Earthquake-Resistant Construction of Adobe Buildings: A Tutorial

Images from El Salvador : top-Manuel Lopez Menjivar; bottom-PRISMA

Earthquake-Resistant Construction of Adobe Buildings: A Tutorial

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INTRODUCTION

Adobe mud blocks are one of the oldest and most widely used building materials. Use of these sun-dried blocks dates back to 8000 B.C. (Houben and Guillard 1994). The use of adobe is very common in some of the world's most hazard-prone regions, traditionally across Latin America, Africa, Indian subcontinent and other parts of Asia, Middle East and Southern Europe.

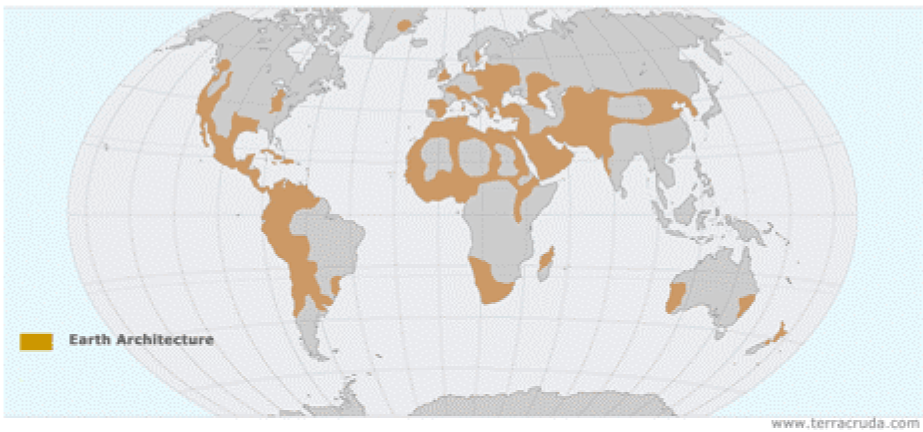


Figure 1 – World Distribution of Earth Architecture (De Sensi, 2003)

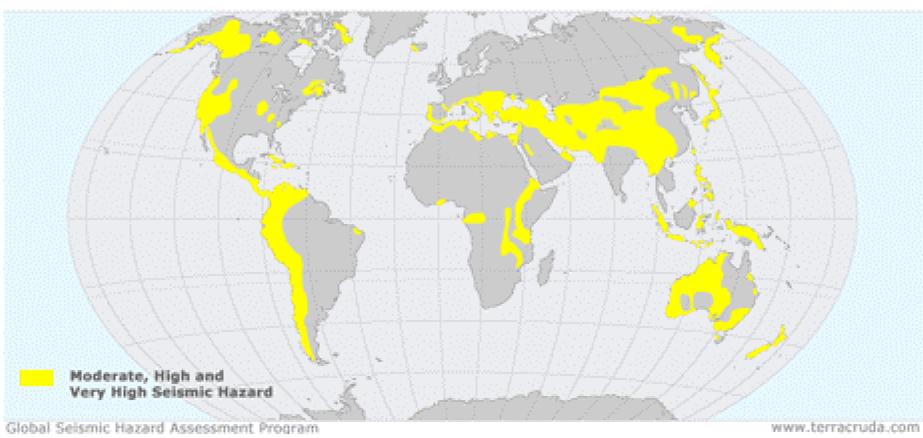


Figure 2 – World Distribution of Moderate and High Seismic Risk (De Sensi, 2003)

Around 30% of the world's population lives in earth-made construction. Approximately 50% of the population in developing countries, including the majority of the rural population and at least 20% of the urban and suburban population, live in earthen dwellings (Houben and Guillard 1994). For example, in Peru, 60% of the houses are built of adobe or rammed earth. In India, according to the 1971 Census, 73% of all buildings are made out of earth (67 million houses inhabited by 375 million people). By and large, this type of construction has been used mainly by low-income rural populations. Examples of adobe construction practices from different countries are presented in the World Housing Encyclopedia. (Select Search Database from the website: www.world-housing.net)

Adobe is a low-cost, readily available construction material manufactured by local communities. Adobe structures are generally self-made because the construction practice is simple and does not require additional energy consumption. Skilled technicians (engineers and architects) are generally not involved in this type of construction, hence the name "nonengineered construction".

El Salvador Report #14(Lopez)

Argentina Report #2(Rodriguez)

India Report #23(Verma)

Peru Report #52 (Loaiza)

Figure 3 – Several of the Typical Adobe Houses Described in the EERI/IAEE World Housing Encyclopedia. (www.world-housing.net)

EARTHQUAKE PERFORMANCE

In addition to its low cost and simple construction technology, adobe construction has other advantages, such as excellent thermal and acoustic properties. However, adobe structures are vulnerable to the effects of natural phenomena such as earthquakes, rain, and floods. Traditional adobe construction responds very poorly to earthquake ground shaking, suffering serious structural damage or collapse, and causing a significant loss of life and property. Seismic deficiencies of adobe construction are caused by the heavy weight of the structures, their low strength, and brittle behavior. During strong earthquakes, due to their heavy weight, these structures develop high levels of seismic forces they are unable to resist, and therefore they fail abruptly. Considerable damage and loss of life has occurred in areas where these materials were used. This is confirmed by the reports from recent earthquakes. In the 2001 earthquakes in El Salvador, more than 200,000 adobe buildings were severely damaged or collapsed, 1,100 people died under the rubble of these buildings, and over 1,000,000 people were made homeless (USAID El Salvador 2001). That same year, the earthquake in the south of Peru caused the death of 81 people, the destruction of almost 25,000 adobe houses and the damage of another 36,000 houses, with the result that more than 220,000 people were left without shelter. (USAID Peru 2001).

Typical modes of failure during earthquakes are: severe cracking and disintegration of walls, separation of walls at the corners, and separation of roofs from the walls, which, in most cases, leads to collapse. Seismic deficiencies characteristic for adobe construction are summarized below.

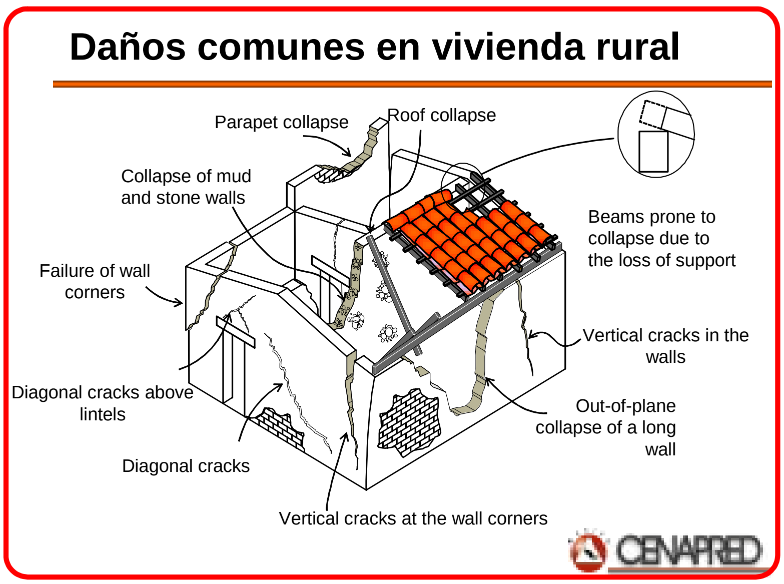


Figure 4 – Seismic Deficiencies of Adobe Masonry (CENAPRED)

Typical patterns of damage have been identified in several reports in the World Housing Encyclopedia (EERI 2003).

Cracking and separation of adobe walls – 1997 Jabalpur, India earthquake (Report #23)

Out-of-plane wall collapse – 1996 Nazca earthquake, Peru (Report #52)

Total collapse of adobe walls – February 2001 El Salvador earthquake (Report #14)

Crushing of adobe walls – 1997 Jabalpur earthquake, India (Report #23)

Figure 5 – Typical Patterns of Earthquake Damage as Illustrated in Reports in EERI/IAEE World Housing Encyclopedia, www.world-housing.net

IMPROVED EARTHQUAKE PERFORMANCE OF NEW CONSTRUCTION

Due to its low cost, adobe construction will continue to be used in high-risk seismic areas of the world. Development of cost-effective building technologies leading to improved seismic performance of adobe construction is of utmost importance to the substantial percentage of the global population that lives in adobe buildings. Based on the state-of-the-art research studies and field applications, the key factors for the improved seismic performance of adobe construction are:

1. Adobe block composition and quality of construction.
2. Robust layout.
3. Improved building technologies including seismic reinforcement

Adobe Block Composition and Quality of Construction (based on Ref. 17)

Key Factors

The characteristics of the soils having the greatest influence on the strength of adobe masonry are those related either to the drying shrinkage process or the dry strength of the material.

– Clay: the most important component of the soil; it provides dry strength and causes drying shrinkage of the soil.

– Controlled microcracking of the soil mortar due to drying shrinkage: required to obtain strong adobe masonry.

– Additives: straw and, to a lesser extent, coarse sand are additives that control microcracking of the mortar due to drying shrinkage, and therefore improve the strength of adobe masonry.

– Construction: the quality of workmanship plays an important role in obtaining strong adobe masonry, resulting in the broad variations in strength on the order of 100%.

Recommendations

– Clay: Perform the "dry strength test"--make at least three mud balls of about 2 cm diameter from the selected soil. Once dry (after at least 24 hours), crush each ball between the thumb and the index finger. If none of the balls can be broken, the soil contains enough clay to be used for adobe construction, provided that microcracking of the mortar due to drying shrinkage is controlled. If some of the balls can be crushed, the soil is inadequate, since it lacks clay and should be discarded.

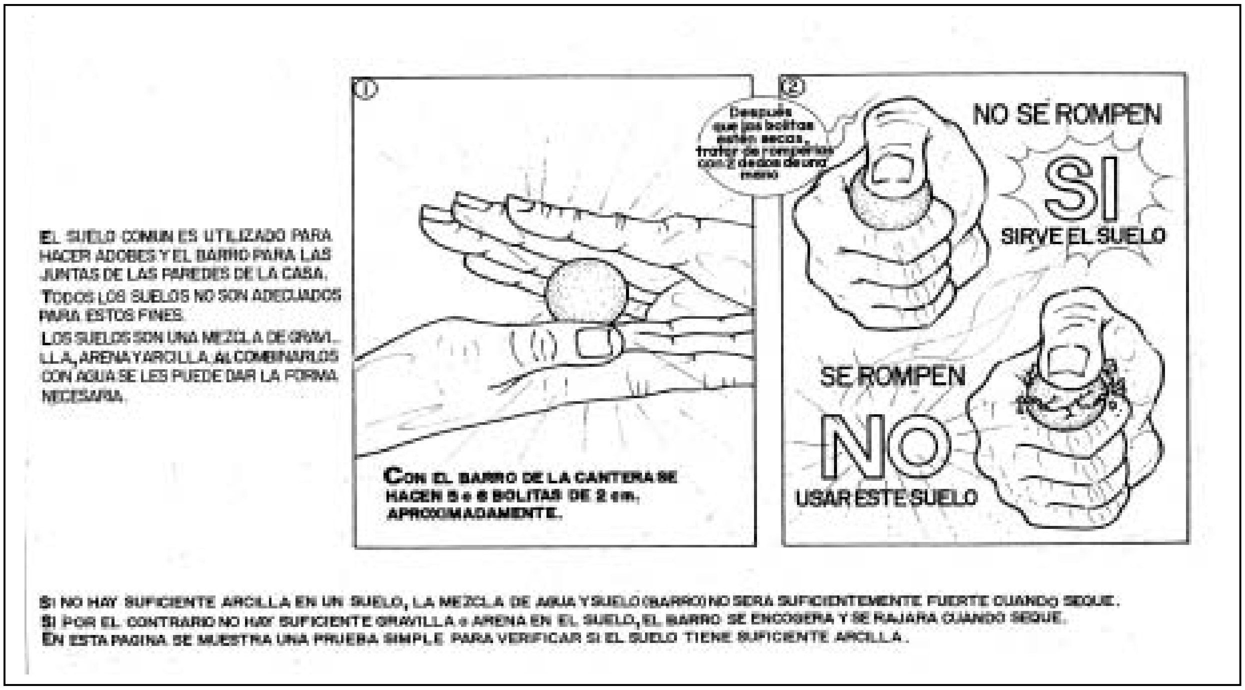


Figure 6 – Dry Strength Test (Pucp/Ciid, 1995)

– Roll test: field alternative for choosing the soil; using both hands, make a little mud roll. If the unbroken length of the roll is between 5 to 15 cm, the soil is adequate. If the roll breaks with less than 5 cm, the soil must not be used. If the unbroken roll is longer than 15 cm, coarse sand must be added. (CTAR/COPASA 2002).

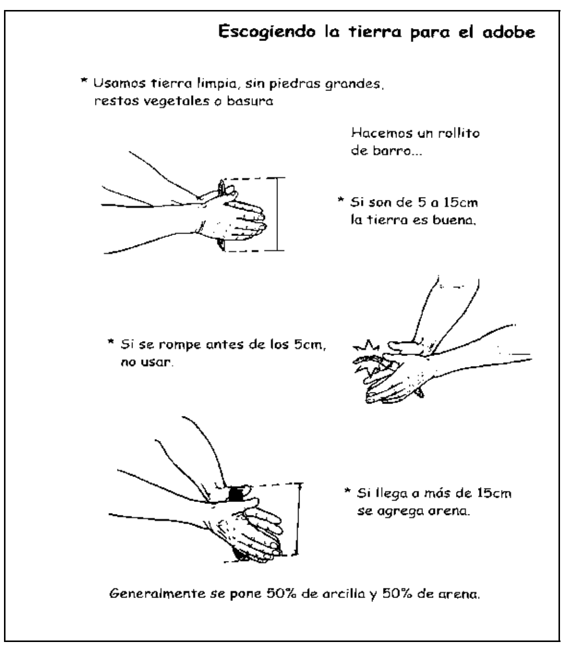


Figure 7 – Roll Test (CTAR/COPASA, 2002)

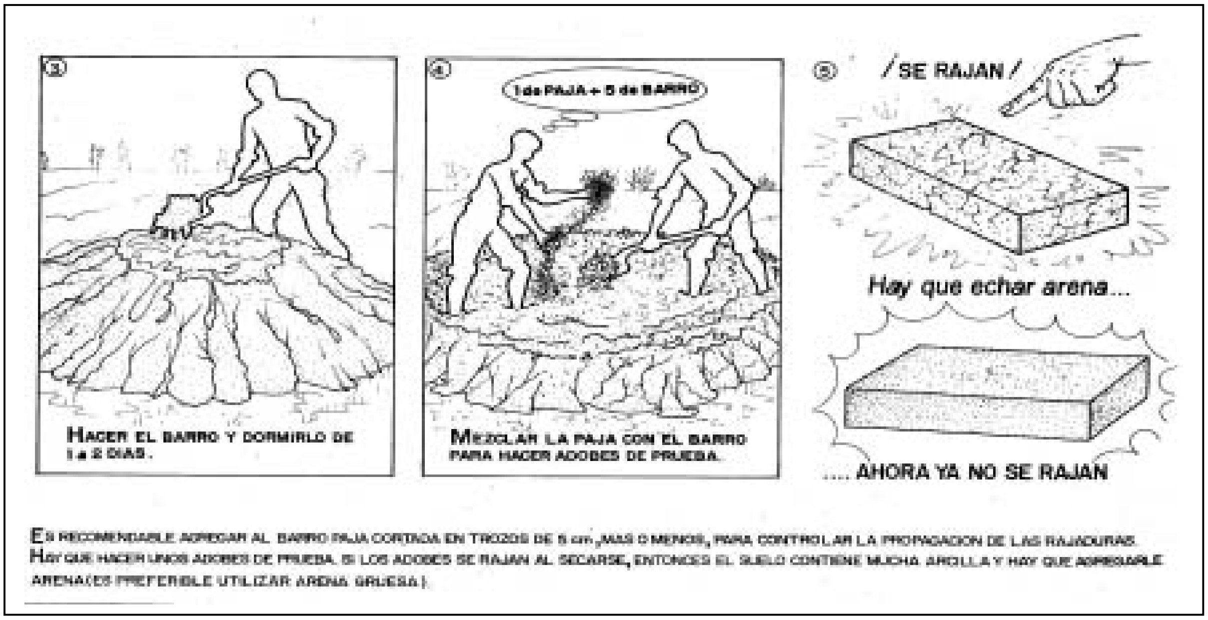


Figure 8 – Control of Microcracking by Adding Straw (PUCP/CIID, 1995)

- Additives: straw; add to the mud, especially when preparing the mortar, the maximum amount of straw that still allows for adequate workability.

  If straw is not available, perform the "microcracking control test". Make two or more adobe sandwiches (two adobe bricks joined with mortar). After 48 hours of drying in the shade, the sandwiches are carefully opened and the mortar examined. If the mortar does not show visible cracking, the soil is adequate for adobe construction. Otherwise, use coarse sand (approximate size 0.5 to 5 mm) as an additive to control microcracking due to drying shrinkage.

- Additives: coarse sand; the most adequate soil-coarse sand proportion is determined by performing the microcracking control test with at least eight sandwiches made using mortars with different proportions of soil and coarse sand. It is recommended that the soil:coarse sand proportions vary between 1:0 (no sand) to 1:3 in volume. The sandwich with the least amount of sand that shows no visible cracking after opening 48 hours after manufacturing indicates the soil:coarse sand proportion to be used for adobe construction.

- Construction issues: wet the adobe bricks before laying. All adobe faces that are to be in contact with mortar should be wetted superficially. This can be achieved by spraying water.

- “Sleeping” the mud: the positive effect of storing the mud for one or two days before the fabrication of adobe bricks or mortar is a traditional practice in Peru. This procedure allows for a better integration and distribution of water with the clay particles, thus activating their cohesive properties.

- Other general recommendations: eliminate all foreign matters from the soil; mix as thoroughly and uniformly as possible, dry the adobe bricks in the shade; clean the bricks before laying, make uniform and complete mortar joints; and ensure that the wall is in plumb.

Robust Layout (based on Ref. 13, 4)

One of the essential principles of earthquake-resistant adobe construction is to use a compact, box-type layout. Key recommendations are summarized below (Coburn et al, 1995, EERI, 2003):

- Build only one-story houses
- Use an insulated lightweight roof instead of a heavy compacted earth roof
- Arrange the wall layout to provide mutual support by means of cross walls and intersecting walls at regular intervals in both directions, or use buttresses
- Keep the openings in the walls small and well-spaced, and
- Build on a firm foundation.

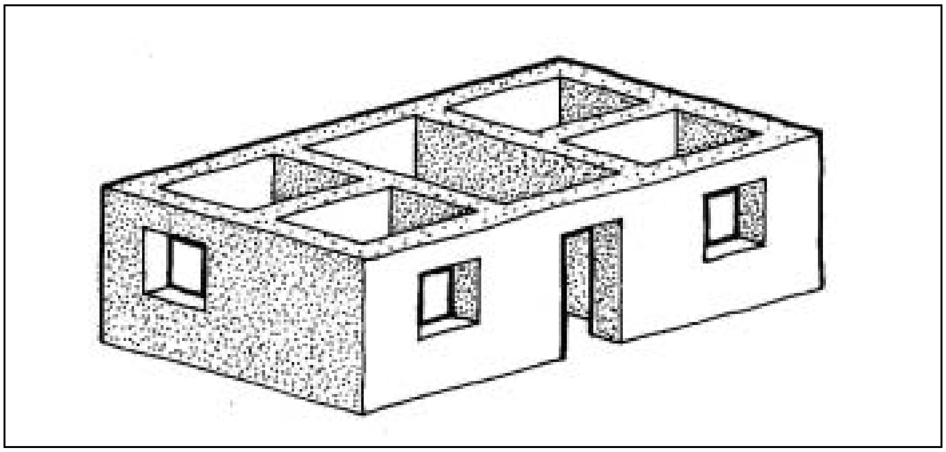


Figure 9 – The Safest Building Form is a Squat, Single Story House, with Small Windows and a Regular, Compact Plan with Frequent Cross-Walls (Coburn et al, 1995)

Walls are the main load-bearing elements in an adobe building. A number of empirical recommendations regarding earthquake-resistant wall construction are as follows:

- The wall height should not exceed eight times the wall thickness at its base, and in any case should not be greater than 3.5 m.
- The unsupported length of a wall between cross walls should not exceed 10 times the wall thickness, with a maximum of 7 m.
- Wall openings should not exceed one-third of the total wall length.
- No opening should be wider than 1.2 m.
- Provide piers of at least 1.2 m width between openings.

The recommendations regarding the wall length and the sizes and distribution of openings in adobe construction are summarized in Figure 10.

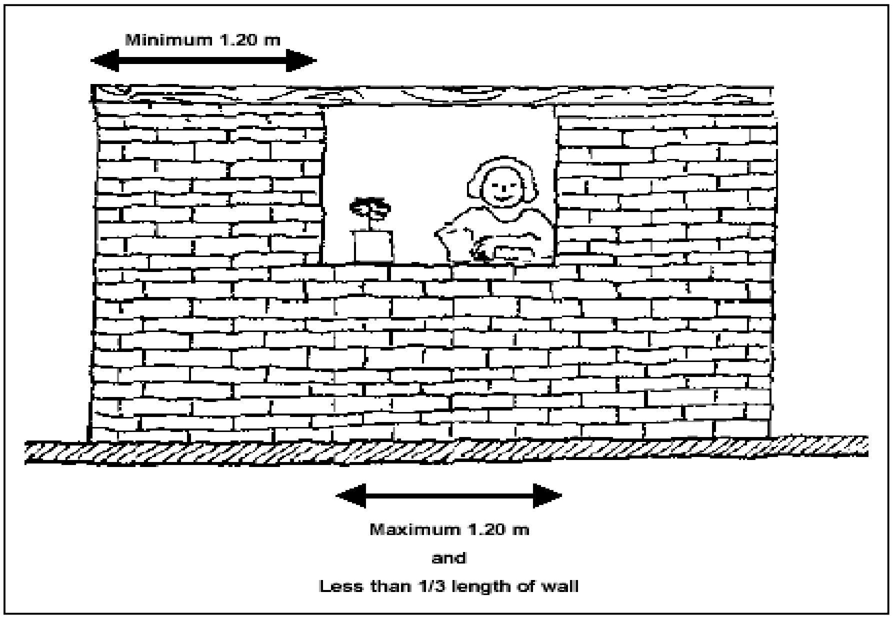


Figure 10 – Wall Openings Guideline (RESESCO, 1997)

Improved Building Technologies (based on Ref. 1, 2, 8, 12, 13)

Use of Horizontal and Vertical Reinforcement

The reinforcement can be made of any ductile material, including: bamboo, reeds, cane, vines, rope, timber, chicken wire, barbed wire, or steel bars. Vertical reinforcement helps to tie the wall to the foundation and to the ring beam and restrains out-of-plane bending and in-plane shear. Horizontal reinforcement helps to transmit the bending and inertia forces in transverse walls (out-of-plane) to the supporting shear walls (in-plane), as well as restraining the shear stresses between adjoining walls and minimizing vertical crack propagation. The horizontal and vertical reinforcement should be tied together and to the other structural elements (foundations, ring beam, roof) by means of nylon string. This attachment provides a stable matrix, which is inherently stronger than the individual components. Placement of reinforcement must be carefully planned and blocks made with special provisions. An illustration of cane reinforcement for adobe walls is shown below.

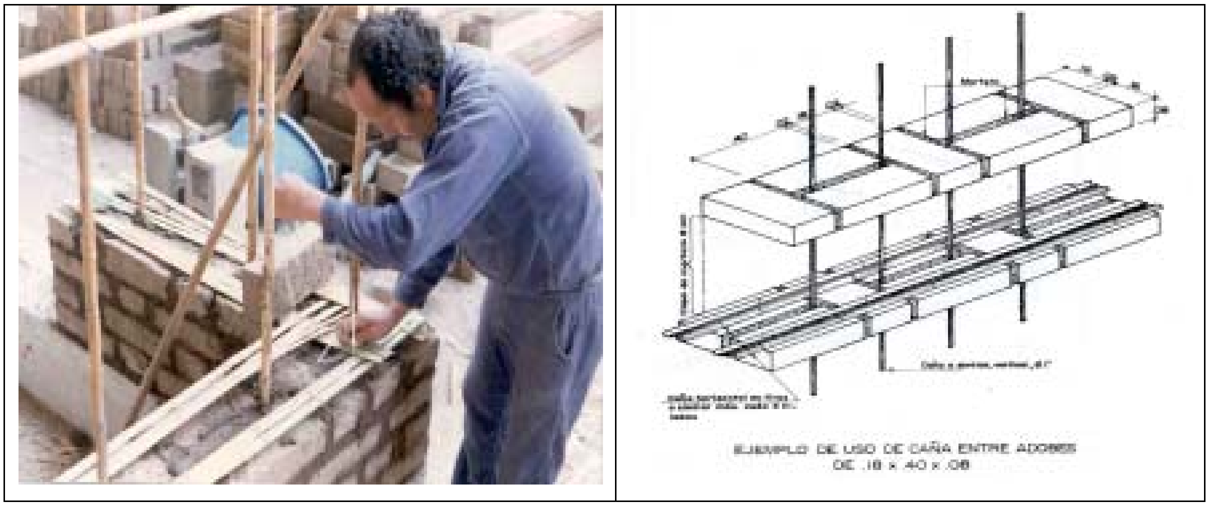


Figure 11 – Construction of Cane Reinforcement In Peru (Blondet et al, 2002)

Figure 12 – Construction of Cane Reinforcement In El Salvador (Dowling, 2002)

Several research studies on adobe buildings reinforced with cane have been performed at the Catholic University of Peru (PUCP), Lima, Peru (Blondet et al, 2002). The first research project developed at the PUCP in 1972 consisted of the experimental study of several alternatives for structural reinforcement of adobe houses, made with materials available in rural regions. The models were built on top of a concrete platform. Testing consisted of slowly tilting the platform and measuring the tilt angle at collapse. The lateral component of the weight of the model was then used to quantify the maximum seismic force. The main conclusion was that an interior reinforcement made of vertical cane, combined with the horizontal crushed cane placed at every fourth row of adobe blocks, notably increased the seismic strength of the model buildings.

Unreinforced specimen

Test specimen strengthened with cane reinforcement

Figure 13- Seismic Performance of an Unreinforced and a Strengthened Adobe Building (Blondet et al, 2002)

In 1992, eight full-size models of a one-room single-story building were tested on a shaking-table. The test results have shown that horizontal and vertical cane reinforcement, combined with a solid ring beam, can prevent the separation of the walls in the corners due to a severe quake and thus can maintain structural integrity even after the walls are substantially damaged. The reinforcement proved to be very effective in preventing the collapse of the building in the tests.

Video clips showing shaking-table testing of the unreinforced adobe building model and the model strengthened with cane reinforcement can be viewed from the html version of this tutorial on the World Housing Encyclopedia website at www.world-housing.net.

Buttresses and Pilasters (based on Ref. 8)

Use of buttresses and pilasters in the critical parts of a structure increases stability and stress resistance. Buttresses act as counter supports that may prevent inward or outward overturning of the wall. Buttresses and pilasters may also enhance the interlocking of the corner bricks. The critical sections include:

- Corners, where pilasters take the form of overlapped (crossed over) walls; and

- Intermediate locations in long walls, where buttresses take the form of perpendicular bracing walls which are integrated into the wall structure.

Use of buttresses and pilasters for the improved seismic resistance of adobe construction has been reported in El Salvador, as a part of a grass root education and rebuilding effort following the 2001 earthquakes (Dowling 2002, Dowling forthcoming).

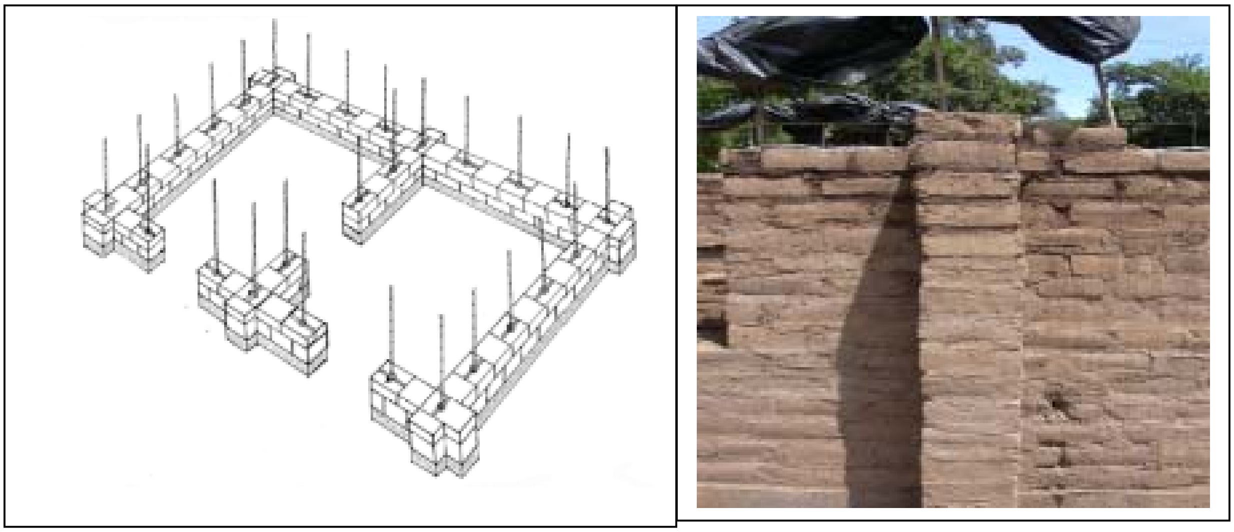
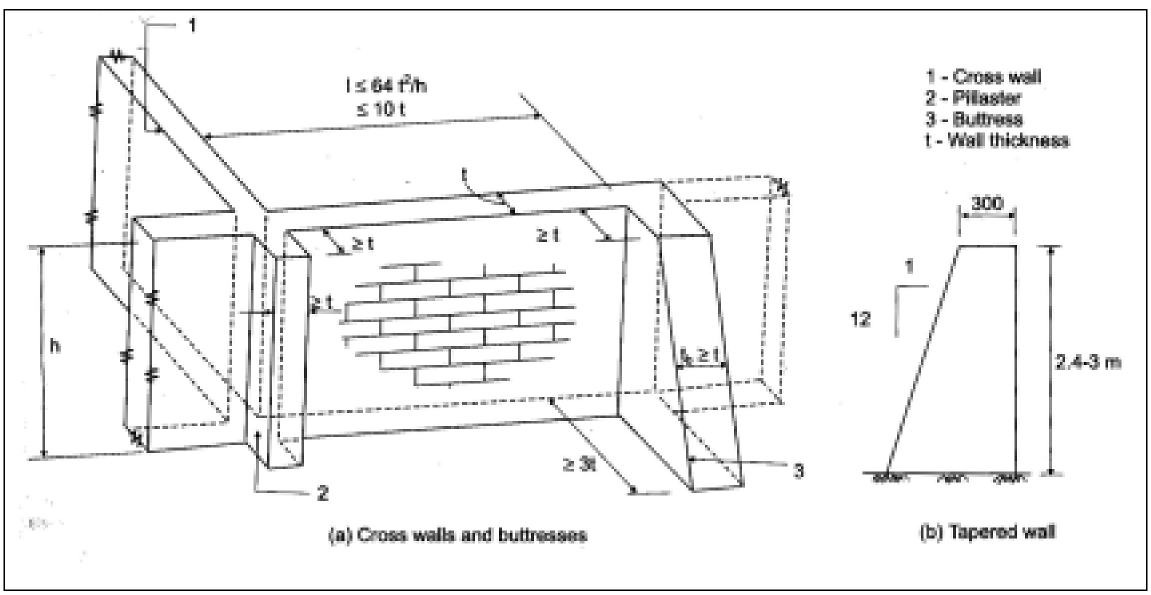


Figure 14 – Adobe Building with Buttresses and Pilasters in El Salvador (Equipo Maíz, 2001, Dowling, 2002)

The recommendations regarding the dimensions of buttresses and pilasters are summarized in the figures below (IAEE 1986).



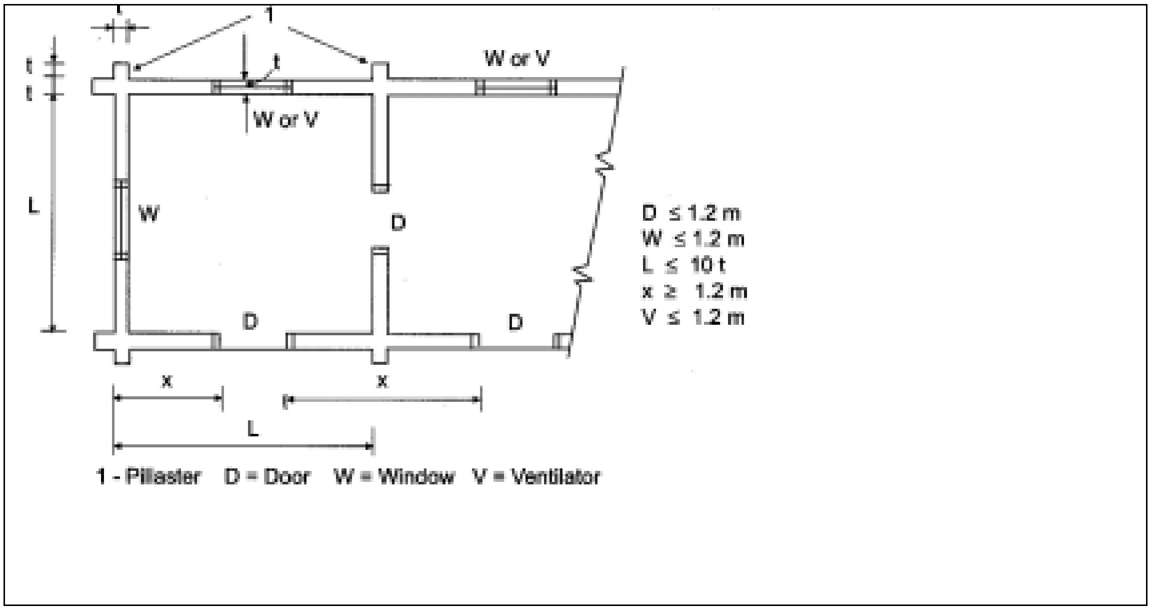


Figure 15 - Guidelines for Wall Construction with Buttresses and Pilasters (IAEE 1986)

Ring Beam (based on Ref. 2, 4)

A ring beam (also known as a crown, collar, bond or tie beam or seismic band) that ties the walls in a box-like structure is one of the most essential components of earthquake resistance for load-bearing masonry construction. To ensure good seismic performance of an adobe building, a ring beam needs to be provided continuously like a loop or a belt. The ring beam must be strong, continuous and well tied to the walls and it must receive and support the roof. The ring beam can either be made of concrete or timber.

Figure 16- Reinforced Concrete Lintel Ring Beam Construction in El Salvador (Dowling, 2002)

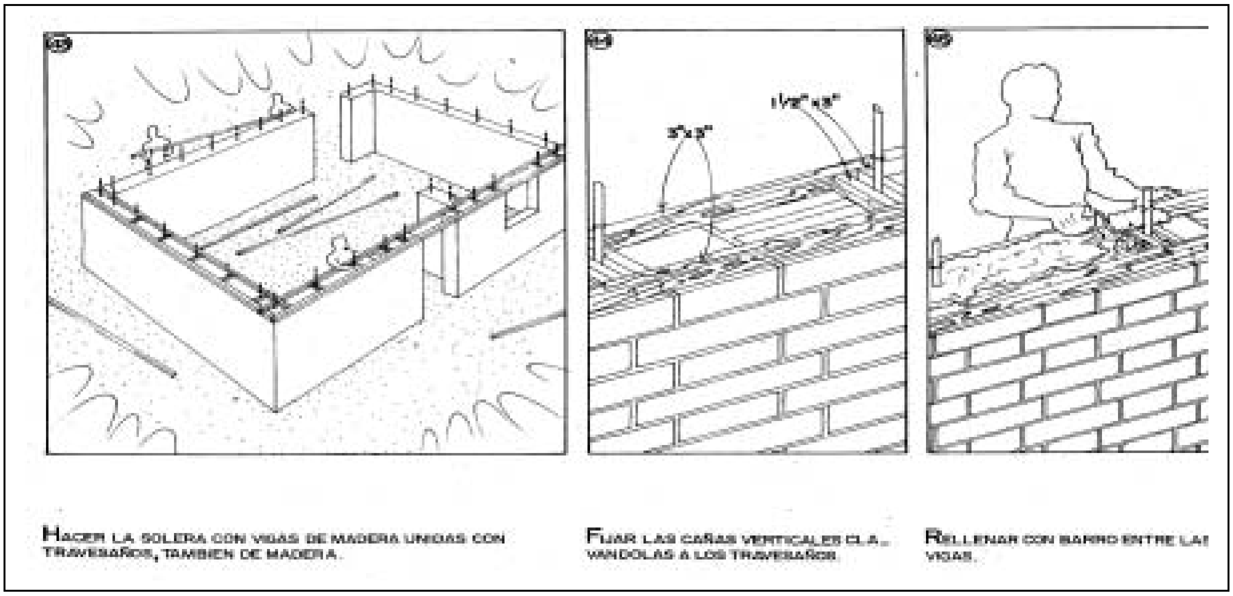


Figure 17 – Guideline for Timber Ring Beam Construction (PUCP/CIID, 1995)

In addition to the ring beam, the use of truss-like timber ties between the lintel and ring beam proved to be effective, based on the tests performed at the PUCP, Peru (Blondet, 2002). The performance of an unreinforced adobe building model and a model with vertical and horizontal cane reinforcement, ring beam and truss-like ties is illustrated below.

FIGURE 18 – Seismic Performance of an Unreinforced Adobe Building (Left) and a Strengthened Adobe Building with Internal Cane Reinforcement and Ring Beam (Right) (Blondet et al, 2002)

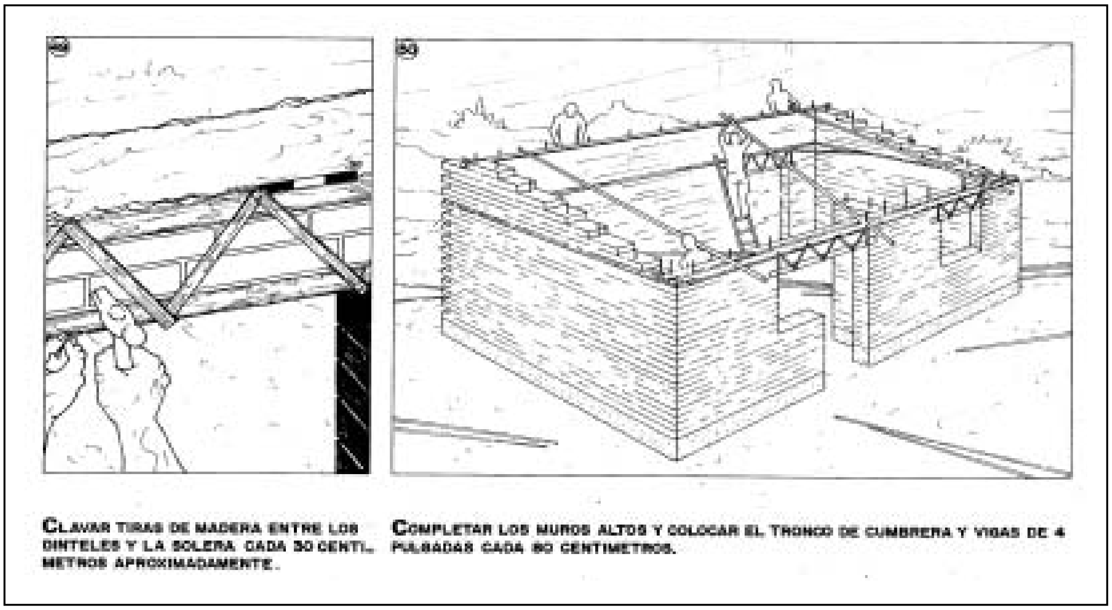


Figure 19 – Timber Ties and Roof Beams Construction Guideline (PUCP/CIID, 1995)

For detailed guidelines (in Spanish) regarding earthquake-resistant adobe construction using the techniques described above, refer to Reference 13, PUCP/CIID, 1995.

SEISMIC STRENGTHENING OF EXISTING ADOBE BUILDINGS (based on Ref. 18, 19, 20)

Simple techniques to reinforce existing adobe houses were tested at PUCP. The proposed external reinforcement was developed to delay the collapse of the structure during a severe earthquake. Different reinforcement materials were tested, like wooden boards, ½-inch rope, chicken wire mesh, and welded mesh. Seismic simulation tests were performed on "U"-shaped walls, with and without reinforcement, as shown in Figure 20.

Figure 20 – Dynamic Testing of "U" Shaped Walls (Zegarra et al, 1997)

The dynamic tests demonstrated that the best solution for existing adobe houses is reinforcement consisting of welded mesh (1 mm wires spaced at ¾ inches) nailed with metallic bottle caps against the adobe as shown in Figure 21. The mesh is placed in horizontal and vertical strips simulating beams and columns, and is covered with cement and sand mortar. This solution proved to be highly effective in delaying the collapse of the structure.

Figure 21 – Placing The Welded Mesh On Traditional Adobe Wall (Zegarra et al, 1997).

During the Arequipa earthquake in Peru (2001), existing adobe houses that had been externally reinforced with welded mesh covered by cement-sand mortar as part of a prototype reinforcement program, withstood the seismic event without any damage, whereas houses with no reinforcement collapsed or were severely damaged, as can be seen in the figure below.

Figure 22 – A House with External Welded Mesh Reinforcement Remained undamaged (front) whereas a House Without Reinforcement (shown at the back) was Severely Affected by the 2001 Arequipa Earthquake, Peru (Zegarra et al, 2001)

SEISMIC PROTECTION OF HISTORIC ADOBE BUILDINGS (based on Ref. 21)

Historic adobe buildings, regardless of their important architectural or cultural value, are prone to suffer the same damage as any other adobe structure during strong earthquakes. Thus, it is important to provide adequate upgrading to these buildings to insure life safety protection and at the same time to preserve their authenticity.

The Getty Conservation Institute recently carried out the Getty Seismic Adobe Project (GSAP) to develop technical procedures for preventing the structural instability of historic adobe buildings during earthquakes, with minimal intervention to their original fabric.

As part of this project, nine small-scale (1:5) model buildings were tested on the shaking table at the John A. Blume Earthquake Center at Stanford University in Palo Alto, California, U.S.A. Two large scale (1:2) model buildings were tested during the final phase of the GSAP research program at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), university "SS. Cyril and Methodius" in Skopje, The Former Yugoslav Republic of Macedonia.

The retrofitting elements that proved to be effective were:

- Nylon straps made of 0.3 cm wide, flexible, woven nylon. They were placed horizontally or vertically, forming a loop either around the entire building or around an individual wall. The straps were passed through small holes in the wall and the two ends were knotted together. Vertical straps were most effective for reducing the risk of out-of-plane wall collapse.

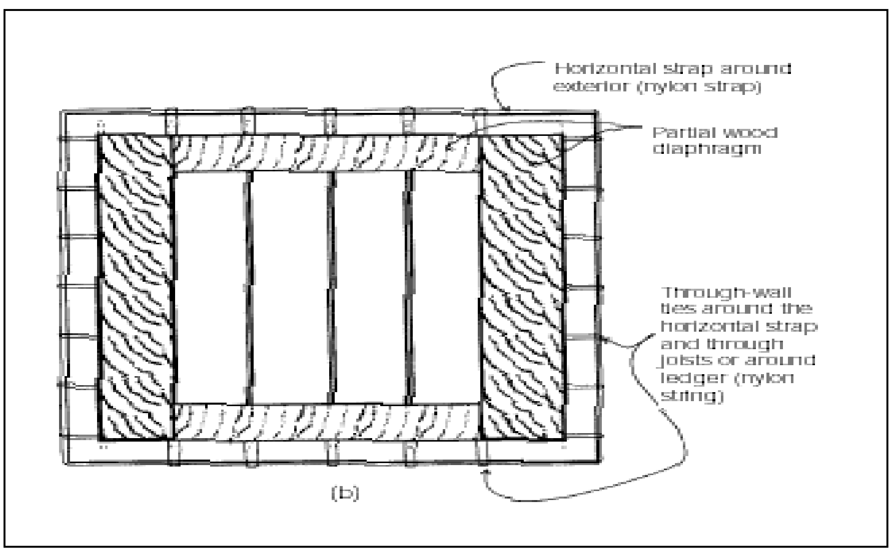


Figure 23 – Roof plan of the test model showing retrofit measures applied at floor level. (Tolles et al, 2000)

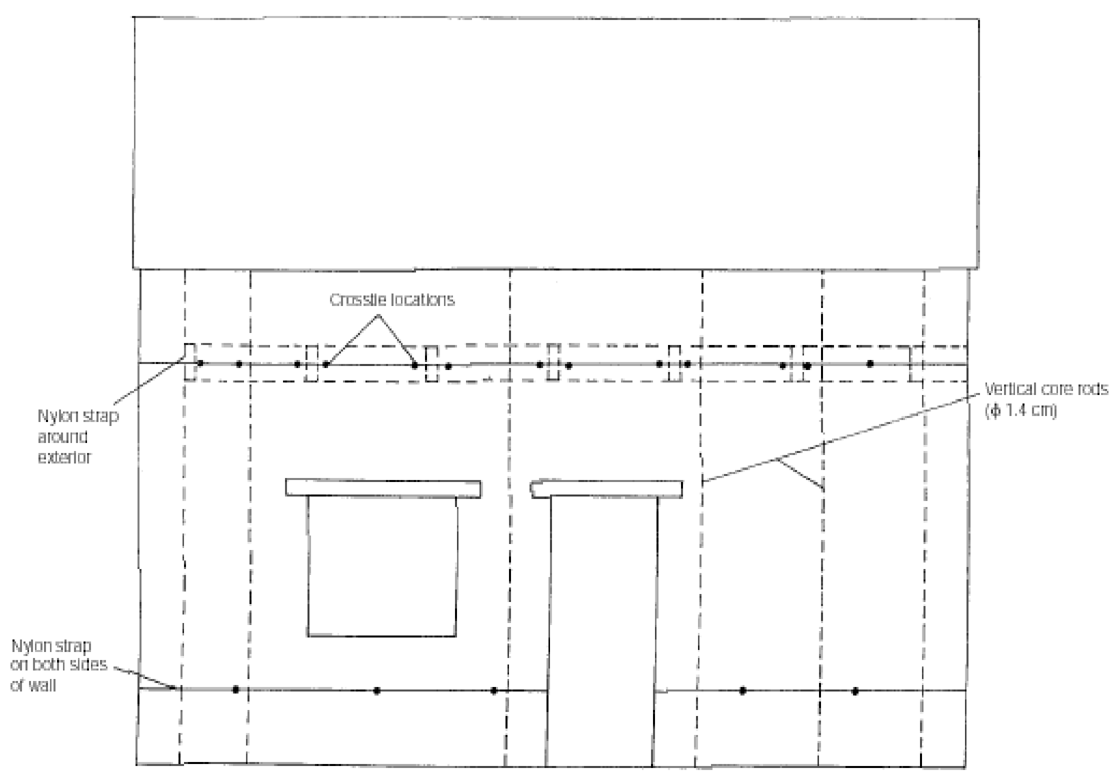


Figure 24 – Model elevation showing retrofit measures applied to an external wall. (Tolles et al, 2000)

- Vertical center-core elements consisting of 3.0 mm or 4.8 mm diameter steel rods anchored with epoxy grout. The rods were drilled directly into the adobe after flattening each end into a V-shaped form. These elements were found to be particularly effective in delaying and limiting both the in-plane and out-of-plane wall damage.
- Wood bond beams anchored to the walls with coarse threaded screws or partial wood diaphragms.
- Cross-ties made out of nylon cord were installed to reduce the differential displacement across the cracks and to provide a through-wall connection.

CONCLUSIONS

The main recommendations for the improved seismic performance of adobe construction are summarized below.

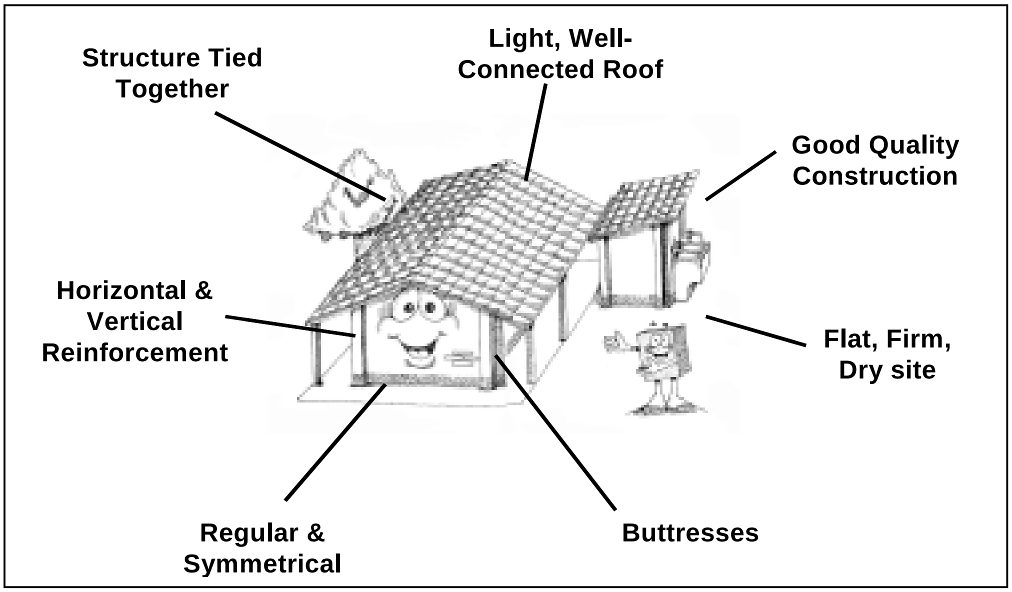


Figure 25 – Guideline For Earthquake-Resistant Adobe Construction (Sketch by Equipo Maíz, 2001; text by Dowling, 2002)

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