Introduction

It gives me pleasure and encouragement to see the attendance at this important workshop and your interest in the subject. For many decades I have deplored the great loss of life in earthquakes, and I have noted that the non-engineered, natural-material residential and light commercial buildings have caused the greatest loss of life on a world-wide basis. Much of this can be prevented while still using natural materials! We have to examine and determine how this can be achieved without requiring some native farmer to engage an architect and an engineer and use a computer to build a structural steel or reinforced concrete frame. You know, and I know, that they simply can't afford that nor will they be able to in the future.

I have heard many engineers and others say the use of adobe, earth, rubble, even unreinforced burned masonry should not be permitted in seismic areas. Few of these authorities have visited the remote regions of countries throughout the world where shelters or housing have to be of absolute minimum cost, have to be "do-it-yourself" construction, and have to utilize to the maximum extent possible readily-available, natural materials including earth used various ways. Moreover, many of these authorities don't realize that any material with predictable properties can be made earthquake resistant.

It is my opinion as an engineer who has designed all types and sizes of structures in all types of materials including adobe brick, burned brick, and Arabian faroush, that the earthquake resistance of earthen buildings can be greatly increased with more attention to, and education about, proper materials properly used. Some new techniques may be needed as well as cartoons and models to demonstrate these techniques to untrained people. There may also have to be some simple standards and reasonable enforcement of those standards, but it can be done.

Local conditions such as climate, available materials, skills, traditions, poverty, etc., vary greatly not only from country to country but within a country. These will have to be allowed for in the improvement procedure I envision. Typical and simple designs could be developed for each major area. Models could be displayed in each area where construction is imminent. To the extent possible, traditional local procedures should be retained -- to expect radical changes to be successful would be folly in most places.

In addition to native residential construction I should note that some very fine homes and many large public and private structures have been built of adobe brick in earthquake regions of the United States and elsewhere. Earthen materials are by no means the exclusive property of the peasant in remote regions. Adobe has charm, warmth and insulation value to many people.

Types of Earthen Buildings

There are many types of earthen buildings which types I expect will be sorted out during this workshop. They vary not only in the materials used and in the combinations of materials used, but in the sophistication, if any, of design and construction. I suppose one could call a cave the most natural and oldest type of earthen building although caves are usually more rock than earth. This introduces the matter of definition, or of particle size applicable to this workshop. Buildings are made of rubble rock, of boulders, of chiseled rock, even of gravel. I shall presume unless corrected that our definition of "earthen" pertains to clays, silts, and some relatively small amount of sand; basically we are dealing with clay and silt somehow cast in place or molded into bricks which are dried in the sun -- adobe bricks, often with straw and sometimes with waterproofing emulsions added to the wet mix. The masonry of which we are concerned has not been burned or fired in a kiln nor has it been made of concrete hollow blocks or bricks.

There are a great many ways in which earth as we have defined it has been used in building. The names of the construction types vary from place to place. Earth has been placed or rammed into wall forms; it has been plastered onto wood or rubble; it has been precast into sun-dried bricks and laid with various types of mortars (often simply mud); it has been mixed with cornstalks, wood, slats, logs, bamboo or branches in various ways; it has been used as the bearing material or simply as a filler material against the weather. Roof construction has included heavy earth fill or insulation and it has often consisted of beams or overhead arches of wood or old corrugated sheet metal with or without earth cover. Sometimes wood branches are used as reinforcement and -- in relatively few cases -- steel bars, wires, or mesh have been used as reinforcement. The earthquake record has been very bad where earthquake engineering has not been a consideration; it has been good in the few cases where good earthquake-resistant design has been employed. The general practice has been, unfortunately, after a damaging earthquake to rebuild in the same place with the same procedures, possibly with a trend toward less adobe and more wood if available and if the climate permits.

Properties of Adobe

Like concrete, concrete block, and burned brick masonry, adobe masonry is relatively weak in tension and in shear and strong in compression. Concrete and brick or block masonry under building code requirements are reinforced so as to compensate for their weakness in tension and shear. Adobe can be also, and has been, in a few cases.

Tests made by the USA National Bureau of Standards and also for the University of Washington Engineering Experiment Station show that adobe brick has unique resistance to impact, or great capacity to absorb energy. An example of this is the capacity to stop M-1 rifle bullets fired at a 50-yd (46 meters) range with only 3 to 4 in. (7.6 to 10.2 cm) penetration without fragmentation or spalling as for other materials. It is important that this valuable property -- ductility and energy absorption capacity -- be effectively utilized in building construction for seismic areas.

The Uniform Building Codes have been allowing 30 psi in compression for unburned clay masonry with Type M or S mortar and 8 psi for M mortar and 4 psi for S mortar in shear or tension in flexure respectively. These values can be increased by one-third under seismic conditions. Tests made years ago of stabilized adobe bricks laid in waterproofed 1:2-1/2 cement-sand mortar supervised by the writer gave considerably greater values. These tests also showed that lime or fire clay in the mortar weakened the bond.

Adobe that is not treated or plastered is subject to erosion by rain and ice formation. Unless any erosion is repaired the wall is weakened for earthquake resistance.

Earth rammed into wall spaces is subject to much shrinkage in place and this leads to cracks and weaknesses. Even the sun-dried bricks have small cracks but these are not generally harmful. Straw particles help to minimize the cracking.

The earth mix itself must be proper for walls or to make adobe units. Too much sand or too large particles can be detrimental. Sieve analysis and/or expert selection of materials is essential.

Contributors to Damage and Collapse

Earthquake weakness is caused by many factors, some of which are listed here, not necessarily in any order of importance:

1. Poor foundation conditions -- subject to liquefaction, rupture, settlement, sliding, flooding, or rockfalls from adjacent hills.
2. Heavy roof materials including tile, earth, etc.
3. Lack of bond between bricks and mortar or mud.
4. Sloped roof beams or arches (without cross ties) that thrust horizontally against the walls.
5. Walls too thin.
6. Walls with too many and/or too large openings.
7. No continuous bond beam at the top of the walls.
8. Exterior walls that are long without connecting interior cross walls; i.e., rooms that are too large.
9. No horizontal diaphragm or bracing at the level of the top of walls or in the roof plane.
10. Inadequate ties of roof construction to bond beam and of bond beam to walls.
11. Asymmetry of walls and of wall openings.
12. Unrepaired erosion or damage.
13. When used with wood framing, shrinkage or other gaps, and/or inadequate ties.
14. Lack of reinforcement where needed.
15. Inadequate foundations; too close to grade; not deep enough.
16. Poor selection and mixing of materials for adobe bricks.
17. Adobe bricks inadequately reinforced with straw or inadequately cured in the sun.
18. Adobe bricks laid without header courses.

Contributors to Reduced Risk

The elimination of all the above contributors to damage and collapse is a giant step toward a reasonable level of risk. To further reduce the risk there are also the following procedures not all of which would apply in all cases:

1. Analysis by relative rigidity of the building and its wall piers by structural engineers familiar with seismic design.

2. Site selection or investigation by geologists, soils engineers, seismologists.
3. Dynamic analysis of structures.
4. A reinforced concrete bond beam, well anchored.
5. A concrete or wood post and frame system.
6. Reinforced walls.
7. Cement-sand mortars; avoid lime and fire clay with waterproofed bricks and avoid mud mortar with all bricks.
8. Waterproof the adobe and the mortar.
9. Properly select and control the quality of the earthen materials and control the manufacture and curing of the bricks.
10. Provide inspection during construction; check masonry bond by tests.
11. Do not chop or chase out too much masonry for pipes, conduits, boxes, etc.
12. Design the roof system so that it is proper, of minimum weight, exerts no lateral force on any wall, is well tied to the bond beam, and acts as a rigid diaphragm.
13. Study earthquake-resistant code provisions; check the local code.
14. Provide for torsional motion.

In general, a small residential building tends to be rigid. It should therefore be made rigid, be well tied together at all connections of walls, roof and elements, it should be very strong, and as tough and ductile as possible. Adobe by its nature should be thick-walled, and thus provide thermal and noise insulation as well as strength. Reinforcement may not prevent all cracking in an earthquake but it tends to hold things together and prevent disaster even though some cracking occurs. There are many ways of reinforcing.

Static Analysis

The calculation of stresses in walls from assumed static lateral forces is a straightforward procedure. The top of the walls must be connected with a rigid horizontal member or bracing -- a rigid roof diaphragm well connected to a continuous bond beam is preferred. If this is not done, the structure lacks one of its most essential elements and is of doubtful seismic value. Assuming a rigid diaphragm and symmetry of walls and wall openings, the wall piers in the direction of the assumed force will be loaded in proportion to their relative rigidities. If there is no symmetry, the building will respond in torsion as well as translation and the forces and stresses will be increased over those forthe symmetrical layout. This too can be calculated.

Relative rigidity is a basic concept in structural engineering but is often overlooked by designers unfamiliar with seismic design. The stiffer the wall element relative to all other parallel wall elements, the more force it will attempt to resist. If it cracks in the attempt, the forces on the next cycle will be increased and greatest for the next stiffest element. The stiffness, R, is the reciprocal of the deflection Δ:

$$R = \frac{1}{\Delta} \tag{1}$$

$$\Delta = \Delta_m + \Delta_v \tag{2}$$

where

Δ_m = deflection due to moment

Δ_v = deflection due to shear

R = rigidity

If the wall piers can be considered as "fixed" top and bottom (i.e., there is no rotation), then

$$\Delta_m = \frac{Ph^3}{12E_m I} \tag{3}$$

and

$$\Delta_v = \frac{1.2Ph}{E_v A} \tag{4}$$

where

P = horizontal force applied to pier, lb

h = height of pier, in.

I = moment of inertia = $td^3/12$, in.^{4}

A = area of pier = td, in.^{2}

E_m = modulus of elasticity, psi

E_v = modulus of shear $\cong 0.4E_m$, psi

d = depth of wall parallel to force, in.

t = wall thickness, in.

E_m and t are linear in the equations; thus convenient values may be assumed to simplify and combine the equations. Let E_m = 1,000,000 psi. Then there is obtained

$$\Delta = \frac{P}{10^6(t)} \left[\left(\frac{h}{d}\right)^3 + 3\left(\frac{h}{d}\right)\right] \tag{5}$$

If the piers cannot be considered fixed at their tops, and are relatively free to rotate at one end, then

$$\Delta = \frac{P}{10^6 (t)} \left[4\left(\frac{h}{d}\right)^3 + 3\left(\frac{h}{d}\right)\right] \qquad (6)$$

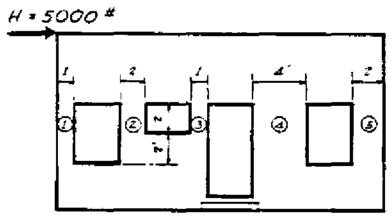
The condition expressed by Equation 5 is much more preferable for earthen buildings than Equation 6. Sometimes the situation falls between these two extremes.

Note that for the same h/d ratio, there will be the same Δ and R. Thus, a 2 ft x 2 ft square pier will be loaded as much as a 6 ft x 6 ft square pier and yet have but a fraction of the resistance to withstand that loading.

Table 1 shows the application of the above principles to a single wall with 5,000 lb assumed lateral force. From the P values, the unit shear can be obtained by dividing by 0.67 td for each pier and the flexural tension, f, can be obtained by dividing the moment, M, by the section modulus, S, which is simply $td^2/6$. Note that $M = Ph/2$.

TABLE 1

Distribution of Lateral Force to Piers of a Wall



H = total horizontal force applied to wall.
P = force to each pier and also the design shear.
M = design moment for each pier, where $M = \frac{Ph}{2}$ for top and bottom of piers fixed.

Pier No	h (in)	d (in)	h/d	R_1	% of H to ea pier(R)	P (lb)	M (in lb.)
1	48	12	4	13.2	2 0	100	2,400
2	24	24	1	250.	38 2	1910	22,900
3	24	12	2	71.	10.8	540	6480
4	48	48	1	250.	38.2	1910	45800
5	48	24	2	71	10 8	540	13,000
				655.	100 0	5000	

Notes:
a. Each pier is assumed to have full restraint top and bottom and relative rigidity values are taken from the corresponding curve in Fig. 5-1, page 158.
b. Wall returns at each end are assumed to be small and are neglected here.
c. Additional forces to be taken into account in the pier designs are those due to dead and live loads and overturning due to the lateral force ΣP.
d. Note that the lateral force taken by pier No. 2 is the same as for pier No. 4 due to the same value of h/d, but the unit shear stress in pier No. 2 is double that in pier No. 4 due to the relative pier size.
e. Wall assumed to be of constant thickness and, therefore, the value of "t" need not enter into the computations for the determination of "P".

ssume t = 16" for the entire wall. Then for Pier No. 2, the shear, v, is

$$v = \frac{1.5P}{td} = \frac{(1.5)(1910)}{(16)(24)} = 7.46 \text{ psi}$$

ut for Pier No. 4,

$$v = \frac{(1.5)(1910)}{(16)(48)} = 3.73 \text{ psi}$$

Pier No. 4 would pass UBC code requirements of 4 x 1-1/3 or 5.33 psi but Pier No. 2 would not.

Consider now the flexural tension on 2 and 4.

Pier No.	t (in.)	d (in.)	S (in.^{3})	M (in./lb)	M/S=f (psi)
2	16	24	1,536	22,900	14.9
4	16	48	6,144	45,800	7.5

There should be reinforcement at the jambs to take the excess flexural tension. Such bars should run from the foundations into the bond beams.

The calculations for a whole building include all piers and also torsional considerations. They are readily done by hand. They should be carried out with applicable forces for special structures and for typical buildings.

Forces Induced by Earthquakes

The lateral inertial forces induced by earthquakes depend upon many things and vary from insignificant to half or more of the weight of the building. Some of the variables are the earthquake magnitude, its location relative to the structure, its depth in the earth, the soil conditions at the site, and the strength and dynamic properties of the building. Close in to the epicenter the shaking is not much different for a rock site and a firm alluvial site. Far away, the alluvium may shake much more than rock, but with longer periods of motion which may not "tune in" to the building. An earthen structure close to a strong earthquake should be very strong to survive, but survival is possible with good design, materials, construction, and quality control of all three.

The forces prescribed by seismic codes are generally fictitious -- the real forces could be much more. However, the real material values can also be much greater. Code forces, where applicable, should be considered as minimum forces and the structure should not only be strong but as tough and ductile as possible, and well tied together, everywhere.

Figures

Some figures are shown which were prepared by the writer during the initial phase of World War II when the excellent military properties of stabilized adobe were found by test. Although the testing work was done early in the conflict, the sketches shown were not released until later, due to war conditions. The optimum type of mortar for bond to adobe brick was found as well as other properties of the stabilized adobe brick. It is believed the figures, although old, are still applicable to stabilized (water resistant) adobe and mortar, and valid in essentially all respects to the current state-of-the art. If anything has changed it is an increase in respect for ground motion and lateral forces; thus values shown should not be considered as applicable to all conditions today. The allowable stresses have not changed.

Conclusion

Earthen buildings can be built to perform well in earthquakes but not by the more-or-less random control processes extent in many countries. Any material with predictable properties and predictable or controlled workmanship can be made to perform satisfactorily. This all indicates a measure of design and of quality assurance, as well as more attention to known basic principles, that is not now existing throughout the world. The risk can be evaluated and the structure, or at least a prototype or sample structure, can readily be analyzed. This can be done at a practical "down to earth" level with local conditions, materials, and traditions in mind but still introducing basic elements and procedures. Cartoons, models and/or prototypes can be used for educational purposes. The objectives are well worth striving for and are within the purview of this workshop. Hundreds of thousands of lives could be saved in future decades.

References

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