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IMPROVED ADOBE MUDBRICK IN APPLICATION – CHILD-CARE CENTRE CONSTRUCTION IN EL SALVADOR

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SUMMARY

Major earthquakes in Latin America, Asia and The Middle East have served as recent reminders of the vulnerability of traditional adobe (mudbrick) dwellings to the force of earthquakes. A host of research, training and construction projects continue to address this precarious situation and there have been various publications describing the developments in improved adobe (mudbrick) design and construction in recent years. These publications have mostly originated from research institutions and have tended to focus on the technical and experimental details of a variety of improvement systems. The dissemination of this important information is a vital component in the challenge to promote and build safer homes. Furthermore, these advances in technical detail must be accompanied by practical information, which relates to the actual application of the proposed systems, addressing the advantages and disadvantages of each technique. This paper attempts to address the current deficiency of this practical information, and thus provide adobe constructors and proponents with a realistic understanding of some of the practical issues related to improved adobe construction. This paper describes the technical and practical aspects and 'lessons learned' from a recent improved adobe construction project in El Salvador, as well as drawing on field investigations, laboratory research and other literature. The paper concludes with a proposed addition to the current technical evaluation of the performance of improvement systems: the assessment of the skill level and resources required to effectively incorporate improved adobe systems. This additional information will be of particular interest and value to supporters of improved adobe projects, such that training and construction activities may be tailored to meet the skill and resource capacities of the organization and beneficiary groups involved.

BACKGROUND

Two major earthquakes rocked the small Central American country of El Salvador in early 2001. The two quakes (registering Mw 7.7 and Mw 6.6) devastated the social and physical infrastructure of the small nation. The earthquakes claimed almost 1,200 lives and affected over 1.6 million people (UNDP [1]). The housing sector was particularly hard-hit, with over 166,000 houses destroyed and 110,000 houses damaged (DIGESTYC [2]). In some regions, up to 85% of the houses were destroyed. The vulnerability of traditional adobe (mudbrick) houses was clearly demonstrated (Figure 1), with 113,000 adobe houses destroyed and 43,000 adobe houses damaged (DIGESTYC [2]). Overall, 44% of the pre-earthquake

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adobe housing stock was affected (damaged + destroyed), and adobe houses accounted for 57% of the total affected houses (DIGESTYC [2, 3]). (For a detailed account of earthquake damages and reconstruction activities with specific reference to adobe housing in El Salvador, see Dowling [4])

Figure 1. Destroyed adobe houses, El Salvador (López [5])

There are two main reasons why adobe houses performed so poorly in the earthquakes. Firstly, adobe is a low-strength, brittle material, which yields under much lower stresses than ‘modern’ materials, such as steel, concrete and conventional masonry. Secondly, traditional adobe houses are often poorly constructed and/or maintained due mainly to resource and skill limitations. These features mean that, in general, adobe structures are more vulnerable to damage during seismic events.

Despite this inherent vulnerability, there is little doubt that adobe houses will continue to be widely used, especially in poor rural communities where no feasible alternatives exist. This aspect highlights the need to reduce the level of vulnerability of adobe housing, which can most practically be achieved by improving the quality of design, construction and maintenance of common adobe dwellings.

IMPROVED ADOBE DESIGN AND CONSTRUCTION

There are a host of useful and detailed publications which describe various systems for safer adobe design and construction (e.g. IAEE [6], Equipo Maiz [7], Blondet *et al.* [8], Flores, *et al.* [9], Minke [10] and Pérez [11]). One approach has been to consider the specific damage patterns and failure mechanisms evident in damaged adobe buildings, and to then evaluate the contribution of different improvement systems in reducing these damages (Dowling [12]). This technical information, coupled with the design specifications detailed in the above publications, allows practitioners to design safer houses. Putting this design into practice, however, is a more challenging matter, especially when a project is intended to promote low-cost, low-tech construction alternatives in a resource- and skill-limited context. The Expedition El Salvador project is one example where the challenges and difficulties of practical application yielded some valuable lessons, many of which are presented in this paper.

EXPEDITION EL SALVADOR – CHILD-CARE CENTRE CONSTRUCTION

The Expedition El Salvador project involved the construction of a small child-care centre in the rural community of El Condadillo, in the Municipality of Estanzuelas, Department of Usulután, in El Salvador. The project was a collaborative venture involving individuals, groups and institutions in El Salvador, the United Kingdom and Australia. The main driving force for the project came from a group of enthusiastic students and staff from Imperial College, London, who desired to develop and participate in a practical project to support the reconstruction efforts in post-earthquake El Salvador. The project had the following key objectives:

- Provision of an important community facility (child-care centre).
- A hands-on community training program in improved adobe construction.
- Promotion of improved adobe as a viable and safe construction system.
- Introduction to international and community development for engineering students from Imperial College, London.
- Practical application and assessment of adobe improvement techniques for further research considerations.

The total project timeframe was twelve months (January – December 2002), which included a five month construction phase (August – December 2002). The direct construction costs were ~US$5,000, which covered materials, tools, transport and a master builder. Other in-kind donations included labor, supervision and additional materials, tools and transport. The project was coordinated by an engineer (the author of this paper) and a master builder (foreman), with labor provided by local community members and nine student volunteers from Imperial College, London. The child-care centre consisted of one room (9.3 x 3.6m) plus a covered verandah area (12 x 3.8m), creating an internal area of ~33.5m^2 and a total covered area of ~105m^2.

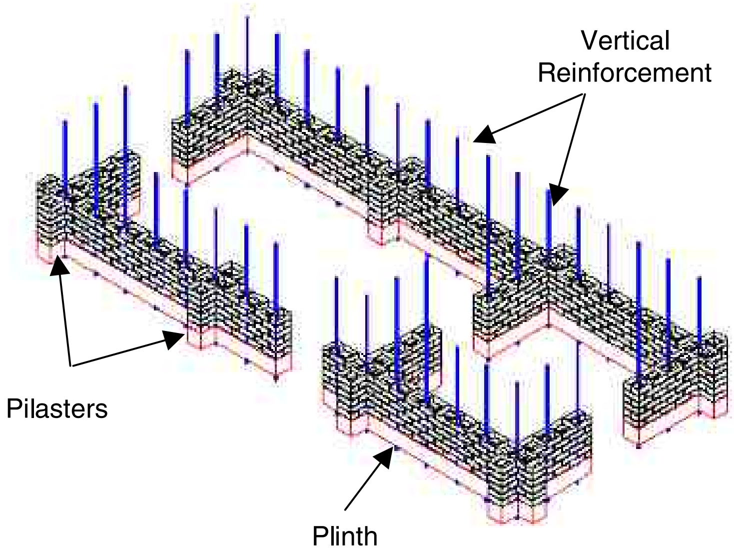

Figure 2. Preliminary design of child-care centre showing plinth, pilasters, door openings and vertical reinforcement (the internal wall was removed in subsequent versions).

Design

The design of the building combined a variety of existing improved adobe construction systems with some new initiatives (Figure 2). The design satisfied the relevant seismic design criteria outlined in the adobe supplement of the El Salvador building code, RESESCO [13] and the International Association of Earthquake Engineering *Guidelines for Earthquake-Resistant Non-Engineered Construction* (IAEE [6]). The design underwent several changes during the course of the project, due to site limitations, community input, new ideas and lessons learned. The design and construction specifications of the building are discussed below.

Site Constraints

The site for the child-care centre was donated by a local family. The site possessed a number of constraints which represented a significant challenge for the preparation and execution of the project. These site constraints included:

- Small site (10 x 15m).
- Sloped site (with a height difference of 2.38m between the highest and lowest points, and a maximum slope of 36% in the SW corner).
- Presence of a large tree trunk with an extensive root system in the middle of the site.
- No direct access to potable water. The nearest tap stand was approximately 300-400 meters away.
- The only established and safe access was through the property of a local landowner.

These site constraints necessitated significant changes to the original design and construction plans. Additional time and resources were required for clearing and excavation (building on fill material is not advised in seismic zones), and a deeper foundation was required on the lower side (with resulting increased costs). As an alternative to excavating the entire site to the lowest level, the design was amended such that the kitchen area (SW corner) was 0.5m below the floor level of the rest of the building. Water was delivered to the site by hand or truck.

Brick Fabrication

An assessment of locally available soil was undertaken prior to the fabrication of the blocks. The available soil was found to have a very high clay content, which necessitated blending with other available soils to obtain adequate strength blocks, with minimal cracking. The decided mix was a 1:2:2 soil-sand-*tierra blanca* mix. (*Tierra Blanca* is a pyroclastic ash deposit, whose geologic and engineering characterization is described by Rolo, *et al* [14] The blending of more than one type of soil presents significant challenges in the brick fabrication process. The process is slower and more resource intensive (sourcing, transporting and mixing) than using a single source of soil. Firstly, all components were thoroughly dry-mixed in measured batches on a concrete mixing platform, water was then added and the soils were then wet-mixed (tools and 'feet'). On more than one occasion, excessive amounts of water were added and the resulting mix was too sloppy for brick fabrication, further slowing the process. Improving the efficiency of adobe mud preparation would be a significant advance in improving the entire brick fabrication process, and should be the subject of further research.

Timber and steel moulds were used to fabricate full size bricks (300 x 300 x 100mm), half size bricks (300 x 140 x 100mm) and channel bricks (for use in the ring beam, as described below). Voids for vertical reinforcement were included in the moulds. The bricks were made on a bare soil or sand ground surface (Figure 3) and covered immediately with opaque plastic sheeting to prevent cracking due to the differential drying of the brick in the hot sun. After two to three days the bricks were turned on edge and allowed to dry in direct sunlight. Bricks were rotated every couple of days to ensure thorough baking throughout. After a period of two to three weeks the bricks were stacked ready for transportation to the construction site (500m away). The bricks were dried for a minimum of four weeks prior to use. Over 2,000 bricks were required for the fabrication of the child-care centre.

Figure 3. Drying bricks (Note: drainage ditches and plastic covers)

Foundations

The foundations were 400mm wide and varied between 250- 750mm deep depending on the slope and underlying rock depth. The foundations were made of river rocks held in a sand-cement mortar. The foundation reinforcement consisted of three 1/2” steel bars in a triangular prism configuration, with 1/4” stirrups every 250mm. 3/8” L-shaped steel bars were tied to the apex horizontal reinforcement bar every 640mm to provide attachment between the continuous horizontal foundation reinforcement and the vertical bamboo reinforcement.

Vertical Reinforcement

A local cane/bamboo, *vara de castilla* (*Gynerium sagittatum,* Hays [15]), was used as internal (within the wall) vertical reinforcement, placed every 640mm (Figure 4). It was attached to the foundation via L-shaped steel bars (tied with wire prior to pouring the plinth / ‘top foundation’) and connected to the ring beam at the top of the wall, thus creating a continuous matrix of reinforcement, tying the structure together. The placement of the vertical reinforcement presented significant problems. Firstly, during the pouring of the foundations a number of the steel L-shaped bars were knocked slightly out of alignment. This misalignment, combined with the natural and unavoidable curvature of the bamboo meant that the reinforcement was not in the precise location as per the design. As each course of the wall was laid, certain bricks needed to be trimmed and cut to fit. This created delays and frustrations during the construction of the wall, and highlights the need to ensure accurate alignment of the vertical reinforcement.

(a) (b)

Figure 4. Location of vertical reinforcement and preparation of plinth formwork.

Plinth / 'Top Foundation'

The plinth / 'top foundation' was 300mm wide and 300mm high and consisted of river rocks in a sand-cement mortar. The plinth serves to raise the adobe wall above the ground level, thus reducing the ingress of ground moisture and erosion due to run-off. The plinth was formed using plywood, which must be adequately braced to prevent buckling of the form (Figure 4). The top surface of the concrete plinth was roughened to increase the bond between the plinth and the adobe wall. A layer of plastic sheeting was placed between the plinth and the first layer of adobe bricks to act as a damp proof course. There is some debate as to whether the inclusion of the plastic damp proof course will act as a low-friction slip plane, thus increasing the risk of the wall slipping off the plinth in a seismic event. This claim can be countered by considering the massive weight of the superstructure (wall and roof) bearing on the plinth, combined with the presence of vertical reinforcement providing a dowel restraint to shear.

Adobe Walls

The walls were 300mm wide, 2.24m high load-bearing walls, which consisted of the plinth layer, 15 courses of adobe bricks and a ring beam. The mortar joints were ~ 20-25mm wide and were made of the same material (mud) as the adobe bricks (Figure 5). String-lines were used to maintain alignment and plumb of the walls. There were some initial problems with the placement of blocks in the walls as the workers adjusted to the new technique. On several occasions blocks needed to be removed and the configuration changed. This was to be expected, but relied on fairly constant supervision to correct errors quickly.

Figure 5. Adobe walls under construction, including plinth, pilasters, vertical reinforcement, plastic rain covers (Note: figure alignment offset due to photograph splicing).

Pilasters

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 (Roselund [16]). Pilasters can be commonly observed in large structures, such as churches and halls, but their use in common housing in Latin America has been limited.

Pilasters were constructed externally at each corner of the building and both internally and externally at third points along the long wall (Figure 5). The pilasters were 320mm deep (equal to one block plus one mortar joint) and extended to the top of the wall (2.24m).

The inclusion of pilasters increased the complexity and resource requirements of the project. Firstly, the preparation of the formwork for the plinth layer became a complex task, requiring multiple right-angled corners and various adjustments (Figure 4). The configuration of the bricks around the pilasters was different to that commonly used by local builders and this created some initial confusion, although this was overcome as the wall construction progressed. The inclusion of the pilasters necessitated the expansion of the roof cover in order to maintain the desired minimum overhang of 600mm. This resulted in an increase of 13% in the plan area of the roof, with various elements of the roof structure designed to support cantilever actions of over one meter. These increases in costs and complexity should be considered in conjunction with the aseismic contribution offered by the pilasters and should be the subject of further research.

Horizontal Reinforcement

Two strands of galvanized barbed wire were placed in the horizontal mortar joints every three courses (Figure 6). The barbed wire strands were weaved between and tied to the vertical bamboo reinforcement to promote continuity. The strands of barbed wire were extended into the pilasters, with U-shaped nails/staples used to connect the wire to the bricks. In some cases, this caused cracking of the bricks, and should be undertaken with caution. In the upper part of the wall (between courses 11-12 and 14-15) a strip of chicken wire mesh was placed horizontally in the mortar joints to augment the barbed wire in this critical section.


(a) (b)

Figure 6. Adobe walls under construction, including plinth, pilasters, vertical and horizontal reinforcement, plastic rain covers.

Openings

The building included three doors and three windows (pre-fabricated, steel, lockable). During construction of the walls 1/4” steel pins were looped around the adjoining vertical bamboo reinforcement and placed in the horizontal mortar bed joints to provide a connection with the frames for the windows and doors.

Timber lintels were placed above the door and window frames and extended ~900mm along the wall. The timber was treated with burnt oil to reduce insect and fungus attack. Holes were bored in the timber at the location of the vertical bamboo reinforcement, thus increasing the connectivity with the matrix of reinforcement. A strip of chicken wire mesh was nailed onto the upper face of each lintel to increase the bonding capacity with the adjoining mortar layer.

Ring Beam

‘Channel’ blocks were formed with special moulds, using a soil-cement mix of 7:1. The channel blocks were wet cured for a minimum of seven days. The ring beam channel blocks were placed on the top course of adobe bricks, using a soil-cement mortar (7:1). Where necessary, holes were bored in the channel blocks to accommodate the vertical bamboo reinforcement. A horizontal reinforcing mesh consisting of two 1/2” steel reinforcing bars with 1/4” stirrups every 250mm was placed in the channel (Figure 7). This reinforcement was tied to the vertical bamboo reinforcement and roof anchors. Finally, the channel was filled with a 5:1 sand-cement mix. At the places where the vertical strands of wire passed through the ring beam, it was difficult to level off the cement mix evenly. This created elevated points, which become points of concentrated load where the timber wall plate rests on the ring beam. One option to prevent this occurring would be to place the timber wall plates whilst the cement mix is still fresh enough to be manipulated to create an even contact surface with the wall plates.

(a) (b)

Figure 7. Ring beam channel blocks and reinforcement (Note: steel pins and wire straps for roof attachment).

Wall – Lintel – Ring Beam – Roof Attachments

Effective attachment between these elements poses a significant challenge because the elements are made of different materials. Two 1/4" steel rods were looped through the timber lintels, then tied to the ring beam reinforcement and left protruding for attachment to the timber wall plates of the roof structure. The vertical bamboo reinforcement was tied to the ring beam reinforcement to resist horizontal shear movement and provide continuity between the vertical and horizontal reinforcement. Two strands of heavy gauge galvanized wire were placed in the horizontal mortar bed (between courses 11-12) then run up with the vertical bamboo reinforcement, attached to the ring beam reinforcement and left protruding for attachment to the timber wall plates of the roof structure (Figure 7). These wire elements formed large U-shaped straps, utilizing the mass of the wall to tie the roof down and restrain vertical uplift.

Roof

The roof consisted of a double-pitch timber roof structure with a Zinc-Alum sheeting cover. The structure comprised of timber wall plates supporting a timber lattice beam, trusses, purlins and diagonal bracing (Figure 8). Connections were bolted, nailed and / or strapped, as appropriate. The wall plate was tied to the ring beam and walls using heavy gauge wire and steel rods, as described above. A minimum overhang of 600mm was maintained around the building to protect from water damage due to rain. One pitch of the roof covered the verandah area, which was supported by timber columns in concrete footings. The gables were closed with welded mesh and screen mesh to allow free flow of air, whilst ensuring a secure and safe building.

Figure 8. Roof under construction.

Wall Finish

The walls were wetted and rubbed down with a sack. This is a slow and meticulous task, but results in a smooth and attractive surface, which retains the natural appearance of the adobe. The external walls were then coated with a mix of linseed oil and mineral turpentine (1:1), which acts as a waterproofing agent whilst still allowing the wall to ‘breathe’ (Woodward [17]). Further research could be conducted on the effectiveness of more widely available and cheaper local alternatives, such as cottonseed oil and corn oil. The internal wall was coated with wall paper paste, which acts as an anti-dusting agent (Woodward [17]). The selected wall finishes had a mixed response from local collaborators; some felt that a concrete render provides a sense of modernity and solidity, whereas others appreciated the natural aesthetic of the adobe wall and the ease of application of the finishes.

Floor

The internal floor consisted of a ~75mm thick concrete slab, without reinforcement. The external, verandah floor consisted of a ~75mm thick concrete slab with mesh reinforcement. Prior to laying the concrete the ground was compacted and leveled.

Additional Infrastructure

A kitchen, including sink, benches and cooking platform, was built in the lower section of the verandah area and a latrine was constructed nearby. Extensive drainage and landscape works were undertaken to expedite storm water removal and reduce erosion. The local municipality committed to providing future connection to electricity and water.

Weather

Wet weather posed significant challenges during the project. In each phase of preparation and construction mitigation measures where required to reduce the impact of frequent and intense rainfall periods. Drainage ditches and tent-like structures were built to protect the bricks during the fabrication process, and plastic covers were required to protect the walls during construction. Additionally, stockpiled soil and bricks needed to be covered. Despite these measures several hundred bricks were lost due to water damage during serious storms. The wet weather also made the manual excavation of the site even more laborious due to the difficulty of working with wet and cohesive soil.

Hot weather during the day took its toll on the workers, with job rotation required for the heaviest tasks. The newly formed bricks needed to be covered immediately to prevent excessive cracking in direct sunlight. Positively, the hot weather ensured that the bricks dried quickly and thoroughly when protected from the wet.

Training Manual and Workshops

The training was undertaken in an informal manner, with new systems and techniques described as they were encountered in the construction process. In some cases, diagrams were drawn and simple models were made to further explain various concepts. Overall, however, the training component of the project would have been more effective and sustainable if a simple construction manual was provided to each participant and some theory sessions undertaken in a less distracting and intense learning environment than an active building site.

Community Perceptions

In general, the local community were interested in the new construction systems presented. However, it was also acknowledged that the building, as constructed, was too expensive, too complicated and too labor-intensive to be widely adopted. There were a number of factors which contributed to the high cost and complexity of this particular building, which would be reduced in the construction of a family dwelling. Firstly, the function of the building (child-care centre) necessitated the use of higher factors of safety in the design. Secondly, there were a number of specific site constraints which added to the complexity and cost of construction (small, sloped site, unsuitable unblended soil material for bricks, etc). Thirdly, there was some uncertainty relating to the characteristics of various materials used, so principles of over-design were utilized. Finally, the project was designed to demonstrate a best-practice example of improved adobe construction, with participants encouraged to utilize the systems which matched their personal resource and skill levels.

Notwithstanding these limitations, there was a positive community response to the design and construction techniques presented. In general, the local community were impressed with the solidity of the building and quality of the construction and many workers commented that they would use some of the ideas in future adobe construction.

CONCLUSIONS

Overall, the majority of the project objectives were met: a safe and secure child-care centre was constructed, the local community engaged in an effective, hands-on introduction to improved adobe construction, the Imperial College students gained invaluable first-hand exposure to international and community development, and a number of practical lessons have been learned about improved adobe design and construction, as described above.

In light of the key lessons learned during the execution and review of the Expedition El Salvador project, it is fitting to suggest that future assessments of the seismic performance of new systems should also include some evaluation or discussion of the skill / experience level (complexity) and resources (costs) required to implement a proposed system. Table 1 presents this type of information as an addition to the technical analysis presented by Dowling [12], which assesses the contribution of each improvement system for reducing common damage patterns. This new information, coupled with the technical assessments of different systems, will allow institutions involved in improved adobe construction projects to tailor projects to satisfy the skill and resource capacities of the organization and beneficiary groups involved, whilst providing maximum aseismic benefit.

Table 1. Complexity and costs of improvement systems for adobe construction.

	Improvement Systems						
	Ring Beam (reinforced soil-cement)	Vertical Reinforcement (internal bamboo)	Horizontal Reinforcement (internal barbed wire / chicken wire)	Vertical Reinforcement / Mesh (External) [*Estimated]	Horizontal Reinforcement / Mesh (External) [*Estimated]	Pilasters (intermediate)	Pilasters (corners)
Complexity (Skill/experience level required)	2-3	2-3	1	2*	2*	2	3
Cost (Resources required)	3	2	1	2*	2*	2-3	2-3

Complexity / Cost Key: 1 – Low, achievable by general population; 2 – Moderate, some building skill + experience / resources required; 3 – High, significant technical skill + experience / resources required.

The project and subsequent review has also raised a number of issues, which should be the subjects of further research:

- Further refinement and expansion of the technical evaluation of the performance of different improvement systems, including verification through comprehensive experimental testing and evaluation of different materials and techniques (currently underway at the University of Technology, Sydney).
- Further review of the complexity and cost assessment aspects for different systems and projects, including the development of a robust method for assessing these aspects, and incorporating the perspectives of different stakeholders.
- Further research and innovation is required to simplify construction methods and reduce costs.

These future research activities combined with further sharing of lessons learned through practical experience will enable improved adobe design and construction to improve in efficiency and effectiveness.

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