INTRODUCTION

The force of earthquakes can cause devastation and destruction to both infrastructure and lifestyle. The housing sector in developing countries is particularly vulnerable due to resource limitations and poor construction quality. Adobe (mudbrick) houses are one of the most severely affected types of building because of their extensive use, general poor quality, and inherently brittle nature. A history of severe earthquakes in El Salvador has exposed the deficiencies in traditional adobe housing, particularly in rural communities. Other devastating earthquakes in Peru, India, Afghanistan, Iran, and México in 2001 and 2002 have confirmed that the loss from earthquakes can be frequent, unpredictable, and global. Despite this key limitation, there is little doubt that adobe will continue to be the chosen construction material for a significant proportion of the population who simply cannot afford any alternative.

The capacity of an adobe house to resist earthquakes is dependent on individual adobe block characteristics, building location and design, and the quality of construction and maintenance. These factors are mutually dependent and should be considered when undertaking an adobe construction project. In recent times there has been an increased emphasis on the seismic improvement of adobe, and research has revealed various methods to improve the seismic resistance of simple adobe dwellings. Despite this ever-expanding body of technical knowledge, there are certain obstacles that are preventing the widespread application of this information. These obstacles relate to deficiencies in the promotion and support of improved adobe, as well as a shortage of skills and resources to facilitate improved construction. A combination of social and technical solutions is required to reduce the vulnerability of adobe structures, and local and international collaboration is necessary to realize these goals.

Adobe housing in El Salvador: Earthquake performance and seismic improvement

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ABSTRACT

Adobe is the predominant housing material in rural El Salvador, due mostly to economic advantages and ease of construction. The high seismicity of El Salvador has repeatedly exposed the vulnerability of traditional adobe housing to the forces of earthquakes, as spectacularly demonstrated in the severe earthquakes of 2001. This paper presents the features of traditional adobe housing in El Salvador, including construction techniques and distribution, followed by a discussion of the performance of adobe buildings in recent earthquakes in El Salvador. The impact of the 2001 earthquakes is demonstrated by statistical data, which also reveal the severe housing deficit in El Salvador. Common damage patterns evident in earthquake-affected adobe buildings are detailed, with emphasis on the failure mechanisms and exacerbation features. These aspects are then linked to a presentation of improved seismic design and construction techniques; seismic retrofitting and damage repair systems for adobe structures are also considered. Finally, the obstacles to reducing damage to adobe houses are presented, and some key recommendations for adobe strengthening in El Salvador are discussed, which involve both social and technical solutions.

Keywords: adobe, housing, El Salvador, earthquake, performance, failure, resistance, mitigation, seismic improvement.

INTRODUCTION

Adobe housing in El Salvador: Earthquake performance and seismic improvement,


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The author of this paper is a Ph.D. candidate who is researching appropriate means of improving the earthquake resistance of adobe dwellings. His focus is on low-cost, low-tech solutions for developing countries and includes static and dynamic testing and analysis of adobe specimens. The author has been involved in various earthquake relief, rehabilitation, research, and reconstruction projects in post-earthquake El Salvador. In early 2002 he undertook an Earthquake Engineering Research Institute-sponsored, Lessons Learned Over Time evaluation of the rehabilitation and reconstruction response to the 2001 El Salvador earthquakes, focusing on adobe housing. In the second half of 2002, the author coordinated the design and construction of an improved adobe child-care center in rural El Salvador, which was a skills-building program in collaboration with the local community, Imperial College, London, and the Catholic Agency for Overseas Development (CAFOD) UK, among others.

ADOBE IN EL SALVADOR

History

Moreira and Rosales (1998) reported that in preconquest times, the indigenous population mainly used light materials, such as palm, straw, and reeds, although there is also evidence of the use of adobe in the region. Colonial constructions generally consisted of stone foundations and thick adobe walls (up to 1.5 m thick), which were reinforced with pilasters and buttresses (external columns that strengthen a wall). Lime was often added to the mud mortar and the walls were rendered. The roofs were built with timber sections covered with tiles. The lack of confidence in the capacity of such structures to resist earthquakes, coupled with the introduction of “modern” construction materials (such as cement, corrugated iron, and brick and stone masonry, followed in recent times by precast concrete, steel, aluminum, plywood, asbestos-cement, and concrete blocks), generated changes in the usage patterns and attitudes toward traditional materials. Despite these changes, adobe is still extensively used in poor rural communities and urban areas outside San Salvador.

Distribution

In 1999, it was estimated that ~1.6 million people (26% of the population) lived in adobe homes, with 70% of these located in rural areas, 26% in urban areas outside San Salvador, and less than 4% in the San Salvador metropolitan area (DIGESTYC, 1999). Table 1 describes the common housing types in El Salvador. Figure 1 shows the housing distribution in El Salvador, considering the whole country, urban areas, and rural areas.

Traditional Adobe Construction in El Salvador

The following generalized aspects relate to the traditional form of adobe construction in El Salvador. Some of the more serious limitations of the current practice are presented, although it should be noted that these shortcomings are not representative of all adobe houses. Some houses feature many deficiencies, whereas others are well built and maintained. Later sections detail practical methods of overcoming some of these limitations.

Land ownership is a key factor influencing the current housing situation in El Salvador. Wisner (2001) suggests that the roots of disaster vulnerability lie in the imbalance of land ownership and the consequent violent struggles that have become a feature of El Salvador’s history. The process of land redistribution, a key part of the 1992 Peace Accords, has been bureaucratic and slow, and as such, a large proportion of families do not possess official land titles. This has created uncertainty, with a general reluctance to commit effort and funds into the adequate construction of a house, when the legal title to the land is in question.

Site selection is linked with land ownership and rarely takes into account local hazards. Most families simply utilize land that is available, and consequently, houses are often built in high-risk areas, which may be subject to flooding, volcanic activity, and slope or soil instability.

Labor is usually family or community based and is normally directed by the family head or someone with experience in construction. Formal training is rarely available, and techniques (both good and bad) are passed on informally.

Adobe blocks are generally made with the locally available soil and may contain unsuitable proportions of sand, silt, and clay, as well as undesirable organic material, large particles, and foreign matter. The mud is often inadequately mixed and placed into molds that are poorly constructed, and the blocks are commonly cured in direct sunlight or exposed to rain. These factors often result in severe cracking, erosion, or deformation of the blocks.

Construction. Crude foundations consist of stones held by a weak cement or mud mortar without reinforcement. Foundations are often shallow and are not raised above the natural ground level, such that the first course of blocks is susceptible to water ingress from the ground and excess rainwater. A moisture-proof course or layer is generally not used. Often, the floor consists of

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
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<tbody>
<tr>
<td>Concrete</td>
<td>For example, concrete block, concrete panel walls, reinforced concrete, etc.</td>
</tr>
<tr>
<td>Mixto</td>
<td>System of confined masonry, consisting of lightly reinforced beams and columns with infill brick masonry.</td>
</tr>
<tr>
<td>Adobe</td>
<td>Sun-dried mudbrick.</td>
</tr>
<tr>
<td>Bahareque</td>
<td>Matrix of vertical and horizontal timber or cane elements confining mud or stones, also known as “wattle-and-daub.”</td>
</tr>
<tr>
<td>Timber</td>
<td>Any type of timber construction.</td>
</tr>
<tr>
<td>Lamina</td>
<td>Metal lamina sheeting, typically corrugated, which is supported by a timber frame.</td>
</tr>
<tr>
<td>Other</td>
<td>For example, plastic sheeting, palm fronds, cardboard, “waste” materials.</td>
</tr>
</tbody>
</table>
Adobe housing in El Salvador

bare earth, which has been compacted and smoothed over time. In other cases, a thin (10–30 mm) concrete layer is applied or tiles are laid. Walls are generally thin (150–250 mm), and mortar joints tend to be thick (>30 mm) and in some cases are thicker than the blocks themselves (Fig. 2). Common features also include unlevel horizontal courses, insufficient horizontal block overlap, and vertical joints running several courses high. Foreign material, such as ceramic, metal, timber, and glass is frequently embedded in the walls, which are often out of plumb. Ring beams (also known as collar-, bond-, or tie-beams), pilasters/buttresses, and reinforcement, either vertical or horizontal, are hardly ever used. The walls may be unprotected or rendered with cement, lime, or mud mortar. The majority of houses are one story high.

The roof structure is normally made from heavy rough-hewn timbers that support a heavy tile covering (Fig. 2). The structure generally rests directly upon the walls, with little or no attachment. The tiles are not normally attached to the frame, or to each other.

Other houses consist of crude timber columns supporting the roof structure, with infill adobe walls (Fig. 3). The walls are seldom attached to the columns and behave as unrestrained cantilever walls, which are highly susceptible to collapse during seismic events. The advantage of this system is that the roof is less prone to collapse if the columns and roof frame have sufficient strength.

Many buildings have been built in stages or repaired using different materials and techniques. Such construction generally lacks continuity, homogeneity, and uniformity. During an earthquake, the response of each component is different, which often causes damage to the adjoining components due to pounding.

Maintenance of adobe buildings is generally poorly done. Many of the buildings that failed during the earthquakes of early 2001 were older buildings that were poorly maintained. The attack of natural agents, such as water, wind, animals, insects, and plants, is often left unattended and reduces the structural integrity of the building (Fig. 4).

Organization and Training

Prior to the earthquakes of 2001, the focus on adobe construction and training programs was limited. Notable exceptions include the activities of a local NGO (nongovernmental organization), Fundacion Salvadoreña de Desarrollo y Vivienda Minima (FUNDASAL), which has been involved in community adobe construction projects since 1979, and the Universidad Centroamericana José Simeón Cañas (UCA), which conducted some training programs with support from institutions from Germany, France, and Peru. Other small-scale initiatives include projects by Alain Hays and Unidad Ecológica Salvadoreña (UNES), among others. The performance of these buildings is discussed later.

Since the earthquakes of 2001, there has been a renewed and concentrated focus on construction projects, training programs, and publications aimed at promoting the principles of improved seismic resistance of adobe buildings. Encouragingly, some over-
seas aid has been provided to support these endeavors (although not on the scale of projects using “modern” materials, such as concrete block). Despite such efforts, the shear magnitude and wide dispersion of need means that many people have been left unsupported and are either living in temporary shelters or rebuilding in the traditional manner because they are unaware of simple techniques that can be adopted to improve seismic resistance.

Throughout this paper, reference is made to the adobe supplement of the El Salvador building code, REESCO (Reglamento para la Seguridad Estructural de las Construcciones). The code itself was published in 1994, and the 1997 supplement provides a set of recommendations for adobe construction. Because of the widespread and unregulated manner of adobe construction in El Salvador, it is understandable that the adobe supplement does not form part of the legal building code of El Salvador.

PERFORMANCE OF ADOBE BUILDINGS IN EARTHQUAKES IN EL SALVADOR

2001

Various estimates as to the extent of damage have been produced by the United Nations (UN) and different departments within the Government of El Salvador (GOES). For this paper, data from the Dirección General de Estadísticas y Censos (DIGESTYC, 1999, 2001), which is part of the GOES Ministry
of the Economy, have been adopted because a correlation can be drawn between official pre-earthquake housing statistics (1999) and official post-earthquake damage statistics (2001) to provide an overall picture of the extent of damage relative to preexisting housing stocks. Analysis of these data sets reveals the following features:

- 20% (276,594) of all houses in El Salvador were affected, consisting of 166,529 (12%) uninhabitable (destroyed) and 110,065 (8%) repairable (damaged).
- 37% of the affected houses were in urban areas and 63% were in rural areas.
- Of the affected houses, 57% (157,070) were made of adobe; of the houses destroyed, 68% (113,469) were made of adobe; and of the houses damaged, 40% (43,601) were made of adobe.
- 8.3% (71,444) of all houses constructed of “modern” materials (concrete and *mixto*) were affected, consisting of 20,432 (2.4%) destroyed and 51,012 (5.9%) damaged.
- 39.5% (205,150) of all houses constructed of “low-cost” materials (adobe, *bahareque*, lamina, and discarded materials) were affected, consisting of 146,097 (28.1%) destroyed and 59,053 (11.4%) damaged.
- 44% (157,070) of all houses constructed of adobe were affected, consisting of 113,469 (32%) destroyed and 43,601 (12%) damaged. The damage percentages for houses of *bahareque* were similar (44% affected: 34% destroyed and 10% damaged), although prior to the earthquakes only 5% of houses were made of this material.

Based on these statistical features, combined with field observations, the following comments can be made:

1. Houses constructed of “low-cost” materials were more vulnerable than those constructed of “modern” materials.
2. Adobe houses were more prone to complete destruction, rather than repairable damage (Fig. 5). This suggests the high susceptibility of traditional adobe houses to sudden and catastrophic failure, thus increasing the risk of fatalities, injury, and loss of possessions. This tendency toward destruction also meant that there was a disproportionately smaller number of damaged adobe houses available for assessment of damage patterns and failure modes.
3. Contrary to widespread local opinion, houses constructed of “modern” materials (concrete and *mixto*) were not “immune” to damage, reaffirming that the type of building material is not the only factor that influences seismic performance.
4. Damage in rural areas was more extensive, reflecting greater use of traditional/low-cost materials, reduced access to resources (materials, tools, technical support), and consequent lower standards of quality.

It should be noted that these statistics cover the whole country and that some departments, such as Morazán, La Unión, and Chalatenango, were practically unaffected, while others, notably Cuscatlán, La Paz, San Vicente, and Usulután were severely affected. In the municipality of San Agustín, Usulután, it was reported that 93.5% of all houses were affected in some way, with 83% of all houses destroyed (DIGESTYC, 2001).

Even prior to the destructive earthquakes of 2001, there was a severe housing deficit in El Salvador. The government housing ministry, the *Vice-Ministerio de Viviendas y Desarrollo Urbano* (VMVDU, 2001), suggested that in 1999 this deficit totaled 554,324 houses and was divided into qualitative and quantitative categories. The quantitative deficit accounts for homes that are deficient in all six of the basic housing requirements (safe/secure walls, safe/secure roof, hygienic floor, adequate sanitation facilities, access to potable water, and access to electricity). In 1999, the quantitative deficit was 42,817. The qualitative deficit accounts for homes that are deficient in up to five of the six basic housing features and was 511,507 in 1999.
VMVDU data suggest that the total post-earthquake housing deficit was 571,250, consisting of a quantitative deficit of 208,136 and a qualitative deficit of 363,114. This implies an overall deficit increase of only 3.1%, suggesting that “adequate” housing was largely unaffected by the earthquakes. As expected, the increase in the quantitative deficit was predominantly due to previously classed qualitative-deficit houses being redesignated as quantitative-deficit houses.

In the aftermath of the earthquakes, many families utilized both a “day house” and a “night house.” The “day house” typically consists of a damaged adobe or bahareque house that has been partially repaired and is used for daytime activities, such as cooking, relaxing, and meeting (Fig. 6). The “night house” is generally made of lamina sheeting that has been constructed as temporary accommodation by the Government of El Salvador (GOES), aid agencies, or the residents themselves (Fig. 7). These shelters have been dubbed hornos (ovens) by the local folk, due to the oppressive internal buildup of heat during the day, and as such, they are only used for sleeping at night. The families are distrustful of the “day houses,” due to the risk of failure in an earthquake, with a greater risk of injury if the occupants are sleeping within.

It is expected that many of the houses that were affected by the 2001 earthquakes were structurally weakened by the 1986 earthquake, as well as other seismic activity in recent years. Bommer et al. (2002) noted the occurrence of a significant seismic swarm in 1999 in the San Vicente area and suggested it was very likely that the damage levels experienced in the area in 2001 were “exacerbated by the damage inflicted during the 1999 swarm.”

1986

The Mw 5.7 earthquake of October 10, 1986, caused severe damage in the San Salvador area. Considerable damage to non-engineered buildings occurred but was largely unreported, due to the more dramatic impacts to engineered buildings, many of which suffered total collapse.

The United Nations Economic Commission for Latin America and the Caribbean (ECLA/CEPAL) estimated that 22,800 dwellings were either totally destroyed or needed to be demolished, and a further 29,800 homes required repair. It was estimated that the earthquake added 40,000 families to the homeless population (Durkin and Hopkins, 1987). It is expected that nonengineered buildings, including adobe, made up a large proportion of these affected houses.

A 1986 reconnaissance team from the Earthquake Engineering Research Institute (EERI), in reference to low-cost housing, stated: “Improving the connection between the rafters and walls, attaching the tiles to the rafters, and ensuring that the roof can function as a diaphragm to transfer lateral wall reactions to shear walls/cross walls are important considerations when using this type of construction” (Anderson, 1987). The same recommendations are being reiterated in the aftermath of the earthquakes of 2001, which indicates the presence of limitations in the transfer of relevant information and/or the capacity of the rural housing sector to take appropriate action. These limitations and various action strategies are discussed later in this paper.

DAMAGE PATTERNS AND FAILURE MODES

This section details the structural response and resultant damage patterns that are commonly observed in traditional adobe housing subjected to earthquakes. A brief description of the damage pattern is given, followed by an analysis of the failure mechanisms that cause the damage and a description of the exacerbation features that increase the structural response and stresses that generate failure.
Vertical Cracking at Corners

**Failure Mechanism**

Large relative displacement between orthogonal walls. Shear walls (subject to in-plane forces) have a low response (displacement). Transverse walls (subject to out-of-plane forces) have little resistance to bending and overturning action, resulting in a larger response. The large relative displacement between shear and transverse walls induces stresses at the connection of the walls (highest stresses at the top). This type of failure is very common because relative response is largest at the wall-wall interface. Cracking occurs when the material strength is exceeded in either shear (Fig. 8) or tearing (Fig. 9). Oblique seismic forces will induce a combination of both shear and tearing stresses (Fig. 10). Vertical corner cracking may lead to the post-failure overturning of the wall panel, as detailed below.

**Exacerbation Features**

1. Large roof mass, which is transferred to the walls. The larger mass generates larger inertial forces, which in turn cause larger response (displacement).
2. Poor block arrangement (block-mortar interfaces are planes of weakness whose seismic resistance is lowered by inadequate overlap, thick mortar joints, and the presence of vertical joints).
3. Thin walls, which have a lower relative area of resistance.
4. Long walls, which attract greater out-of-plane response about the vertical axis due to bending, which induces a splitting-crushing cycle at the corners, thus reducing the shear area.

Vertical Cracking and Overturning of Upper Part of Wall Panel

**Failure Mechanism**

Out-of-plane seismic forces inducing bending about the vertical axis (dominantly) and the horizontal axis. Bending about the vertical axis causes a splitting-crushing cycle generating vertical cracks in the upper part of the wall (Fig. 10). These vertical cracks reduce the resistance to bending about the horizontal axis in the damaged panel, which may result in overturning (Figs. 11 and 12).

**Exacerbation Features**

1. Poor roof anchoring, where roof beams and trusses often rest directly on the wall, creating zones of high stress.
2. Long walls, which attract greater out-of-plane response about the vertical axis due to bending, which induces a splitting-crushing cycle at the corners, thus reducing the shear area.
concentration (exacerbated by large roof mass). Both localized shear (dominant) and localized bending stresses are generated in these zones.

2. Poor block arrangement (inadequate overlap, thick mortar joints, vertical joints).
3. Long, thin, and slender walls, which are more susceptible to bending about the vertical and horizontal axes.

Overturining of Wall Panel

Failure Mechanism
Out-of-plane seismic force acting on a wall panel with lack of edge restraint on three sides (wall-wall corner connection, wall-roof connection). The lack of fixity of the wall-wall connections may be due to vertical cracking at the corners (Figs. 8 and 9) or the presence of timber columns at the corners that are inadequately attached to the walls (Fig. 3). In these cases, the wall-foundation interface behaves as a pin connection, which has little resistance to overturning when an out-of-plane force is applied (Fig. 13). This type of failure is particularly common for long walls without intermediate lateral restraint, such as boundary walls and garden walls. For buildings, the wall panel will generally overturn outward, due to the outward force exerted by the roof in the absence of an adequate roof diaphragm. This type of failure frequently results in the total collapse of the building, as commonly observed in El Salvador in 2001.

Exacerbation Features
1. Same features as for vertical cracking.
2. Poor conditions at the base of the wall, due to moisture damage and/or poor mortar-block bonding, which have little rotational restraint.

Inclined Cracking in Walls

Failure Mechanism
1. Out-of-plane deformation due to bending, causing “bulging,” which generates “X” pattern cracking (Fig. 14). Adequate three- or four-sided restraint is required for this condition.
2. Very large in-plane shear forces, which generate tensile stresses at ~45 degrees, thus causing single-direction inclined cracking, or “X” pattern cracking due to cyclic loading (Fig. 15).

Exacerbation Features
1. Poor block arrangement.
2. Thin walls, which have a smaller shear area and are more susceptible to bending about the vertical axis.
3. Slender walls (large height-thickness ratio), which are more susceptible to bending about the horizontal axis.
4. Long walls, which attract greater out-of-plane response due to bending.

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4. Long walls, which attract greater out-of-plane response due to bending.

Exacerbation Features
1. Same features as for vertical cracking.
2. Poor conditions at the base of the wall, due to moisture damage and/or poor mortar-block bonding, which have little rotational restraint.
5. Openings (doors and windows), which induce high stress concentrations, as well as reducing the effective area of the walls. The wall panel between openings acts as a slender column and as such is subject to greater shear stresses, as well as greater compressive stresses due to the weight of the wall above. The influence of openings is further exacerbated when they are located close to other zones of high stress concentration, such as corners and other openings (Figs. 12 and 15).

Dislocation of Corner

Failure Mechanism

Initial failure is due to vertical corner cracking induced by shear or tearing stresses, as described above. The lack of fixity at the corners allows greater out-of-plane displacement of the wall panels, which generates a pounding impact with the orthogonal wall. The top of the wall has a greater response, which causes a greater pounding impact, thus inducing greater stresses that lead to failure (Figs. 10 and 16). An oblique seismic force will cause both orthogonal walls to respond, and the pounding impact will be greater.

Figure 14. Inclined cracking in wall due to “bulging.”

Figure 15. Inclined cracking in wall due to in-plane shear.

Figure 16. Sequence leading to corner dislocation.
**Exacerbation Features**
1. Same features as for vertical corner cracking.
2. High stress concentrations due to poor roof anchoring and lack of uniform distribution of roof loads.

**Horizontal Cracking in Upper Section of Wall Panel**

*Failure Mechanism*
Out-of-plane or in-plane shear failure, which generally occurs when there is a ring beam or the roof is securely attached to the top of the wall. A seismic force creates a relative difference in lateral movement between the wall and roof, which induces high shear stresses leading to shear cracking when the shear resistance is exceeded (Fig. 17).

*Exacerbation Features*
1. Lack of adequate fixity of ring beam to wall.
2. Poorly anchored roof structure, which creates zones of high stress concentration.
3. Poor mortar-block bonding, creating a horizontal plane of weakness. The resistance to shear due to friction is greatly reduced at the top of the wall because there is less applied weight force.

**Displacement of Roof Structure**

*Failure Mechanism*
Relative displacement between different components of the roof structure and the walls. The worst-case scenario of this type of failure is the total collapse of the roof structure.

*Exacerbation Features*
1. Inadequate three-dimensional roof diaphragm, with a lack of triangulation and diagonal bracing.
2. Poor connection to walls and between different roof components. In many cases, the only connection between roof components is provided by nails, which only provide limited resistance to shear.
3. Heavy roof mass, which attracts greater seismic force due to inertia.

**Falling Roof Tiles**

*Failure Mechanism*
1. No attachment between tiles and roof structure. The roof tiles are simply held by friction, which is easily overcome during seismic events, resulting in the roof tiles sliding off the roof.
2. The failure of purlins, which support the tiles, resulting in tiles falling inside the building.

*Exacerbation Features*
1. Deteriorated purlins, which easily fail when an additional force is applied.

**Linking Simplified Analysis to Improved Design and Construction**

It should be stressed that in the above assessments the seismic force is generally considered as acting in a single plane. This should not alter an appreciation that during a seismic event any given wall in a particular structure will act as both a transverse wall and a shear wall, being subjected to components of both in-plane and out-of-plane forces (in alternately opposite directions). A wall will influence and be influenced by other structural members and experience bending, tensile, compressive, shear, and tearing stresses. The resulting loads and stress conditions are a complex blend of these factors, and combinations of the above damage patterns are common. Despite this limitation, assessment of simplified scenarios allows a greater understanding of the performance and response of structural elements, which supports the development of concepts of improved seismic design and construction.

**IMPROVED SEISMIC DESIGN AND CONSTRUCTION OF ADOBE BUILDINGS**

*Design Concepts*

There are many design concepts that can greatly improve the seismic resistance of a building. Some of these design concepts are simple and inexpensive, while others are more complex and resource-dependent. The design concepts discussed below have been divided into separate structural components and configurations for ease and clarity. This should not alter the appreciation that a structure will behave as an integrated unit under earthquake loading. In order to take full advantage of this integration, the structure must be securely tied together, thus promoting redundancy. Furthermore, a focus on improved seismic design should not diminish the importance of other design factors, such as design for wind loading.

It should be remembered that earthquakes are unpredictable, variable, and dynamic in nature. The recommendations below do not guarantee that an improved building will be unaffected by an earthquake. It is hoped that the use of these suggestions will, at the
very least, reduce the loss of life during seismic events, and hopefully minimize the damage and destruction to common housing.

Site Conditions

The main consideration when choosing a site for construction is the stability of the ground. This takes the form of slope stability and soil stability. Sloping ground is highly susceptible to slipping or sliding during earthquakes, and it is recommended that buildings not be built on or near excessively sloping ground.

Certain soils exhibit unstable characteristics when shaken or wetted, as occurs during an earthquake. Settlement, compaction, loss of shear resistance, and liquefaction are some of the unstable results of ground movement and inundation. The soils that are most vulnerable to such instability are fill materials, very loose sands, and volcanic ash deposits. The predominance of the volcanic ash tierra blanca in El Salvador has been linked to the large number of landslides that occurred during the 2001 earthquakes (Bommer et al., 2002).

The ideal site is flat, firm, and dry, with good drainage. For the majority of the rural poor, however, access to such ideal sites is limited because land is expensive and terrain is variable. This is particularly the case in El Salvador, where “the roots of the civil war were in land ownership conflicts” (J. Bommer, 2003, personal commun.). Various remediation measures, such as leveling, drainage, stabilization, and revegetation, are available, which may improve site conditions.

Foundations

Foundations are key elements of a building, which serve to evenly distribute the wall load on the ground, thus minimizing zones of high stress concentration. If the foundation fails, then the superstructure will almost inevitably fail also. It is recommended that some form of continuous horizontal reinforcement (e.g., steel bar, bamboo) be included in the foundations, which will provide resistance to the bending, tensile, and shear stresses that are generated during a seismic event. Obviously, the addition of reinforcement will increase the cost and complexity of the construction, although it is suggested that even simple reinforcement will provide significant benefits. Figure 18 shows the foundation configuration as outlined in the RESESCO (1997) adobe supplement.

The plinth is a concrete “top foundation,” which elevates the adobe wall above the ground, thus reducing potential moisture damage.

Adobe Soil

Various investigations and regulations recommend that a certain mix of the components of the soil (sand, silt, and clay) will improve the structural integrity of the adobe blocks, although there is no universal agreement as to the most appropriate mix. The volcanic ash tierra blanca is widely used in adobe block fabrication in El Salvador, and it has been suggested that it possesses pozzolanic properties (P. Meyer, 2002, personal commun.). Table 2 is a compilation of soil mix proportions recommended by various sources.

Despite these recommendations, it should be noted that the average rural homebuilder will generally not have access to various soil types or to accurate means of testing the soil. The most effective manner of assessing the suitability of the soil is to make several trial bricks (using combinations of the available soils) and cure these under different conditions (direct sun, shade, with additives, etc.). It is suggested that at the end of the curing period blocks should “be able to be handled without crumbling or being easily damaged; and not have developed any crack longer than 75 mm and wider than 3 mm or deeper, irrespective of length or width, than 10 mm” (Middleton, 1987).

Adobe Block Dimensions

There is no firm agreement relating to the ideal dimensions of adobe blocks, although several factors should be considered,

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<tbody>
<tr>
<td>Sand</td>
<td>55–75%</td>
<td>55–70%</td>
<td>50–70%</td>
<td>40%</td>
</tr>
<tr>
<td>Silt</td>
<td>10–28%</td>
<td>15–25%</td>
<td>5–20%</td>
<td>40%</td>
</tr>
<tr>
<td>Clay</td>
<td>15–18%</td>
<td>10–20%</td>
<td>15–30%</td>
<td>20%</td>
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</table>
including wall thickness, horizontal overlapping, block weight, and provision for reinforcement. In general, a larger block is recommended, although this will be limited by a manageable block weight. A 300 × 300 × 100 mm block will weigh ~15 kg. Larger blocks will be more difficult to handle.

Wall Dimensions

General recommendations for acceptable wall dimensions include:

1. Long walls without intermediate support should be avoided. The RESESCO (1997) adobe supplement recommends that the length of unsupported wall should be less than ten (10) times the thickness of the wall. IAEE (1986) recommends that the length of unsupported wall “should not be greater than 10 times the wall thickness t or greater than $64t^2/h$ where $h$ is the height of the wall.” If longer walls are desired, they should be restrained by intermediate vertical walls or pilasters, as shown in Figure 19.

2. The height of a wall should be less than eight (8) times its thickness (IAEE, 1986; RESESCO, 1997; Minke, 2000).

3. Thicker walls are more resistant to seismic loading, although they attract greater seismic force. Thicker walls also require more materials and greater labor energy to construct.

The above suggestions relating to suitable wall dimensions are assumed to refer to traditional, unreinforced adobe walls, which do not employ improved seismic resistance systems (e.g., reinforcement, ring beam, pilasters, roof diaphragm, etc.). The provision of improvement systems is expected to alter these recommendations, although further research is required to ascertain the degree of such changes.

Mortar Joints

Mortar-block interfaces are planes of weakness in an adobe wall. Effective mortar bonding between blocks increases the shear resistance and can be achieved by:

1. Selecting a suitable mortar (ideally the same as the soil used for the bricks). Mortars with high clay contents are subject to excessive shrinkage, which causes mortar cracking.

2. Roughening the bonding surfaces of blocks prior to laying (increases the friction coefficient of the blocks).

3. Wetting the blocks prior to laying (promotes better adhesion of mortar).

4. Maintaining a mortar thickness of between 15 and 25 mm (RESESCO, 1997).

There should be sufficient horizontal overlap of bricks and continuous vertical joints should be avoided, as these provide very little resistance to shear and bending stresses. This is particularly important at the intersection of orthogonal walls, where high stress concentrations exist.

Reinforcement

Horizontal and vertical reinforcement may take the form of any ductile material, including bamboo, reeds, cane, vines, bur- lap, rope, timber, chicken wire mesh, welded mesh, barbed wire, and steel bars. A local cane, *vara de castilla* (*Gynerium sagittatum*, Hays, 2001) is widely used in the construction of *bahareque* houses and has been used as internal vertical and horizontal reinforcement in improved adobe construction projects in El Salvador. The durability, availability, and expense of each material should be considered when selecting the most effective material within resource constraints. As described above, a complex array of responses and stresses are generated in a structure subject to seismic forces, and the specific location and structural properties of the reinforcement should be carefully considered. The shear, tensile, and bending capacity of the mortar-reinforcement interface is an important factor in the structural performance of the system, and this aspect requires greater research. All reinforcement should be securely tied together and to the other structural elements (foundations, ring beam, roof). This attachment provides a stable matrix, which is inherently stronger than the individual components.

Table 3 provides a generalized assessment of the benefits of key improvement systems (ring beam, reinforcement, and pilasters) in reducing the common damage in adobe housing, as described above. This assessment assumes ideal integrity of the systems, particularly the connections.

Internal (within the wall) vertical reinforcement transfers lateral forces to the ring beam and the foundation beam, thus restraining in-plane and out-of-plane shear (in a doweling action), as well as providing restraint to out-of-plane response due to bending. Internal vertical reinforcement provides a moderate to high contribution in the mitigation of vertical corner cracking, overturning of wall panels, inclined cracking, corner dislocation,
and horizontal cracking (Table 3). Internal vertical reinforcement is protected from exposure to the environment, but is difficult to place and align, as well as requiring blocks with voids that need to be specifically made and positioned (Fig. 19).

Horizontal reinforcement helps to transmit the bending and inertia forces in transverse walls to the orthogonal shear walls, as well as increasing the shear resistance capacity at the wall-wall interface and minimizing vertical crack propagation. In the case of out-of-plane shear forces causing corner cracking (Fig. 8), the shear stress concentration is generally largest at the mid-thickness of the wall (and negligible at the face), so internal reinforcement is more effective at minimizing crack formation than external reinforcement. In the case of in-plane shear forces causing inclined cracking in wall panels (Fig. 15), the shear forces are uniformly distributed across the wall thickness, and therefore wide reinforcement (such as mesh or burlap) would be more effective than thin reinforcement (such as barbed wire). Table 3 shows the contribution of internal horizontal reinforcement in the mitigation of common damage patterns. Internal horizontal reinforcement is easy to position along horizontal mortar joints.

External (outside the wall) mesh reinforcement provides restraint to the out-of-plane forces due to bending about both vertical and horizontal axes. A strong mesh and an effective connection to the wall are critical in achieving restraint. Connectors must have sufficient tensile, shear, and axial capacity (for both inward and outward motion). Ties attached to internal vertical reinforcement or external mesh (on the other side of the wall) would provide adequate fixity. Nails and staples are less effective connectors (due to a lack of axial resistance and minimal shear capacity due to poor interaction with adobe).

External mesh reinforcement also provides some restraint to in-plane shear forces. The horizontal component of the external mesh binds orthogonal walls, thus providing some resistance to the vertical cracking induced by shear and tensile stresses at the corners. It also provides resistance to overturning and corner dislocation after the formation of vertical cracks, as well as restraining the response due to shear and bending stresses that cause inclined cracking (Table 3). The vertical component of the external mesh serves to maintain the form of the mesh, as well as acting to restrain the shear and bending stresses that generate inclined and horizontal cracking (Table 3). External reinforcement is easy to place, but is vulnerable to deterioration due to exposure to the environment.

### Pilasters

Pilasters can be positioned at critical parts of a structure to increase stability and stress resistance. A pilaster is a projection from a wall, which is interconnected by masonry bonding such that both components respond as a single unit during seismic events (Fig. 19). The term “buttress” is also often used to describe this type of element, although technically speaking, buttresses are not connected to the wall and act independently when subject to seismic forces (Roselund,
Pilasters are counter supports that act to restrain out-of-plane response, and are most effective at intermediate locations in long walls. Intermediate pilasters offer resistance to the formation of common damage patterns, such as vertical cracking, overturning, and bulging (Table 3). Corner pilasters provide some resistance to the out-of-plane response that generates tearing stresses in the corners. Corner pilasters, however, do not offer restraint to the shear stresses that form vertical corner cracks because the critical section remains in the same location and has the same contact area. In this case, the pilasters may actually attract greater seismic force due to the increased mass at the corners.

Several organizations in El Salvador are building improved adobe houses with pilasters, with the depth of the pilasters varying from 160 to 420 mm. Deeper pilasters provide greater restraint but are more costly and attract greater seismic force. Further research is required to determine optimal pilaster size and ideal pilaster location.

The inclusion of pilasters requires a considerable amount of additional skill, labor, and expense in the preparation and construction of foundations, plinths, pilasters, and roof system. The inclusion of 300 mm deep pilasters on a 6 m by 8 m building with 600 mm roof overhang results in an increase of 20% in the plan area of the roof, and various elements of the roof structure must be designed and built to adequately support cantilever actions of up to one meter to provide this overhang. This represents a significant increase in resource requirements. The additional skills, labor, and expense associated with using pilasters should be balanced with the structural benefits provided, and should be the subject of further research.

**Openings**

Openings are locations of high stress concentration and reduce the effective area of a wall. The RESESCO (1997) adobe supplement suggests several design concepts that will reduce the risk of failure, as shown in Figure 20.

External diagonal reinforcement around the corners of openings would also provide restraint to the stresses that induce cracking from these locations of high stress concentration. This diagonal reinforcement should be firmly attached to the walls in a similar fashion to external wire mesh, as described above.

**Ring Beam**

A ring beam (also known as a collar-, bond-, or tie-beam) is a continuous horizontal beam that encircles a building (Fig. 21). In the case of single-story buildings, a ring beam should be located at the top of the wall to form part of both the wall and roof structures. The ring beam allows a more uniform distribution of the roof load onto the walls, thus minimizing zones of high stress concentration. The ring beam also provides fixity for vertical reinforcement and transfers forces from vulnerable transverse walls to stiffer shear walls, thus restraining...
out-of-plane response. The ring beam is a very effective seismic resistance system, which significantly contributes to the mitigation of vertical corner cracking, overturning of wall panels, and corner dislocation (Table 3).

The ring beam should exhibit good tensile and shear strength (e.g., reinforced concrete, reinforced soil-cement, timber) and should be continuous. A soil-cement beam with bamboo or vará de castilla reinforcing is often used as a low-cost alternative. The effectiveness of the ring beam depends on the wall–ring beam and ring beam–roof connections. Connections must have the capacity to withstand strong shear, tensile, and bending stresses induced by seismic and wind forces. A strong connection between the ring beam and the wall can be achieved by attachment to vertical reinforcement, which provides restraint to shear stresses, combined with strapping, which utilizes the large wall mass to restrain uplift of the roof due to wind loading. Strapping can take the form of steel straps or heavy-gauge wire or nylon.

**Roofing**

The two main parts of the roof are the structure (trusses, beams, rafters, purlins, braces) and the covering (sheeting, tiles, natural material). If a reinforced concrete or soil-cement ring beam is used, an effective connection between the roof structure and ring beam can be achieved by placing a longitudinal timber beam atop the ring beam and attaching it to the ring beam and wall using strapping. A securely attached and strong roof diaphragm will transfer seismic forces to orthogonal walls, thus reducing the relative displacement between the walls and the roof structure. Diagonal bracing provides significant additional restraint to torsional response. Roof structure connections should adequately resist shear, tensile, and bending stresses. For many connections, nails do not provide sufficient restraint, so strapping or bolts should be used. Where possible, roof beams and rafters should not be positioned above openings, as this increases the bending stresses in the wall panel above the opening. If this is unavoidable, the lintels should be reinforced.

A lighter roof will attract less seismic force, although it is subject to greater response during wind loading. Corrugated iron sheets are light, relatively cheap, and widely available, although they are less heat resistive than traditional tile roof covers. Iron roof sheeting can be covered by natural materials, such as grasses or palm fronds, to improve the thermal properties. More expensive, lightweight roofing materials are also available, including steel sheeting with a zinc-aluminum coating, fibercement sheeting, fiberglass sheeting, and microcement tiles. A light roof cover also allows resource savings in the roof structure, which supports a smaller roof mass.

**Building Configuration**

The above considerations relate to the individual components of a structure. These considerations should also be viewed in the broader context of total building design. The following recommendations relate to overall building configuration:

1. Buildings should be regular and symmetrical. Simple regular shapes (e.g., rectangles) will perform better than shapes with many projections. Asymmetry will promote detrimental torsional stresses in a building. Symmetry in each axis, as well as in openings (size and location) will reduce the effects of torsion (IAEE, 1986; Equipo Maíz, 2001).

2. Building height should be restricted to one floor (plus attic) in earthquake zones (IAEE, 1986; Norton, 1986; Equipo Maíz, 2001).

3. The length of a building should be no greater than three times the width (Norton, 1986).

**Erosion and Moisture Control**

The structural integrity of an adobe building is severely reduced if erosion and moisture damage are not controlled. Some of the recommendations to control erosion and moisture include:

1. Provision of adequate drainage that allows water to be cleared from the vicinity of the wall.

2. Construction of a plinth, or “top foundation,” which raises the adobe wall from the ground (Fig. 18). The plinth may be constructed of stabilized blocks or concrete and should be raised at least 200 mm above the ground level. A moisture-proof course (e.g., plastic sheeting) should be laid between the plinth and adobe wall to prevent water penetration due to capillary action.

3. An overhanging roof means that the area of wall susceptible to direct wetting by rain is reduced. An overhanging roof does, however, increase the complexity and expense of the roof construction.

4. Application of a protective coating is the most economical and practical way to reduce the vulnerability of superstructure walls. Woodward (1996) suggests that impervious membranes should be avoided. He argues that impervious membranes crack and deteriorate over time, which allows the penetration of water that is not easily evaporated. Woodward suggests that a combination of linseed oil and mineral turpentine performs particularly well. The linseed oil–turpentine mix is a clear finish, so the natural appearance of the adobe is demonstrated. Mineral turpentine is widely available in El Salvador, whereas linseed oil is difficult to obtain outside San Salvador. A simple, but valuable, research investigation would be to assess the use and effectiveness of locally available oils (e.g., corn oil, cotton seed oil) as a protective coating.

Because adobe is often associated with poverty and “cheap” housing, local homeowners would generally prefer to have a “non-adobe-looking house.” Rendering of the walls not only provides protection and durability, but it also improves the appearance and increases the impression of “solidity” of the structure. Common renders are made using various combinations of the following materials: soil, cement, sand, lime, bitumen, straw, cow dung, and cactus “glue.”

5. Use of stabilizers. Addition of stabilizing agents (such as cement, lime, asphalt emulsion, organic or chemical compounds)
is designed to improve the resistive capacity of a block. Improvements in the soil cohesion result in increased durability and may also increase compressive, tensile, and shear strengths. The use of stabilizers, however, should be undertaken with caution. Stabilizers increase the costs of production, and each stabilizer responds uniquely to different soil components and proportions and requires specific preparation and curing conditions. For this reason, it is important that tests be carried out to determine the correct procedure and quantities to be used. The fabrication of trial blocks is highly recommended to ensure satisfactory results.

Examples of Improved Adobe Construction in El Salvador

The effectiveness of improved adobe construction has been demonstrated by the performance of several improved adobe buildings that were constructed prior to the 2001 earthquakes. These include:

1. Three hundred houses constructed around the country since 1977 by the Salvadoran NGO FUNDASAL, which have “passed the test of two earthquakes” (Moreno et al., 2001).

2. A series of houses constructed in 1994 in San Francisco de Ayutuxtepeque, San Salvador, and a house constructed in 1994 in San Juan de Letrán, Usulután, under the coordination of Alain Hays, which suffered no significant damage (Hays, 2001).

3. A community hall constructed in 1997 in San José de La Ceiba, San Vicente, by FUNDASAL, which suffered some minor cracking that has been repaired.

4. A small house constructed in 1999 in La Palomera, Santa Ana, by the Salvadoran NGO Unidad Ecológica Salvadoreña (UNES), which suffered no damage (Fig. 22).

These buildings exhibited excellent performance during the earthquakes, despite the damage and destruction of nearby houses made of mixto, traditional adobe, and bahareque. It is, however, difficult to provide a strong statistical confirmation of the success of improved adobe based on a relatively small sample size (due to the scarcity of such buildings prior to the earthquakes of 2001). Nevertheless, such examples indicate that improvement is possible, and they have also proved to be extremely valuable tools in the promotion of improved adobe to a generally skeptical population.

SEISMIC RETROFITTING AND DAMAGE REPAIR OF ADOBE STRUCTURES

Seismic retrofitting can be undertaken on adobe buildings to reduce the likelihood of damage due to future earthquake events. Many retrofitting systems are also suitable for the repair of damaged adobe buildings. The option to repair a damaged building is often overlooked, as minor cracking is often perceived as serious damage, and such buildings are commonly abandoned or demolished. In other cases, minor damage is ignored, which increases the risk of collapse during future seismic events. There are widespread needs and opportunities for programs aimed at training in seismic retrofitting and damage repair in El Salvador. Current institution-supported adobe projects tend to focus on new construction rather than rehabilitation and improvement of existing dwellings.

In each retrofit or repair case, the connection between the existing structure and the supplementary system is extremely important. If the connection does not adequately resist the imposed shear, tensile, and bending stresses, then the system will be less effective. The systems described below attempt to address the common structural deficiencies of traditional or damaged adobe houses, as described earlier.

Chicken Wire Mesh or Welded Mesh

Mesh is placed over the entire wall or in 45 cm wide horizontal and vertical strips at the corners and upper part of each wall, simulating beams and columns. Experiments undertaken by the Pontificia Universidad Católica del Perú (Zegarra et al., 2000) and Centro Nacional de Prevencion de Desastres (CENAPRED), México (Flores et al., 2001), have revealed this to be a very effective method of reducing the damage to adobe specimens. They report that the mesh is held with bottle tops and nails that are attached to the wall at 250–300 mm spacings and then covered with render.

The mesh provides restraint to out-of-plane response due to bending that generates vertical, horizontal, and inclined cracking, as well as overturning of wall panels. The mesh also provides restraint to in-plane shear cracking. Unless the mesh is connected to the foundations, it is unlikely to provide base restraint to overturning, although the restraint at the corners should minimize this overturning motion. It is recommended that some form of through-wall cross tie that resists tensile and shear stresses be used, because nails and staples have little resistance to out-of-plane movement. There is also some concern that the use of nails and staples may cause local cracking in the adobe. These aspects should be subjects of further research.

Figure 22. Undamaged adobe house, Santa Ana, El Salvador, 2002 (UNES project).
Adobe housing in El Salvador

Strapping

Shake table testing undertaken at Stanford University, California, and University SS Cyril and Methodius, Republic of Macedonia, revealed that the addition of vertical and horizontal straps “reduced the amount of severe damage and dramatically decreased the risk of collapse” (Tolles et al., 2000). In these experiments, nylon straps were looped horizontally and vertically around the building and walls and securely connected by ductile cross ties that passed through holes drilled in the walls. Wire mesh was placed under the straps at the corners to reduce local stress concentrations. The mechanisms of restraint are similar to those for external wire mesh, described above. It is expected that other ductile materials, such as wire, steel strapping, or rope, would also be effective in this system, provided that adequate tension in the material can be maintained and local failure of the adobe at the connections is restricted.

Rope

Rope is placed in a horizontal channel formed in the wall, tightened, and then rendered. Zegarra et al. (2000) report that this system performs better than unreinforced specimens under earthquake simulations but is not as effective as the application of mesh as described above. The rope loop provides restraint to overturning due to out-of-plane seismic forces and may also provide some restraint to the tearing stresses that induce vertical corner cracking.

Buttresses

Buttresses can be built adjacent to walls to restrain out-of-plane motion. Unattached buttresses will provide limited restraint to motion toward the buttress only, although the presence of an adequate roof diaphragm will restrain motion away from the buttress. If the buttress can be securely attached to the wall, using cross ties, then greater restraint can be achieved for motion both toward and away from the buttress.

Ring Beam

A ring beam can be added to a building, although the roof will need to be removed to undertake this process. The ring beam should be securely attached to the walls, which can be achieved using external strapping and/or inserting dowels into the walls. In all cases, great care must be taken to prevent damage to the adobe wall during this process. The mechanisms of restraint achieved by ring beams are detailed above.

Other Systems

Other retrofit and repair systems include the insertion of fiberglass or steel center-core rods, which are epoxy-grouted in place (Tolles et al., 2000), and injection of cracks with a mix of soil, cement, expansive additive, and synthetic adhesive emulsion, which is under development at the Universidad Centroamericana José Simeón Cañas (R. Castellanos, 2002, personal commun.). Despite these advanced systems being more complex and expensive, they are regarded as being an important alternative in the conservation of historical and culturally significant adobe buildings. It is hoped that this technology can be applied to common housing in the future.

OBSTACLES TO REDUCING DAMAGE TO ADOBE HOUSES

Key obstacles to the reduction of earthquake damage to adobe houses include:

1. Lack of confidence in adobe as a construction material.
2. Lack of widespread promotion and support of improved adobe, due to limited resources, traditional attitudes, and vast populations.
3. Lack of experience and skill in seismically resistant design and construction.
4. Lack of personal financial resources, which restrict skills development and the use of better materials and techniques.

Recommendations to overcome these obstacles are discussed below.

RECOMMENDATIONS FOR ADOBE STRENGTHENING IN EL SALVADOR

A combination of social and technical solutions is required to improve the current housing situation in El Salvador and other developing countries. The key components are research and development, and implementation. The implementation component consists of three interconnected elements; namely, promotion, skills, and resources.

Promotion

General promotion is first required to demonstrate the existence and effectiveness of improved adobe construction techniques to local communities, government institutions, and nongovernmental organizations. In local communities, visual presentations tend to be more effective and should include examples of the seismic performance of improved adobe houses, as well as general aspects of improved seismic design and construction. Where possible, interested community members could be invited to visit nearby examples of improved adobe housing, thus providing a tangible demonstration of the improved system. Effective promotion increases the interest, awareness, and acceptance of improved adobe, which are prerequisites for any skills-building training and community construction projects.

Skills

“Skills” relates to both skills building and provision of adequately skilled personnel to support improved construction.
Skill building involves the training of interested and capable people in techniques of improved adobe construction, considering both theoretical and practical components. In order to thoroughly cover all aspects of the design and construction process, the most effective training program involves the construction of a complete building (Fig. 23). This process requires a significant period of time (upwards of two or three months) and, as such, requires the full commitment and interest of all stakeholders. The program should be organized such that participants are not unduly burdened by the lengthy process, with options for worksite rotation rosters and payment (cash or food) for work. Naturally, the initial assessment of the project and community should include such discussion and should focus on the needs, interests, and availability of the participants. The training program should be complemented by a workbook or construction manual that details each step of the preparation and construction process.

Current improved adobe techniques have placed adobe construction in the domain of skilled artisans. It is unlikely that local people with little or no construction experience or skill will be capable of applying the full range of improvement suggestions in the construction of their homes, even after participation in a skills-building project. Nevertheless, it is hoped that some of the simpler techniques will be adopted by unskilled owner-builders, and at the very least there will be a greater awareness that improved adobe houses can be constructed. The real benefit of the training programs lies in the improved capacity of local artisans to construct safer adobe homes.

Skilled personnel are required to coordinate adobe promotion activities, facilitate training programs, and provide post-training support for community construction. Skilled personnel are also sought for large-scale improved adobe construction projects, such as those implemented in the aftermath of the 2001 earthquakes, including those by Asociación Salvadoreña de Desarrollo Integral (ASDI), Asociación Bálsamo, Atlas Logistique, FUNDASAL, Trocaire, and Unidad Ecológica Salvadoreña (UNES), among others. Improved adobe is increasingly being seen as a viable and appropriate alternative for agency-coordinated housing projects, which have tended to focus on concrete block construction.

Research and Development

The research and development component involves the improvement of the current state of technical knowledge, while maintaining strong social links to ensure the investigation of appropriate solutions. Further research is required to improve the statistical depth of knowledge, leading to greater confidence in analysis and design. Research may focus on individual adobe blocks (soil composition, additives, mechanical properties, etc.), adobe masonry components (block-mortar bonding, reinforcement-block interaction, mechanical properties, etc.), and complete building response (wall length-width-height ratios, pilasters, reinforcement, ring beams, connections, computer modeling, etc.). Research and development also relates to the social aspects of implementation, such that lessons are learned and effective programs are developed, thus increasing the capacity of affected communities to respond appropriately.

There is great value in research undertaken in El Salvador that assesses the performance of local materials and building techniques. The relative lack of testing facilities in El Salvador, particularly a shake table, is seen as a key obstacle to further research in-country. It is expected that key findings from research conducted around the world will increase the profile of improved adobe and the confidence in its use, both in El Salvador and in other countries where adobe is commonly used.

Research findings combined with active promotion are required to increase the acceptance of improved adobe by local and international agencies. Government support for adobe in El Salvador is still tentative, and in a global context funding for development projects is extremely competitive. If the advantages of adobe can be shown in some quantifiable measure, then support for improved adobe is expected to increase.
CONCLUSIONS

Adobe (mudbrick) is one of the most widely used construction materials in the world. Two factors are responsible for the predominant use of adobe in El Salvador and other developing countries. These are (1) low cost, and (2) minimal specialist skills required for traditional adobe construction. Other advantages of adobe include durability, energy efficiency, ecological sustainability, and thermal capacity. The main disadvantages of adobe include longer fabrication and construction time, susceptibility to water damage, “poor” image, and vulnerability to damage by earthquakes. This final feature has been tragically observed in earthquake-prone areas around the world, particularly El Salvador.

The vulnerability of adobe buildings to damage from earthquakes and an assessment of damage patterns and failure modes have led to various recommendations for improved seismic resistance. A number of low-tech and low-cost amendments can be made to existing construction practices to improve the seismic resistance of an adobe structure. These include tying the structure together, use of vertical and horizontal reinforcement, inclusion of pilasters, and construction of wide walls with good horizontal overlap of bricks. Other factors relate to foundations, floors, walls, openings, ring beams, roofing, building configuration, erosion and moisture control, and construction and maintenance quality. There is large scope for further research in this field.

There are several challenges associated with the introduction of change to traditional building practices. These challenges focus on overcoming resource limitations and the lack of awareness, experience, and skill in improved seismic design and construction. Any solution must incorporate both social and technical aspects and requires the involvement of local, national, and international institutions to promote and support improved adobe design and construction systems. Advances in the development and application of improved adobe are essential to reduce the vulnerability of common housing to the effects of earthquakes. El Salvador has both the need and the opportunity to lead this advance.

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