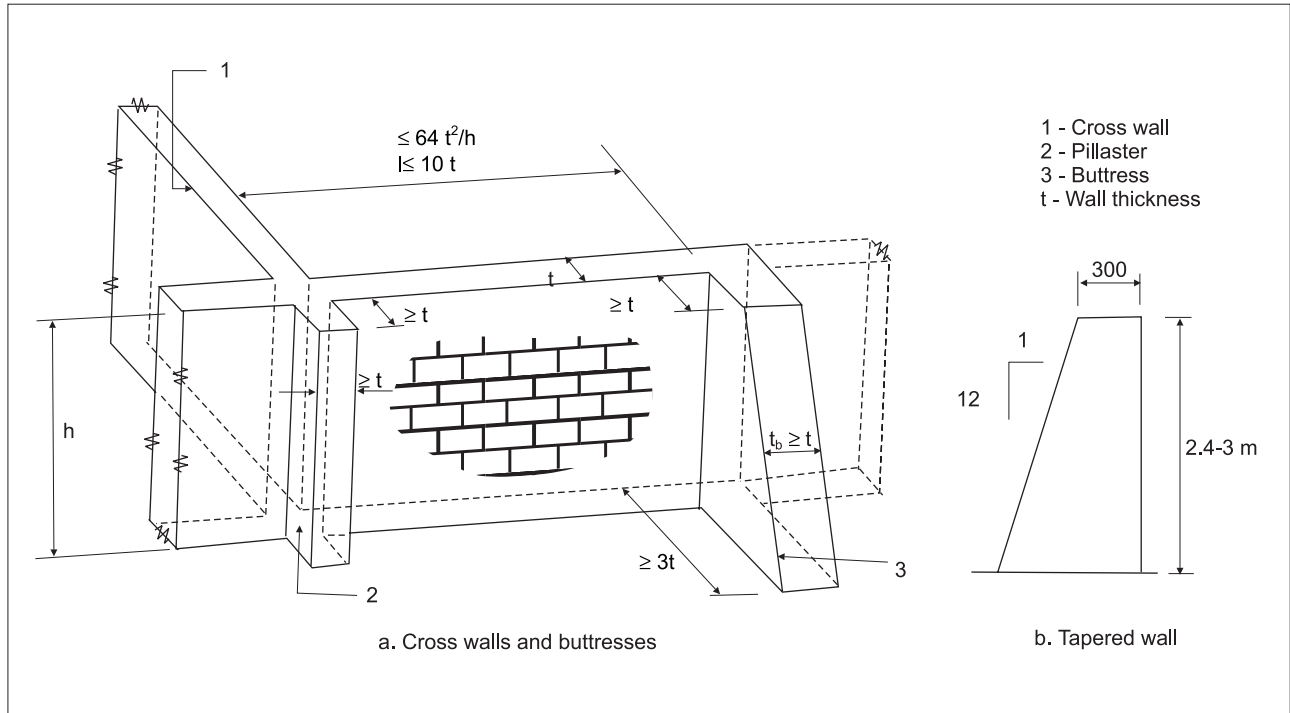


Fig 7.6 Wall dimensions

which should preferably be of concrete, stone or bricks laid with cement, lime or gypsum mortar.

- Additionally, it is recommended that the panel filling material should consist of wood or cane mesh, over which a layer of mud and straw (1:1 in volume) is placed on each face in

the form of plaster. Very often, the meshes are knit in themselves and around the structure.

- In houses built as a continuous system as well as in those made with pre-fabricated panels, an upper ring beam should be placed, the purpose of it being two fold:

- Ensure the integral behaviour of all walls, and
- Distribute evenly the roofing load.

Only after fixing this upper ring beam and the roof (after completing the nailing), the mud filling must be placed. This will avoid fissuring caused by the strokes of the nailing operation.

In the case of pre-fabricated panels, the frames could have very small and economical sections 25 × 50 or 25 × 75 mm. The

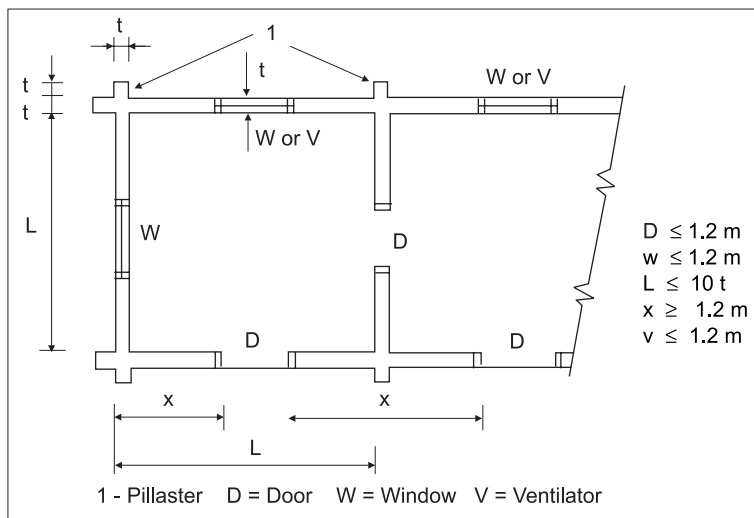


Fig 7.7 Pillasters at corners

connection between panels is made through nails, but the wood or cane knit mesh over which the mud filling is placed, can be fixed without the use of nails.

7.5 GENERAL RECOMMENDATIONS FOR SEISMIC AREAS

7.5.1 Walls

- (a) The height of the adobe building should be restricted to one story plus attic only in seismic zones A and B and to two storeys in zone C.
- (b) The length of a wall, between two consecutive walls at right angles to it, should not be greater than 10 times the wall thickness 't' nor greater than $64t^2/h$ where h is the height of wall.
- (c) When a longer wall is required, the walls should be strengthened by intermediate vertical buttresses, Fig 7.6 (a).
- (d) The height of wall should not be greater than 8 times its thickness.
- (e) The width of an opening should not be greater than 1.20 m.
- (f) The distance between an outside corner and the opening should be not less than 1.20 m.
- (g) The sum of the widths of openings in a wall should not exceed one-third

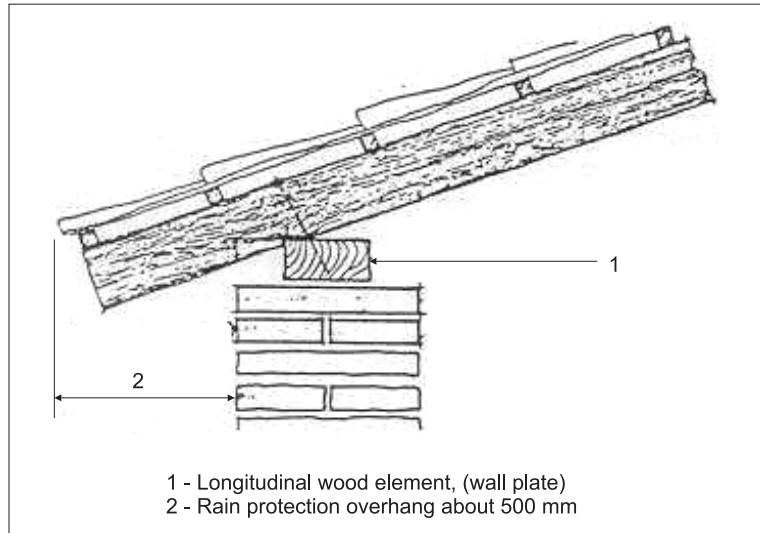


Fig 7.8 Use of longitudinal wood under roof rafters

- of the total wall length in seismic zone A, 40 percent in zones B and C.
- (h) The bearing length (embedment) of lintels on each side of an opening should not be less than 50 cm. An adequate configuration is shown in Fig 7.5 for an adobe and tapial house.
- (i) Hand-formed walls could preferably be made tapering upwards keeping the minimum thickness 30 cm at top and increasing it with a batter of 1:12 at bottom, Fig 7.6 (b).
- (j) Providing outside pillasters at all corners and junctions of walls will increase the seismic stability of the buildings a great deal, Fig 7.7.

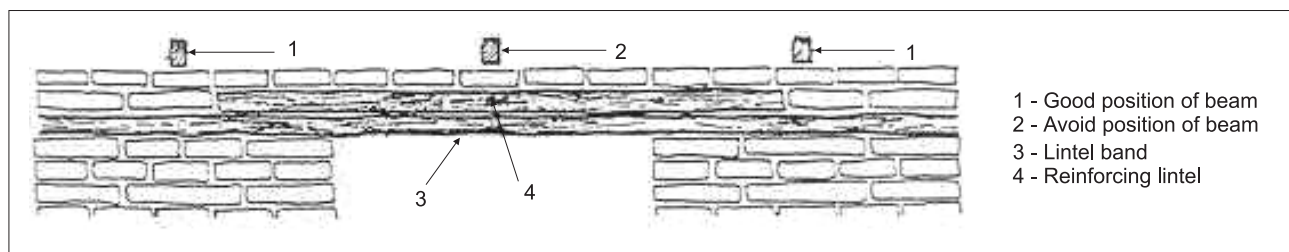


Fig 7.9 Reinforcing lintel under floor beam

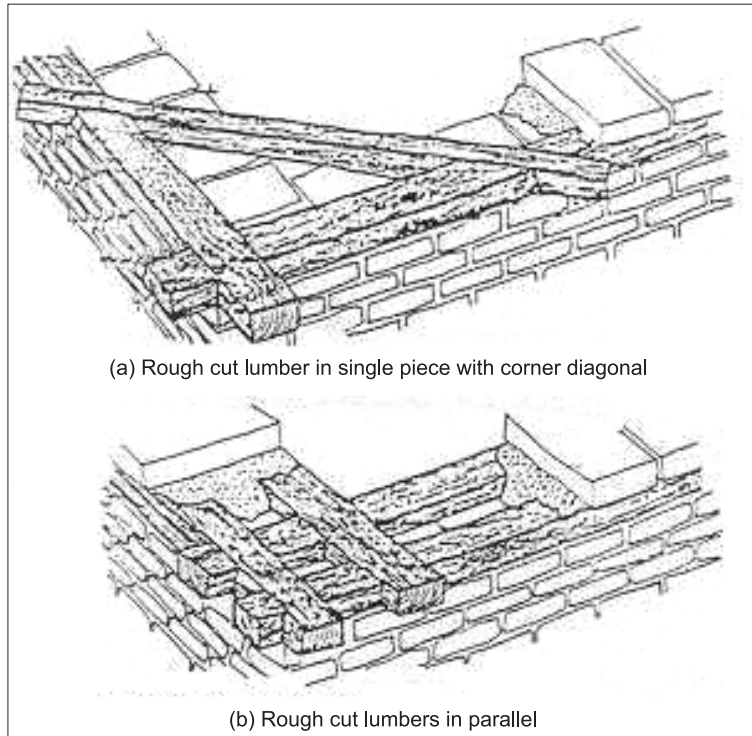


Fig 7.10 Collar band in walls at lintel level

7.5.2 Foundations

(a) The brittleness and reduced strength of adobe constructions restricts the possible locations of these buildings to areas associated with firm sub-soils.

Sandy loose soils, poorly compacted clays and fill materials should generally be discarded due to their settlements during seismic vibrations.

Also, soils with very high phreatic level (water table) should be avoided. These recommendations are particularly important for seismic zones A and B.

(b) Width of strip footings of the walls may be kept as follows:

One storey on firm soil — Equal to wall thickness

1.5 or 2 storeys on firm soil — 1.5 times the wall thickness

One storey on soft soil — 1.5 times the wall thickness

1.5 or 2 storeys on soft soil — 2 times the wall thickness

The depth of foundation below ground level should at least be 400 mm.

(c) The footing should preferably be built using stone, fired brick using

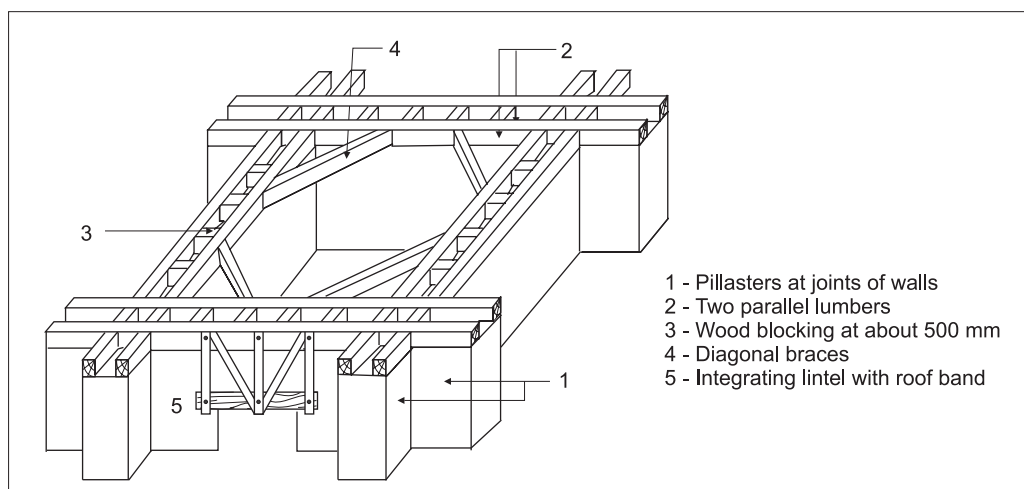


Fig 7.11 Roof band on pillastered walls

cement or lime mortar. Alternatively it may be made in lean cement concrete with Plums (cement : sand : gravel : stones as 1:4:6:10) or without plums as 1:5:10. Lime could be used in place of cement in the ratio lime:sand:gravel as 1:4:8.

(d) Plinth masonry: The wall above foundation up to should preferably be constructed using stone or burnt bricks laid in cement or lime mortar.

Clay mud mortar may be used only as a last resort. The height of plinth should be above the flood water line or a minimum of 300mm above ground level. It will be preferable to use a waterproofing layer in the form of waterproof mud (para 7.7 (c)) or heavy block polyethylene sheet at the plinth level before starting the construction of superstructure wall. If adobe itself is used, the outside face

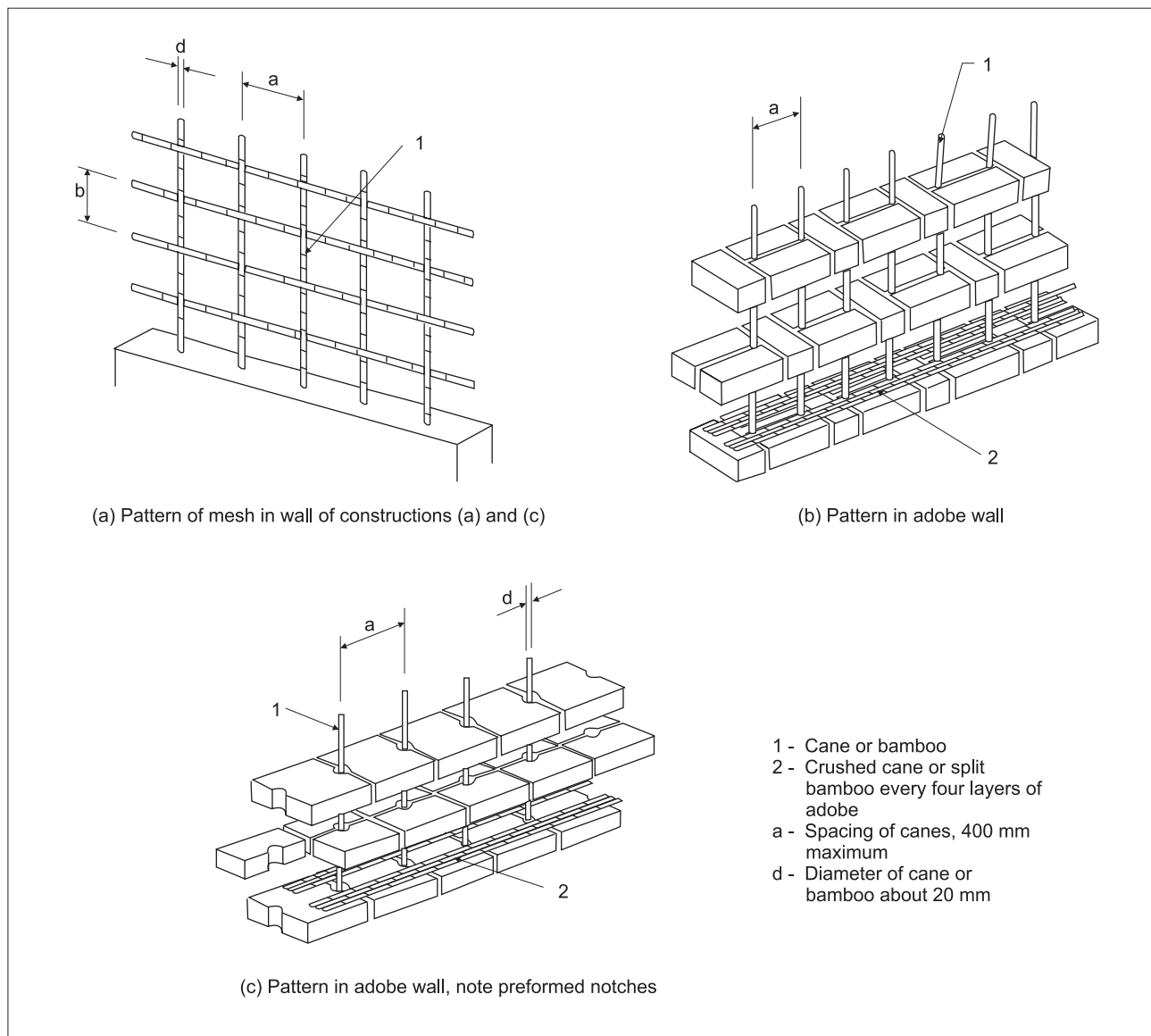


Fig 7.12 Reinforcement in walls of earthen constructions in zone

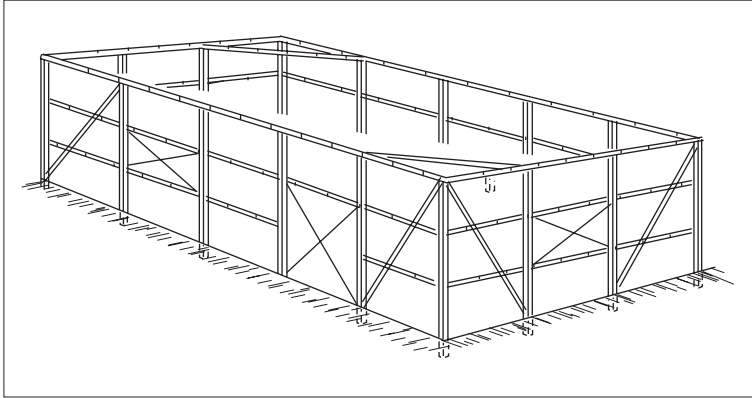


Fig 7.13 Diagonal bracing of wood-structures of earthen construction

of plinth should be protected against damage by water by suitable facia or plaster. A water drain should be made slightly away from the wall to save it from seepage.

7.5.3 Roofing

Roofs have two main parts: the structure and the cover. The roofing structure must be light, well connected and adequately tied to the walls.

- (a) The roof covering should preferably be of light material, like sheeting of any type.
- (b) If thatch is used for roof covering, it should better be made waterproof and fire resistant by applying water mud plaster, para 7.7(c).
- (c) The roof beams, rafters or trusses should preferably be rested on longitudinal wooden elements for distributing the load on adobe, Fig 7.8. If wood is not used preferably two top courses of burnt bricks may be laid instead of adobe for resting the roof structures.
- (d) The slopes and the over-hanging will depend on local climatic condi-

tions. In zones subjected to rain and snow, walls protection must be ensured by projecting the roof by about 0.5 m beyond the walls, Fig 7.8.

- (e) The roof beams or rafters should be located to avoid their position above door or window lintels. Otherwise, the lintel should be reinforced by an additional lumber, Fig 7.9.

7.6 SEISMIC STRENGTHENING FEATURES

7.6.1 Collar beam or horizontal band

Two horizontal continuous reinforcing and binding beam or bands should be placed, one coinciding with lintels of doors and window openings and the other just below the roof in all walls, in all seismic zones for constructions of types (a), (b), (c), described in section 7.3.1. Proper connection of ties placed at right angles at the corners and junctions of walls should be insured. Where the height of wall is no more than 2.5 m, the lintel band can be avoided but the lintels should be connected to the roof band as shown, in Fig 7.11. The band could be in the following forms:

- (a) Unfinished rough cut lumber in single pieces provided with diagonal members for bracing at corners, Fig 7.10(a).
- (b) Unfinished rough cut or sawn (50 × 100 mm in section) lumbars two pieces in parallel with halved joints at corners and junctions of walls placed in parallel, Fig 7 10(b).

7.6.2 Pillasters and buttresses

Where pillasters or buttresses are used, as recommended in 7.5.1(j) at T-junctions, the

collar beam should cover the buttresses as well as shown in Fig 7.11. Use of diagonal struts at corners will further stiffen the collar beam.

7.6.3 Vertical reinforcement in walls

a. In mesh form of bamboo or cane

In seismic zone A, mesh form of reinforcing will be preferable. Here the whole walls are reinforced by a mesh of canes or bamboos as shown in Fig 7.12 along with the collar beams, which may in this case be made from canes, or bamboos themselves. The vertical canes must be tied to the horizontal canes as well as the collar beam at lintel level and the roof beam at eave level.

b. With collar beams or bands

For seismic zones A and B, in addition to the collar beams recommended in 7.6.1 and 7.6.2 provision of vertical reinforcement in

earthen walls of earthen constructions types (a), (b), (c) will be necessary whereas it can be avoided in zone C.

The most effective vertical reinforcement will be in the form of wood posts, bamboo or cane located at corners and junctions of walls. It should be started at the foundation level and continued through and tied to the lintel and roof bands by binding wire, fishing line or rope etc.

7.6.4 Diagonal bracing

In case of earthen constructions type d (Section 7.3.1), it will be necessary for achieving adequate seismic resistance in zones A and B to provide diagonal bracing members in the planes of walls as well as horizontally at the top level of walls as shown in Fig 7.13. This can be done by using canes or bamboos nailed to the framing members

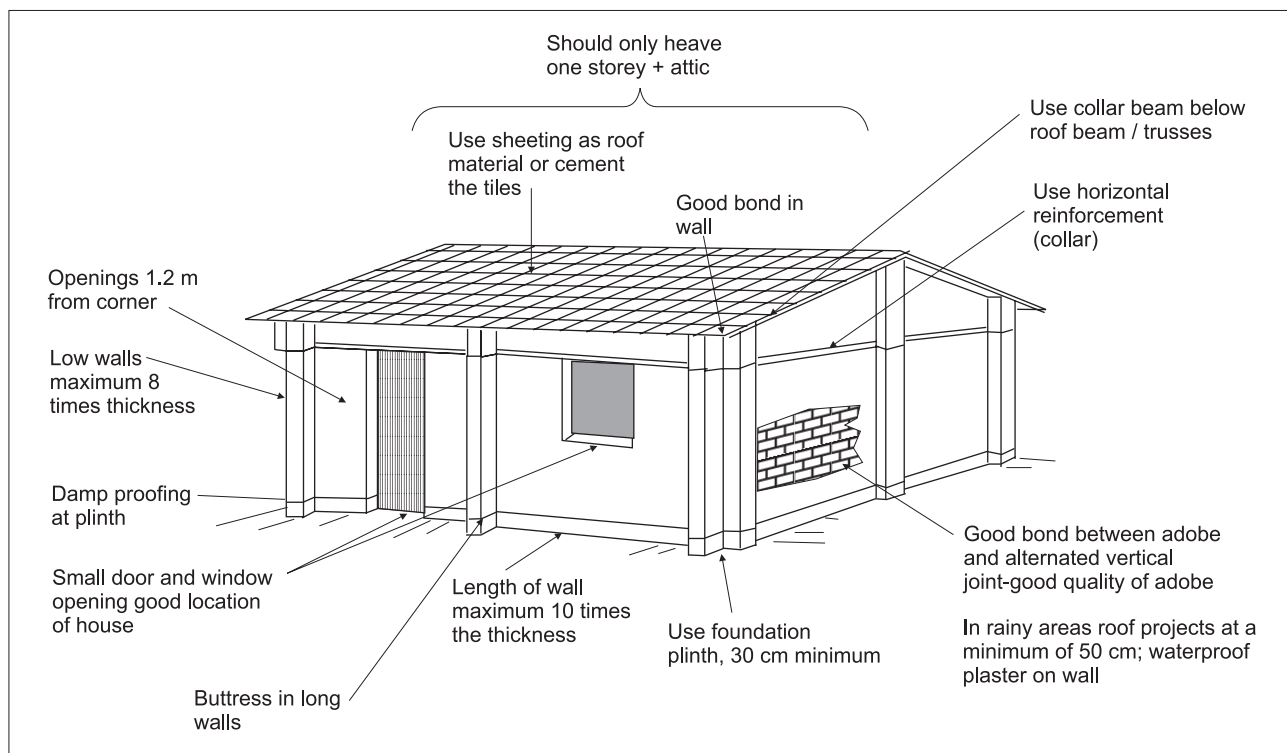


Fig 7.14 Good features of earthquake resistant construction

at the ends and intermediate points of intersection.

7.7 PLASTERING AND PAINTING

The purpose of plastering and painting is to give protection and durability to the walls, in addition to obvious aesthetic reasons.

- (a) Plastering based on natural additives could be formed in two layers. The first one of about 12 to 15 mm, is a mixture of mud and straw (1:1 in volume), plus a natural additive like cow dung used to increase the moisture resistance of the mud, thus preventing the occurrence of fissures during the drying process. The natural additive helps to withstand the shrinkage tensions of the restricted drying process. The second and last

layer is made with fine mud which when dried, should be rubbed with small, hard, rounded pebbles.

- (b) A technology has been developed which consists of plastering walls with a mud stucco stabilized with cactus as described hereunder:

The main recommendations for plastering adobe walls with this type of stucco are to

- (i) Prepare the cactus stabilizer by soaking cactus chopped pieces until the soft (inside) part dissolves completely leaving the skin only as residue. The obtained product is characterized by gluey consistency, green color and strong smell of decomposed organic matter.
- (ii) Remove dust from the wall surface.
- (iii) Apply the stucco in two layers, a first layer of 12 mm thickness and a second very thin layer (approximately 3 mm). The first layer contains straw, and coarse sand in amounts that allow an adequate workability. The second layer contains straw in small pieces (approximately 50mm) and should not contain coarse sand. The second layer covers the cracks of the first layer and provides a surface adequate to be polished. Both layers are mixed with cactus stabilizer (water is not used).

- (iv) Rub the stucco surface with a coarse stone (granitic). Thereaf-

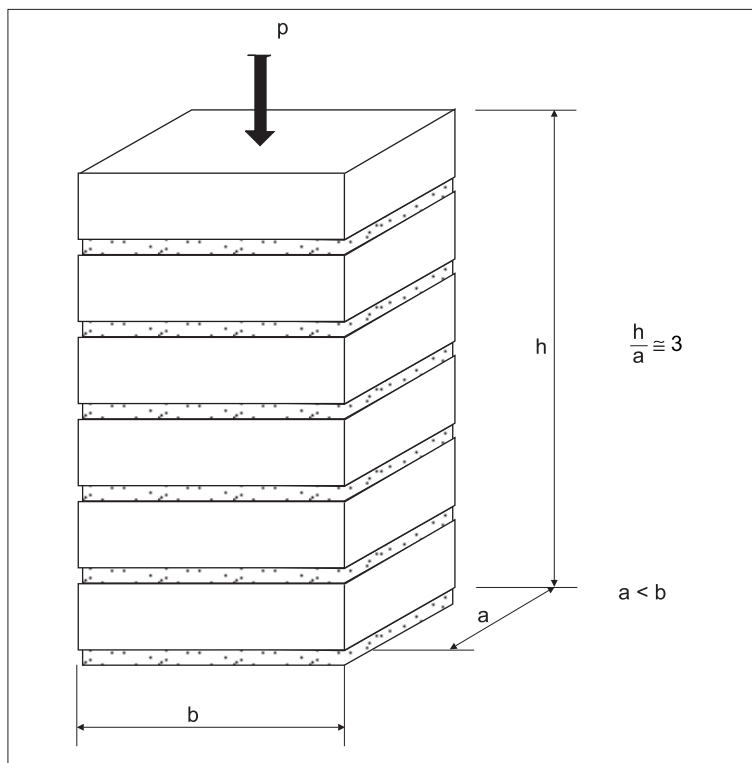


Fig 7.15 Axial compression test

ter, moist the surface with the stabilizer and polish it with a smooth stone (basaltic stone).

- (v) Paint the finished surface with the cactus stabilizer.
- (c) To obtain a truly waterproof mud plaster, bitumen may be used in the following way where this material is found feasible to use: cut-back is prepared by mixing bitumen 80/100 grade, kerosene oil and paraffin wax in the ratio 100:20:1. For 1.8 kg cut-back, 1.5 kg bitumen is melted with 15 grams of wax and this mixture is poured in a container having 300 millilitre kerosene oil with constant stirring till all ingredients are mixed. This mixture can now be mixed with 0.03 m^3 of mud mortar to make it both water repellent as well as fire protection of thatch.

The exterior of walls may then be suitably painted using a water-insoluble paint or wash with water solutions of lime or cement or gypsum and plant extracts.

7.8 SUMMARY OF DESIRABLE FEATURES

The desirable features for earthquake resistance of earthen houses are briefly illustrated in Fig 7.14.

7.9 WORKING STRESSES

7.9.1 Unit compressive strength

The compressive strength of the unit is an index of its quality and not of the masonry.

It will be determined by testing cubes of approximately 100 mm. The compressive strength f_o is the value exceeded by 80% of the number of specimens tested.

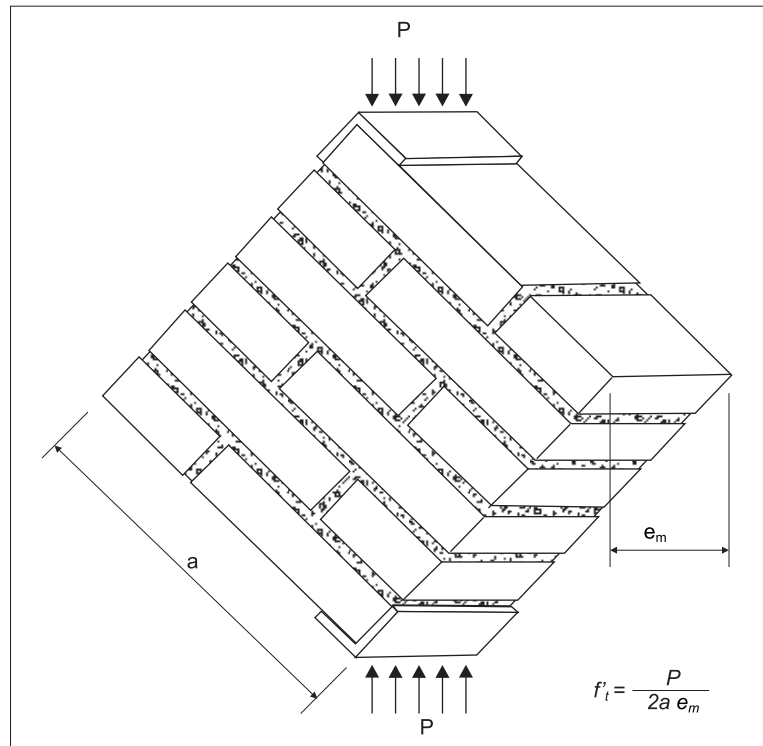


Fig 7.16 Diagonal compression test

The minimum number of specimens is six (6) and they should be completely dry at the time of testing. The minimum value of f_o is 1.2 N/mm^2 .

7.9.2 Masonry compressive strength

The masonry compressive strength may be determined by:

- (a) Prism test with materials and technology to use in the field.

The prisms will be composed by the number of full adobes necessary to obtain a height/thickness ratio of three.

The minimum number of adobes will be four and the joint thickness less than 20 mm, Fig 7.15.

Special care should be observed to keep the specimens vertical. They

should be tested after 30 days of construction to obtain a mortar completely dry. The minimum number of prisms will be three.

The permissible compressive stress f_m in wall will be:

$$f_m = 0.4R f'_m$$

where:

R = Reduction factor due to wall slenderness.

R can be obtained by analogy to an elastic column but not greater than 0.75.

f'_m = Ultimate compressive stress of prism. Two of every three prisms should have greater values than the compressive strength.

Alternatively the following expression can be used:

$$f_m = 0.2 f'_m$$

(b) If no prism test is conducted, the permissible compressive stress will be

$$f_m = 0.2 \text{ N/mm}^2$$

The permissible crushing stress will be: $1.25 f_m$

7.9.3 Shear strength of masonry

The shear strength of adobe masonry can be determined by:

(a) Diagonal compression test with materials and technology to be used in the field, Fig 7.16.

A minimum of three specimens should be tested. The permissible strength of wall (v_m) will be obtained from :

$$v_m = 0.4 f'_t$$

Where: f'_t = ultimate strength of specimen tested. Two of every three specimens will have values that exceed f'_t .

b. When no tests are conducted, the following value for the shear strength may be used

$$v_m = 0.025 \text{ N/mm}^2$$

7.9.4 Permissible tensile strength of masonry for loads perpendicular to its plane (f_a)

$$f_a = 0.04 \text{ N/mm}^2$$

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