REINFORCED POURED ADOBE AND ITS APPLICABILITY TO EARTHQUAKE RESISTANT CONSTRUCTION

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ABSTRACT

Results of rational analyses of reinforced poured adobe walls indicate that the structural concepts of this construction method are valid and satisfy the intent of the Uniform Building Code, even in high-seismic zones. Wall-forming techniques and shrinkage cracking represent major obstacles to the practical application of poured adobe. However, several solutions, including the use of plasticizers, bamboo rather than steel reinforcing, and fiber reinforcing, show promise for overcoming these obstacles in the future.

Introduction

Meli, et al. stated in a recent paper (1) that:

> "In developing countries the main cause of loss of human lives and of economical damage following strong earthquakes is the collapse of small houses built of unreinforced masonry, mainly with adobe or stones bonded with mud and mortar."

In the United States this has not been the case, primarily because of the wide-spread adoption of the Uniform Building Code (2) which imposes very restrictive requirements on the use of adobe masonry as a structural material. However, because of the ever-increasing economic pressure and scarcity of conventional materials such as wood and concrete, building materials such as adobe, which are readily abundant, are being re-evaluated. Many local county and city governments that originally adopted the UBC code as their own have since amended their requirements so that the restrictions on adobe construction have been liberalized. Such is not the case in California, where the seismic requirements are the most stringent in the United States.

However, adobe being as abundant and versatile as it is, it behooves us to devise new methods of incorporating it into structures without sacrificing seismic safety. One method of adobe construction which shows promise in the area of seismic resistance is the use of reinforced poured adobe walls in residential construction. The primary difference between poured adobe and adobe block construction is the use of the wet mix directly rather than molding the blocks and then mortaring them together in a wall. Reinforcement in the form of welded steel wire fabric or bamboo may be incorporated in a manner similar to the reinforcement in poured concrete construction (see Figure 1).

This paper presents a description of the reinforced poured adobe process and its applicability to seismic resistant construction. A rational structural basis for using reinforced poured adobe is presented along with a discussion of some of the problems related to its application and possible solutions to those problems.

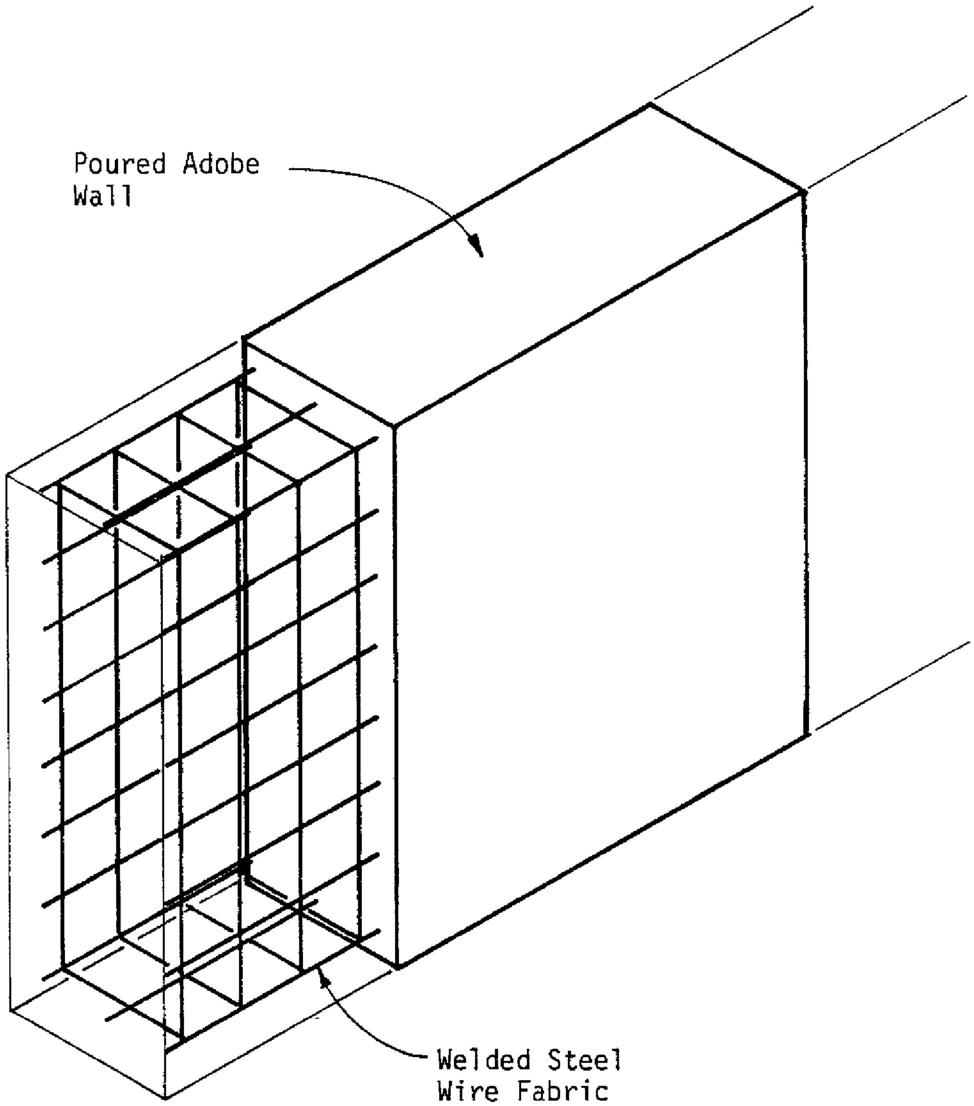

FIG. 1

Reinforced Poured Adobe Walls

Background

Little, if any, technical information on the earthquake resistance of reinforced poured adobe is found in the literature. Most information which is widely available concerns traditional adobe block construction (1, 3, 4, and 5) and is aimed at the less developed countries. For example, Razani (3 and 4) has developed seismic design criteria in Iran for low-rise, low-cost housing with brittle behavior. These criteria include minimum required design lateral loads and base-shear coefficients for ensuring against damage and collapse. In addition, Razani proposes that roof collapse, which he states is the main cause of death during earthquakes, can be prevented by means of a braced skeleton system within the unreinforced building.

Vargas-Neumann (5) presents minimum requirements for material strengths to be used in reinforced block adobe construction in Peru. The use of cane and wire as reinforcing is suggested, with vertical reinforcing being placed in concrete mortar between double adobe walls. This type of sandwich construction with steel reinforcing bars is typical of the adobe construction in California.

Meli, et al. (1), in considering existing adobe structures, present the results of dynamic shake table tests on three separate methods of strengthening adobe block constructed houses after they have been constructed without reinforcement. The three methods considered are:

- Concrete bond beam with corner spurs
- Tie rods at the tops of walls to hold the top of the walls together
- Wire mesh with cement rendering

In each of these methods the strength transverse to the plane of the wall was increased by varying degrees. However, because the wire mesh with cement rendering provides vertical as well as horizontal reinforcement, the increase was most dramatic for this method. The wire mesh is also advantageous, since it does not require removal of the roof for retrofitting.

Each of these references discusses the major concerns of adobe construction in seismic zones, namely the brittle behavior of the material, and the need of reinforcement to provide ductility and strength. The same concerns are valid for poured adobe. However, since this process is not widely recognized at the present, it appears necessary to first present a rational argument for its acceptance, followed in the future by experimental research and verification.

A Rational Basis for Using Reinforced Poured Adobe

The Uniform Building Code does not prescribe standards for reinforced poured adobe as a method of construction. However, Section 105 of the Code states:

> "Provisions of this code are not intended to prevent the use of any material or method of construction not specifically prescribed by this code, provided any alternate has been approved and its use authorized by the building official.
>
> "The building official may approve any such alternate, provided he finds that the proposed design is satisfactory and complies with the provisions of this code and that the material, method or work offered is, for the purpose intended, at least equivalent to that prescribed in this code in suitability, strength, effectiveness, fire resistance, durability, safety and sanitation."

Thus, in lieu of empirical evidence, a rational structrual analysis is believed to provide the building official with sufficient evidence to substantiate the suitability, strength, effectiveness and safety of reinforced poured adobe construction.

For a reinforced poured adobe wall to satisfy the provisions of the Code as a load bearing structural element, it must withstand the prescribed lateral and vertical loads. This means that, in addition to resisting in-plane shear forces and overturning moments, a wall must withstand out-of-plane forces and moments (see Figure 2). It is, in fact, these out-of-plane forces on the wall caused by inertia effects of the wall and roof which appear to be critical.

Assuming that in-plane forces and moments can be resisted by a combination of adobe compressive strength and steel tensile and shear strength, Section 2312(g) of the Code prescribes lateral forces normal to the wall to be:

$$F_p = ZIC_pW_p$$

where Z depends on the earthquake zone, I is the occupancy importance factor, C_p is a force factor dependent on the type of structural element, and W_p is the weight of the wall. For a single-story building with exterior bearing walls eight feet tall, 16 inches thick and located in seismic zone 4, the lateral load F_p is 44 lbs/ft^2.

The distribution of moments and shear forces caused by this lateral load depend not only on the unsupported length of the wall, but also on the edge conditions, namely whether the vertical and bottom edges are fixed or simiply supported and whether the top edge is free or simply supported.

Diaphragm action of the roof is one of the most important considerations in the design of any type of adobe wall for transverse lateral loads caused by earthquakes. For example, if the roof is incapable of diaphragm action, which is usually the case in at least one direction of lateral load, the top of the wall must be considered an unsupported free edge and transverse lateral inertia loads due to the roof, as well as the wall itself, must be carried by the wall, rather than transferring these loads to the shear walls. Meli, et al. (1) discussed the

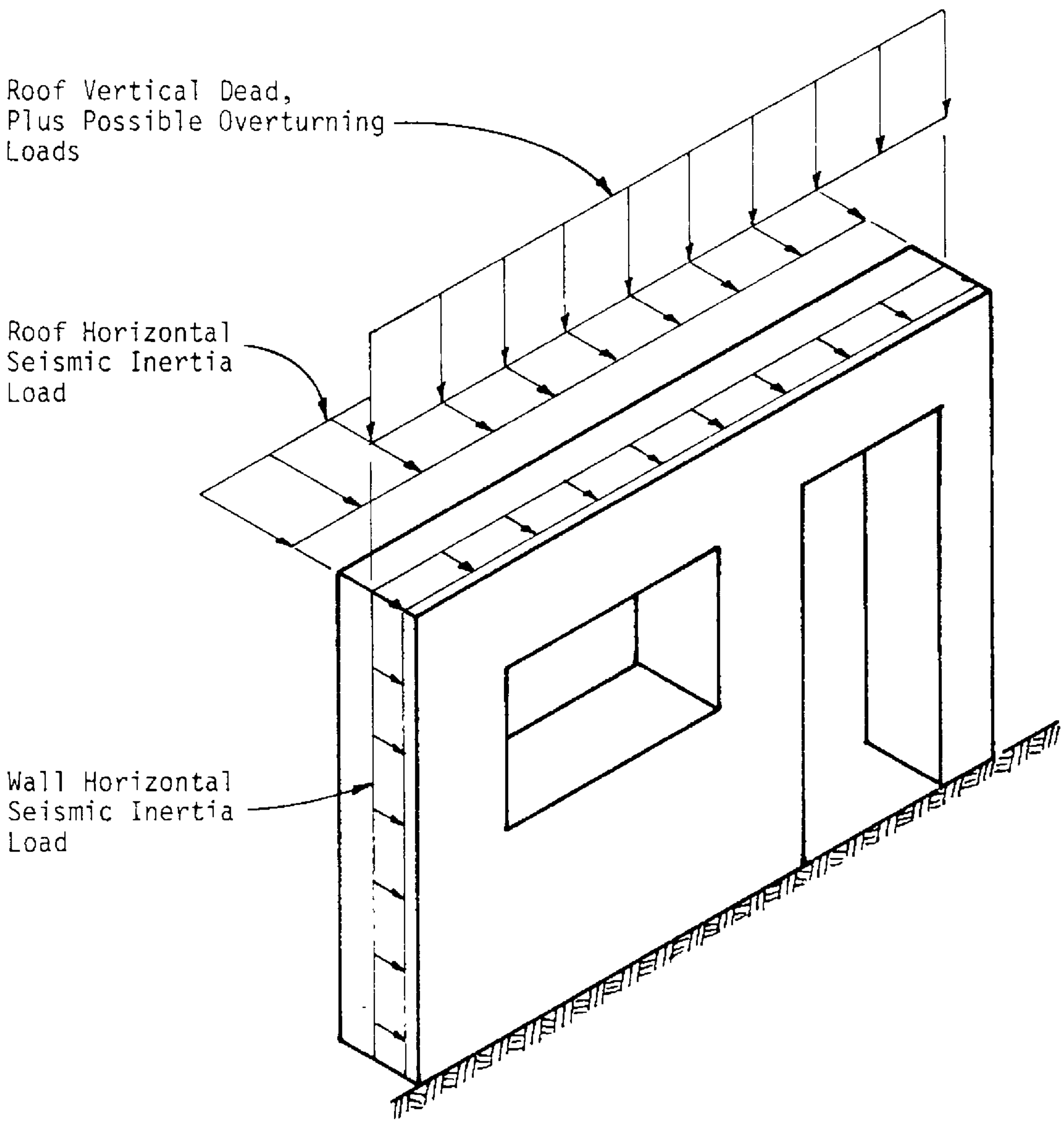

FIG. 2

Seismic Load Demand on Adobe Wall

dynamic behavior of this type of construction in unreinforced adobe structures, stating that:

> "The vibration of the longer walls normally to their plane induces bending moments that are maximum at their lateral ends and that produce vertical cracks that propagate downwards in such a way that the upper part of the wall starts vibrating as a cantilever; overturning moments in the base of the cracked length become critical as the crack length increases and finally the wall falls generally outwards producing the collapse of the roof."

If the wall is analyzed as a flat plate with a free edge at the top, the maximum unit bending moments are found to occur either at the top or bottom of the wall along the vertical centerline, or at the vertical edge of the wall at the top, depending on the assumed fixity of the vertical and bottom edge supports. For a wall 8 feet high and 16 feet long, the maximum unit bending moment is in the range of 15.4 F_p to 19.3 F_p, where F_p is the lateral inertia load per square foot of wall. Considering a 16-inch thick wall, the unit bending moment from wall inertia alone can be as high as 850 lb-ft/ft.

Unit shear forces on the wall are also maximum under these construction limitations, with the largest shear occurring at the top of the vertical edge. Shear forces range from 12.6 F_p to 15.8 F_p for the 8 by 16 foot wall. For a 16-inch thick wall, the unit shear stress can be as high as 695 lbs/ft at these upper corners. Figure 3 shows the maximum unit moments and shears for different edge fixity conditions.

Assuming a wall edge fixity shown in Figure 3b, a 16-inch thick wall with a UBC lateral inertia force of 44 lbs/ft^2, and a roof load on the wall of 210 lbs/ft producing a UBC lateral inertia load of 39 lbs/ft, the maximum unit bending moment at the base of the wall is 998 lb-ft/ft. The steel area required to resist this bending moment is based on the formula:

$$A_s = M/f_s jd$$

Assuming f_s = 20,000 psi and d = 14 inches, the required tension steel area for this moment is 0.0464 square inches per foot. This required steel area can be met by using 12½ gauge wire welded mesh with 2-inch spacing.

Even if steel reinforcing is capable of withstanding the bending stresses, the UBC allowable axial and bending compressive stresses on the adobe itself are quite restrictive. Axial compression at the bottom of the wall is equal to the roof load plus the weight of the wall, or 1,380 lbs/ft. Assuming that the working stress provisions of the UBC for masonry construction are valid for poured adobe, and if the compressive strenth, f_m', of the adobe is 300 psi,* the allowable bending compressive stress according to Table 24-H and Section 2303(d) of the Code is 65.8 psi, while the allowable axial compressive stress is

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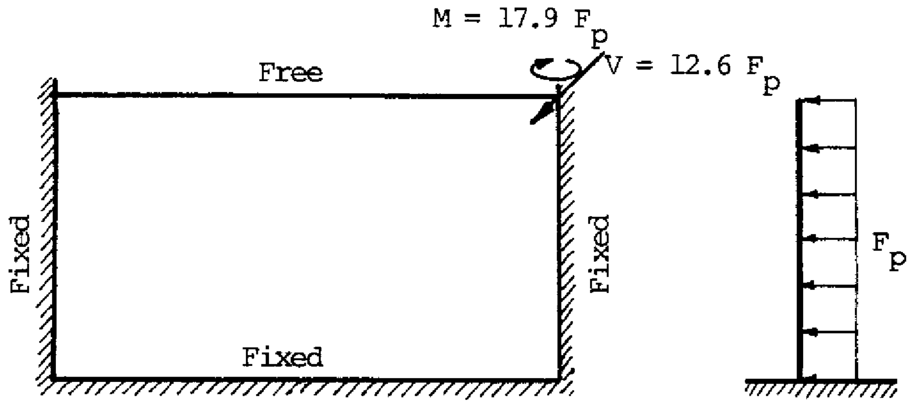
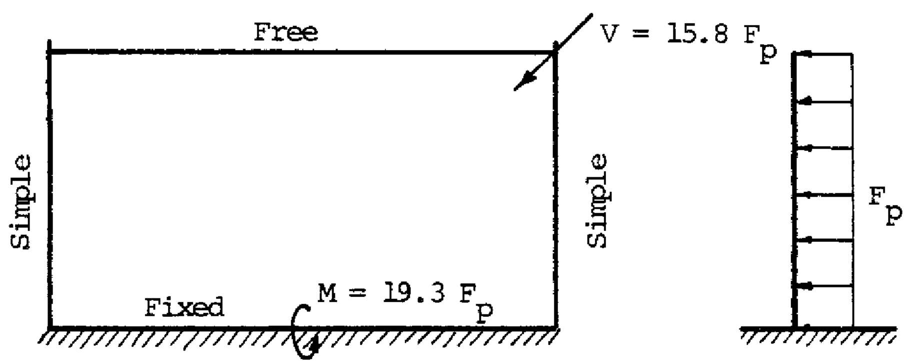
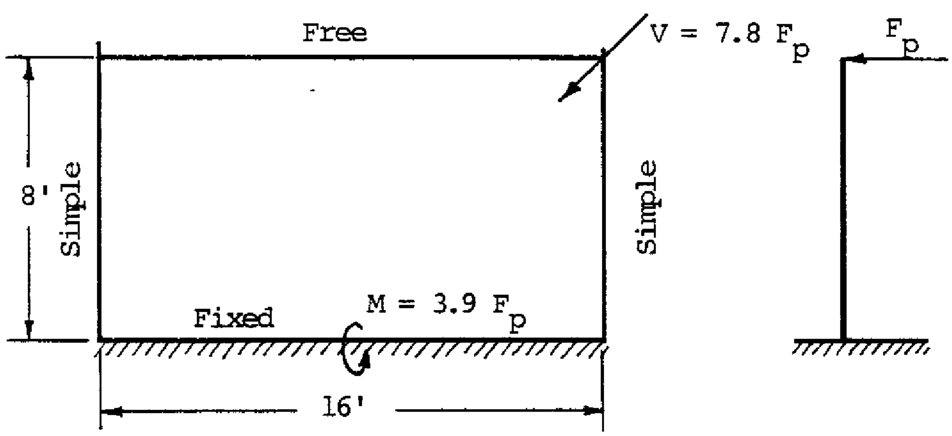
*Assuming a minimum compressive strength implies that a quality control program for mixing the adobe is followed, and sample specimens are periodically tested for strength.



a. Three Fixed, One Free Edge, Uniform Area Load (9)



b. Two Simple, One Fixed, One Free Edge, Uniform Area Load (9)



c. Two Simple, One Free, One Fixed Edge, Uniform Line Load (10)

FIG. 3

Maximum Unit Moments and Shears on Laterally Loaded Flat Plates

$1.33 \times 0.1 f_m'R$, where R is a reduction factor based on the unsupported height to thickness ratio. For this example, the allowable compressive stress is 38.8 psi. The UBC required combined stress interaction equation is:

$$\frac{f_a}{F_a} + \frac{f_b}{F_b} \leq 1$$

where $f_b = 2M/bd^2jk$ and $f_a = P/A_g$. For this example, the interaction of axial and bending compressive stresses is 0.91, which indicates that a 16-inch thick wall is adequate for combined out-of-plane bending and vertical axial force.

The maximum shear stress at the top corner of the 16-inch thick wall is 6.0 psi, whereas the allowable out-of-plane shear stress on the wall from Table 24-H of the Code is $1.33 \times 1/2 \times 1.1 \times \sqrt{f_m'} = 12.8$ psi.

These computations are not intended to be exhaustive, but are meant only to illustrate the potential use of reinforced adobe poured in high seismic zones. The following two sections discuss the unique problems associated with using reinforced poured adobe and some possible solutions. Since so few poured adobe structures are known to exist, not all problems related to this technology can be foreseen at the present time, and solutions even to known problems are in need of research and evaluation.

Forming Poured Adobe Walls

Although there may be others, this author knows of three examples of poured adobe structures (6, 7, 8) in the United States, only one of which (7) has included welded wire fabric reinforcing. The key to this method of building according to Belshaw (6) is a simple light-weight form that is placed where needed on the walls, filled with adobe, and then moved to another location as soon as the adobe has begun to "set up." Where speed in curing is necessary, Belshaw recommends that soil cement be used.

Forms for poured adobe are lighter than those necessary for rammed earth. The form designed by Belshaw for unreinforced walls is shown in Figure 4. The form is a box joined at the back with continuous hinges. The hinges allow the sides to be spread apart when the form is removed.

Depending on the water content of the adobe, humidity of the air, wind, and size of the block, the form can be removed anywhere within four to twenty-four hours, although full curing takes weeks or months. However, it is strong enough to withstand the next step or even support another block on top.

A simple sequence of constructing the walls is shown in Figure 5. Adobe is poured and tamped. According to Belshaw, the adobe will have set up sufficiently to resist slumping when water does not ooze out when a firm imprint of a finger is made. The next step involves erecting simple plate forms which span between the already formed adobe blocks and filling with wet adobe as shown in Figure 6. Shrinkage in this forming process is reported by Belshaw to be negligible.

The process of manufacturing the adobe and pouring suggested by Belshaw requires the use of a backhoe to mix and carry the forms, although the adobe may be mixed in a cement mixer and carried in wheelbarrows up ramps to the forms.

A modification to the basic form designed by Belshaw is shown in Figure 7. This modified design allows for the inclusion of reinforcing welded wire fabric to be imbedded in the adobe, and also includes the use of expanded metal lath rather than wood as the basic siding of the form. The use of metal lath rather than plywood or boards enhances a more rapid and uniform "set up" time, since more surface area of wet adobe is exposed to air. If the size of the form is large, wire ties may be needed between the inner and outer lath of the form to ensure that the form does not bulge due to the hydrostatic pressure of the wet adobe.

In another example, Nelson (7) used forms to place a full wall height (up to 13 feet) of wet adobe at one time. A modular forming system was developed using expanded metal lath as the siding of the form. The wet adobe was placed using a concrete pumper. This method requires a wetter mix than is generally desirable to resist shrinkage cracking, although shrinkage cracking of the adobe did not appear to be a problem for Nelson.

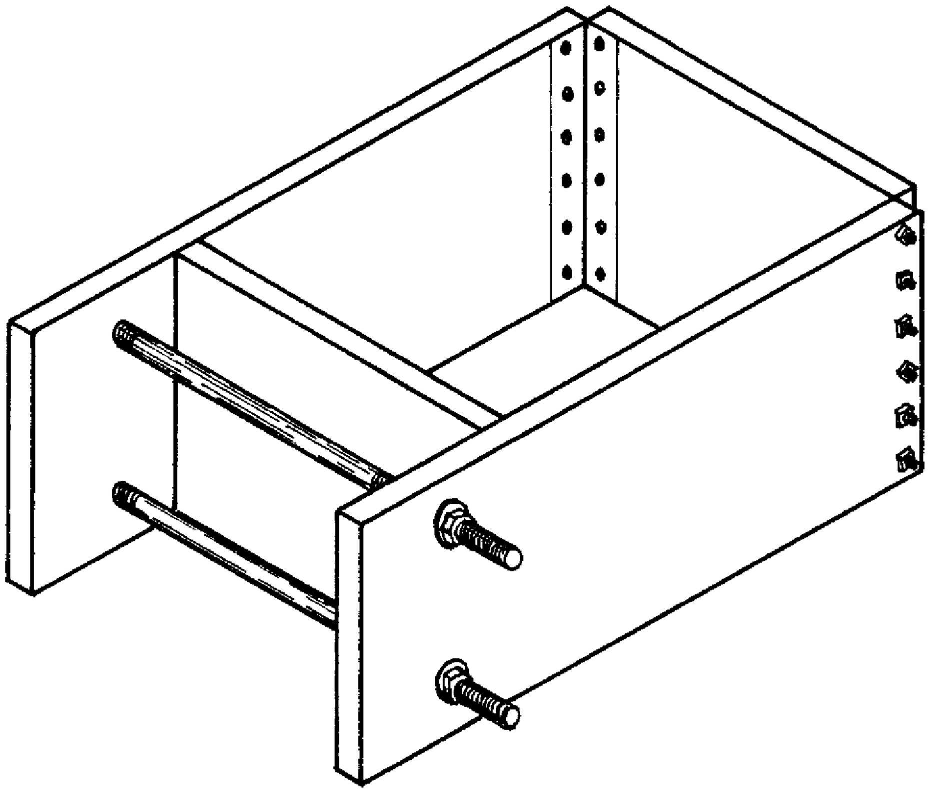


FIG. 4

Basic Forming Block (6)

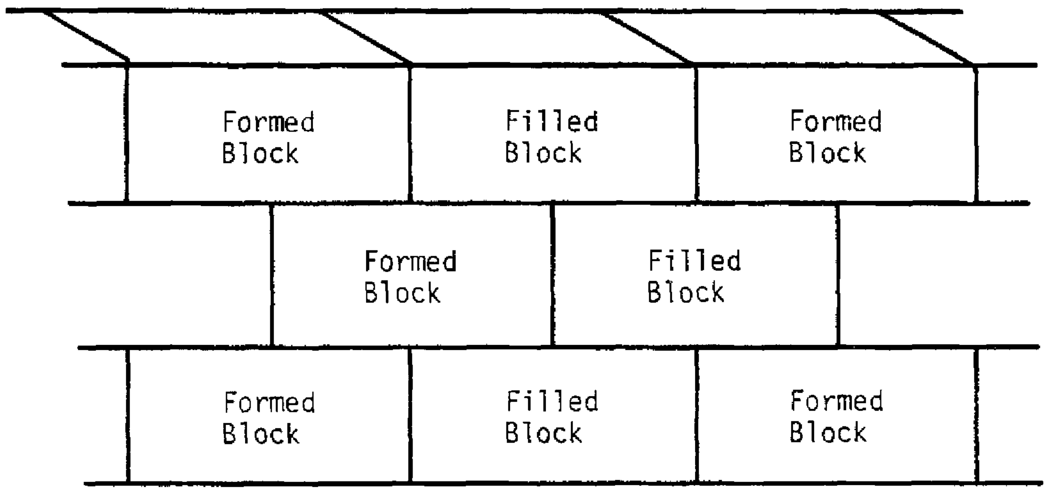


FIG. 5

Basic Sequence of Forming (6)

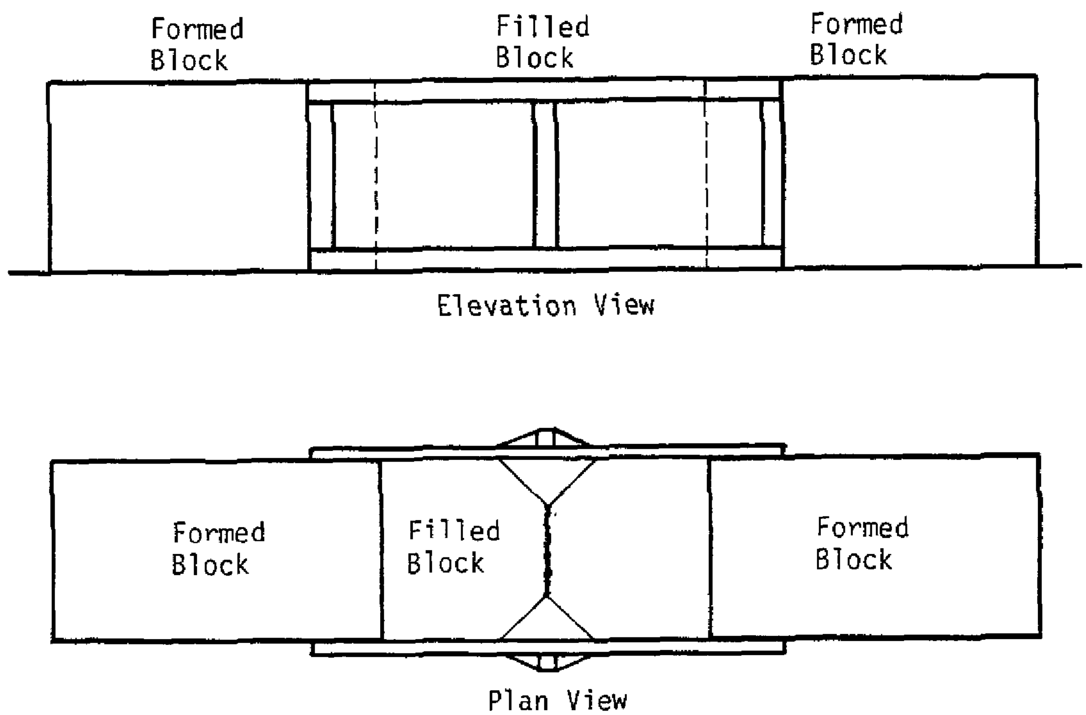


FIG. 6

Plate Forms for Filled Blocks (6)

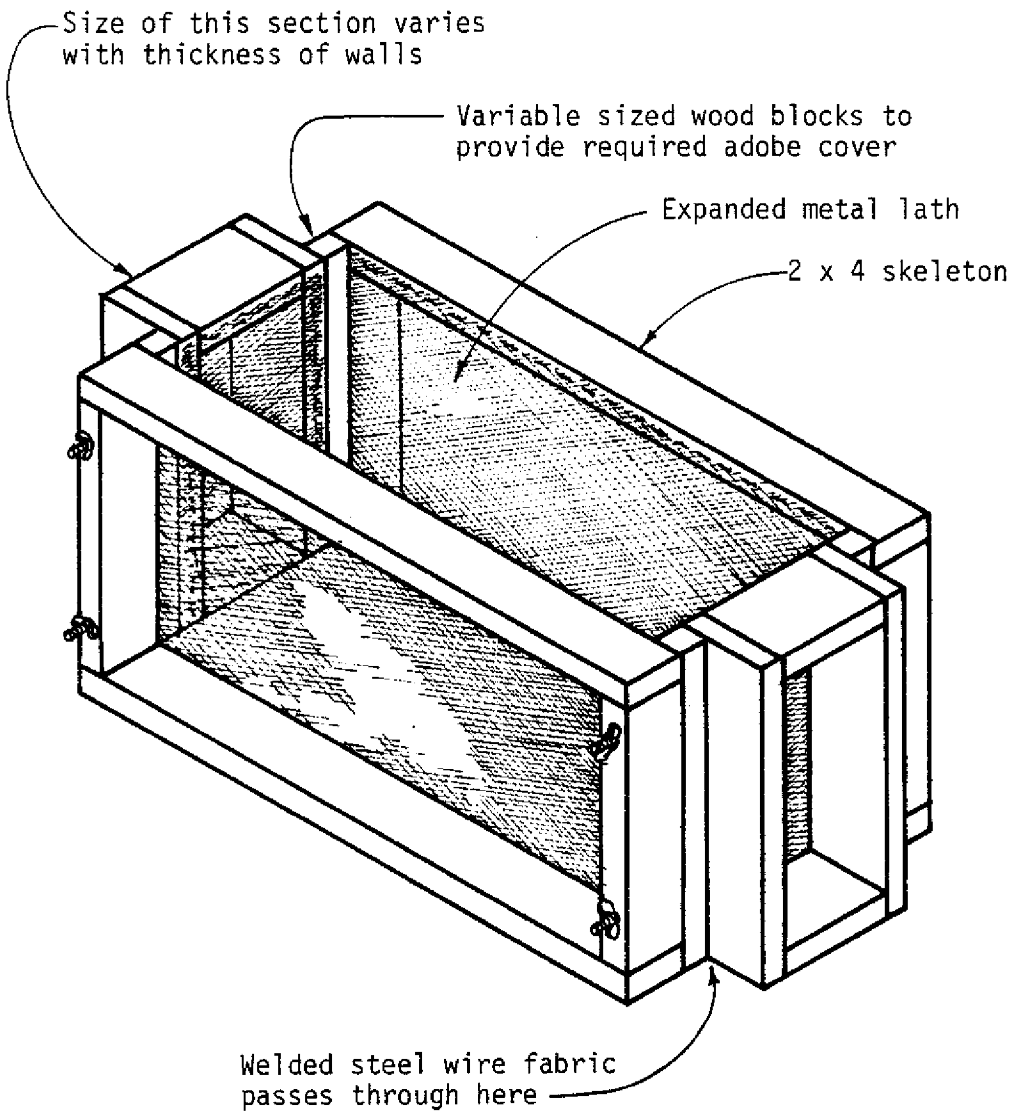


FIG. 7

Alternative Forming Block for
Reinforced Poured Adobe

Shrinkage Cracking

Shrinkage cracking appears to be another of the major problems to overcome in the application of poured adobe. This problem is amplified when steel reinforcing is embedded in the wet mix, since the adobe, when it drys, will tend to shrink away from the fixed position of the steel reinforcing. The following ideas are offered as potential mitigating schemes.

Superplasticizers

Schultz (11) has suggested the use of superplasticizers in adobe. Chemical additives to adobe, such as some of the lignin sulfonates, show potential as dispersants, binders, and emulsifiers. In the application to poured adobe the potential is greatest for reducing the required water content while maintaining the fluidity necessary to pour, thereby reducing shrinkage, shrinkage cracking, and drying time.

Fiber Reinforcing

The relatively high cost of man-made fibers as a reinforcing material has produced an interest in natural fibers as possible substitutes in construction. This is particularly true in developing nations where either the cost of reinforcement for seismic considerations represents a major portion of the total cost, or these man-made products are simply not available. A recent paper (12) in the American Concrete Journal describes the use of natural agave fibers, which exist in reasonably large quantities in many countries of the world, as possible reinforcement for Portland cement-based matrixes.

The logical extension of this technology to the issue at hand is the incorporation of natural fibers in the adobe mix as a reinforcement, providing ductility in a material normally characterized by brittle behavior.

The experimental program conducted by Castro and Naaman (12) included tests on individual fibers to determine strength, modulus of elasticity, and other physical properties, as well as flexural tests on fiber reinforced mortar specimens, to determine the influence of the volume fraction of the fibers. In a random sample of these agave fibers, the tensile strength ranged from about 40 to 70×10^3 psi, while the modulus of elasticity ranged from about 1.0 to 1.7×10^6 psi at 1.56 percent strain. These values compare quite favorably with man-made fibers.

Flexural tests were performed on mortar matrix specimens 12 inches long, 3 inches wide, and 1/2 inch thick. Fibers were cut to lengths of between 2 and 3 inches and mixed into the mortar in different volume fractions. Figure 8 shows average load-deflection curves of beam specimens reinforced with Maguey fibers for different volume fractions. It was generally observed that first cracking in flexure is not significantly influenced by the volume fraction of fibers. However, for a volume fraction greater than about 7 percent the load increases beyond first crack, providing the desired ductile behavior. Equivalent flexural stresses in the composite matrix with a 10 percent fiber volume fraction were

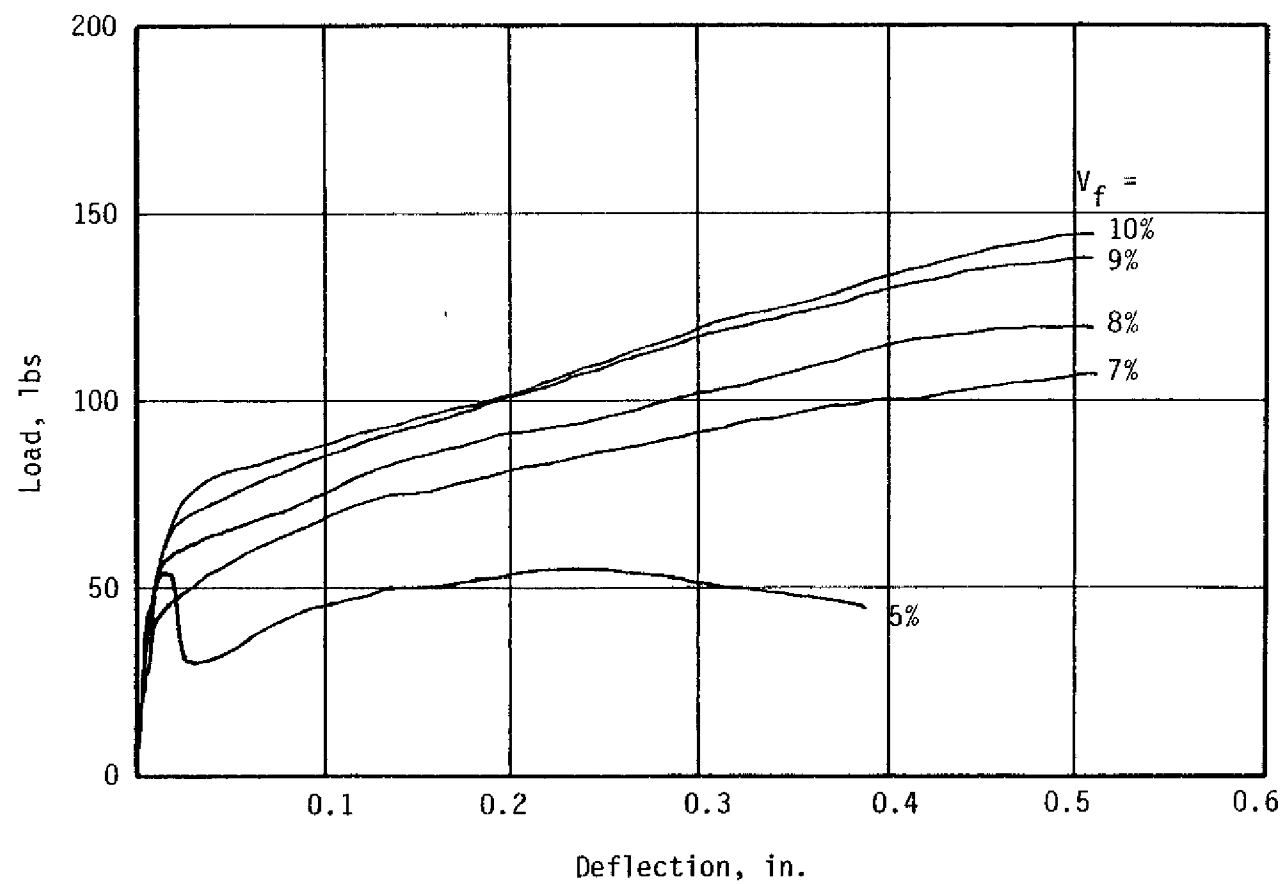


FIG. 8

Average Load-Deflection Curves of
Beams Reinforced with Maguey Fibers (12)

three times higher than the flexural strength of plain mortar specimens. It was also observed that with high fiber volume fractions the increased load capacity, after the first crack, was accompanied by multiple cracking in the specimens, showing a favorable distribution of stresses at ultimate load.

In the United States, man-made fibers such as polypropylene and polyester are readily available and relatively inexpensive, and, therefore, show promise in the poured adobe process. These fibers have ultimate strengths of between 50 and 80×10^3 psi and were primarily developed for use in the concrete industry to provide resistance to shrinkage cracking and to increase impact strength.

The addition of fibers to the adobe mix, in many respects, is analogous to the traditional addition of straw to help prevent cracking. However, the strength of the agave fibers and man-made fibers appear to be much greater than straw and can further provide resistance to brittle failure during earthquakes.

Bamboo Reinforcing

As a substitute for steel wire reinforcing, the use of bamboo shows potential for mitigating the shrinkage cracking of adobe associated with steel reinforcing. It was pointed out by Fang, et al. (13) that bamboo contains a large percentage of high strength fibers with ultimate strengths up to 25×10^3 psi.

The swelling and shrinking property of bamboo, which makes it undesirable for concrete construction, may in fact make it desirable for use in poured adobe construction. When dry bamboo absorbs water, swelling occurs. If the swelling pressure is large enough, it pushes the wet mix aside. At the end of the curing period for concrete the bamboo loses its water and shrinks at a greater rate than the concrete, leaving voids between the bamboo and concrete.

On the other hand, if wet bamboo is placed in poured adobe walls, both the adobe and the bamboo will shrink during the drying period for adobe. If the adobe mix is properly controlled, the shrinkage rates of the adobe and bamboo will be compatible, leaving no voids between adobe and bamboo.

Conclusions and Recommendations

The main conclusion of this paper is that the technique of using reinforced poured adobe as a structural load-bearing material can meet the intent of the UBC provisions for residential buildings in high seismic zones. The desired ductility and strength can be provided with the inclusion of welded steel wire fabric or other types of reinforcement in the walls. In lieu of experimental strength data, the existing technology for reinforced masonry appears to be adaptable to reinforced poured adobe.

Several areas of research needs are implied in this paper, the most pressing of which is the need for information on the static and dynamic behavior of poured adobe walls and structures subjected to vertical and lateral loads. Wall strengths must be tested both in-plane and out-of-plane. Many types of strength tests routinely performed on different masonry units will also prove to be appropriate for poured adobe. Shake table tests, similar to those performed by Meli, et al. (1) on unreinforced block adobe structures should be performed on scale reinforced poured adobe structures.

Finally, it is recommended that serious consideration be given to constructing and instrumenting one or more half-scale, half-strength poured adobe structures in an area of high seismicity, such as the Imperial Valley of California, where the occurrence rate of moderate-magnitude earthquakes is high enough to actually collect field data on the seismic behavior of these structures within a relatively short period of time.

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