STRUCTURAL ENGINEERING CRITERIA FOR ADOBE CONSTRUCTION

S. TANVIR WASTI [x]
POLAT GÜLKAN [x]

SUMMARY

A discussion of the seismic behaviour of adobe construction is presented. Using the provisions of the Uniform Building Code, an attempt is made to ascertain the structural adequacy of a two roomed adobe dwelling to lateral loads. Stress and overall stability checks are carried out for each wall. An experimental investigation of adobe structural components is proposed.

Keywords : Adobe, adobe walls, seismic loads, masonry, rural dwellings, structural design.

[x] Civil Engineering Department
Middle East Technical University

Ankara Turkey

INTRODUCTION

Earth, stone and timber are the oldest building materials known to man. Earth is still the most commonly used material of construction in large parts of the world, and in the form of sandy clay puddled with water it is known as adobe. Depending on soil types and climatic conditions, adobe construction can achieve both strength and durability. In low cost construction, especially in rural areas in Asia, Africa and the Americas where individual dwellings and farm structures are often built by the villagers themselves, adobe in some form is often the preferred building material. Construction in adobe ranges from simple one roomed dwellings such as depicted in Fig. 1 taken from a slum area in Lahore, Pakistan,to the ornate timber reinforced mosque from Mopti in Mali, West Africa, which is shown in Fig. 2. It is estimated that a quarter of all houses in the rural areas of Turkey are built of adobe {1}.

As a result of recently acquired knowledge of the behaviour of soils and partly of the increased housing demand in most countries, a vast amount of literature exist: on various aspects of earthen construction. The report on Earthen Home Construction ists a total of 294 items its bibliographies. There

o doubt that adobe as a construction material will be with us or a long time to come A thoughtful article by Germen {3} ighlights the historical and contemporary architectural importance f this versatile, readily available and relatively inexpensive uilding material.

Different properties of adobe have been the subject of everal research investigations in Turkey. In 1964 an "Adobe Seminar" was held in Ankara under the auspices of the Ministry of Construction and Settlement, wherein a lot of information on the mechanical properties of adobe and the manufacture of adobe blocks was presented. A detailed description of the physical parameters of clay was given by Kumbasar {4} and a discussion on the stabilization of clay was presented by Toğrol {5}. Alkan {1, 6} has continued research on the improvement of adobe blocks by the addition of various stabilizating ingredients. The earlier work of Sönmez {7, 8} also deserves special mention. The Adobe Seminar also incorporates a set of recommendations drawn up for adobe construction by the Turkish Bridge and Structural Engineering Association {9}.

In Fig. 3, an attempt is made to classify the main varieties of adobe used in rural construction.

With reference to Fig. 3, stabilization involves the employment of various physical or chemical additives (straw, lime, cement, bitumen, et to imp ve he strength, resistance to water or other properties of the re ting adobe. Structural adobe refers to load bearing components such as adobe walls, as opposed to adobe used strictly as an infill in timber framed construction or adobe plastering, which are considered non-structural. Finally, the difference between blocks and rammed earth is essentially one of technique; in rammed earth construction large forms are used and a whole layer of adobe placed and tamped in situ, whereas blocks are individual building bricks made and placed manually.

Adobe construction will probably continue to remain an art and a craft rather than develop into a science, but an engineering appraisal of the advantages and disadvantages of structural adobe and an assessment of some structural parameters related to adobe elements like bricks and walls may indirectly help to substantiate design assumptions that are tacit and traditional. Such an appraisal should seek to investigate whether the structural behaviour of adobe construction is amenable to theoretical approaches of the kind used for the prediction of the load carrying capacity of brick and stone masonry structures. It should be pointed out that the methods for the analysis and design of masonry structures themselves embody considerable departures from the generally established "rational" design procedures for steel, concrete and timber structures.

The present paper will deal mainly with structural engineering aspects of stalibized adobe blocks for structural use only. It may be considered as connected with the preservation of adobe structures only in the sense that stronger adobe bricks and better structural design and detailing lead to longer lasting structures.

II. SEISMIC BEHAVIOUR OF ADOBE STRUCTURES

One of the major defects of adobe as a constructional material lies in its inability to show adequate resistance to earthquake loading. The poor performance of adobe dwellings in seismic zones has been discussed in the case of Turkey by Arıoğlu and Anadol {10}, for Iran by Tchalenko and Ambraseys {11} and for Pakistan by Wasti and Ahmad {12}. These references point out that layers of mud-straw mix added to the roofs of village dwellings each year increase the roof weight, and in the event of an earthquake the heavy roof collapses and causes damage to life and property. As opposed to the unsatisfactory response of load-bearing adobe construction to lateral loads, it has been observed that adobe infilled timber frame construction when properly detailed and excuted shows satisfactory behaviour under earthquake loading {13, 14}. In proposals aimed at prevention of roof collapse in adobe and other "brittle" structures during earthquakes, Razani {15} suggests the incorporation of a braced skeleton system within the building. As also mentioned above, the main cause of destruction in non-engineering rural struc is due to the collapse of the roof and the retrofitting systems of Razani, if implemented, would not only decrease loss of life but help preserve adobe structures from complete failure in the event of an earthquake.

The Turkish Specifications for structures to be built in disaster areas {16} stipulate minimum wall thicknesses for adobe structures although in a separate section a required procedure for calculating lateral forces on structures, such as might be engendered in an earthquake, is also given. However, allowable stresses for adobe construction are not specified, and hence the calculated lateral forces cannot be applied to the design of adobe structural elements. The minimum wall thicknesses in the Specifications are given as 45 cm for load-bearing walls and 30 cm for non-bearing walls. In addition, the specifications require that the lateral stability of all walls be ensured by the provision of perpendicular intersecting walls spaced no further than 4.5 m centre to centre. Other clauses restrict the wall height to a maximum of 2.7 m and the maximum wall height to thickness ratio to 6 for bearing walls.

The measures incorporated in the Turkish Specifications ave been drawn mainly from the observed behaviour of adobe tructures and masonry structures under earthquake conditions in he past. As ıch, the ations consis of empirical restrictions intended to increase the safety of such buildings. For example, adobe dwellings are limited to single storey and flat earth roofs prohibited altogether in 1st and 2nd degree earthquake zones. The importance of timber bond beams, both along and transverse to the wall is stressed and limiting dimensions of door and window openings are given.

The 1976 Uniform Building Code {17} offers a slight improvement in that stresses for adobe masonry are specified for different conditions, as shown in Table 1. It should be noted that in the Uniform Building Code, adobe is referred to as masonry of unburned clay units". Among the general requirements, the minimum wall thickness for adobe is given as 40 cm and the height of an unsupported wall is restricted to a maximum of 10 times the wall thickness. Another difference between the Turkish Specifications and the Uniform Building Code is that the latter stipulates the use of Type M or S cement-line-aggregate mortar, whereas the former refers to a lime mortar only for the walls.

III. TOWARDS ADOBE STRUCTURAL DESIGN

Considerable research has been carried out with the purpose of providing an engineering framework for brick masonry calculations {18, 19}. The extensive use of brick masonry for residential nd office construction many industrially developed countries as led to refinements s as diaphragm walls consisting of parallel brick ls whose cavities are braced by transverse brickwork to form a series of box sections, and reinforced masonry, used especially in areas of seismic activity, wherein steel reinforcement is provided in high tension regions in beams and walls.

In his treatise on structural masonry, Sahlin [19] mentions the importance of the following properties separately for bricks and mortar :

(a) Compressive strength

(b) Tensile strength

(c) Modulus of elasticity

(d) Rate of water absorption

Based on an empirical syhthesis of structural theory with experimental results, Sahlin treats the strength and stability of concentrically and eccentrically loaded masonry walls.

The four properties given above also need to be investigated and standardized for adobe blocks, and for mortars used in adobe wall construction. It may then be possible to apply more rigorous analytical approaches to adobe structures.

In a preliminary attempt to ascertain the adequacy of adobe wall thickness specified by the Uniform Building Code to earthquake loads, a one-storey masonry dwelling will be analysed using the allowable unit stresses of Table I.

The chose hypothetical stru ture is shown in Fig. 4. The objective is to check the design, which in fa does conform typical dwellings made of adobe in several countries. Only the load-bearing walls are shown ; the problem is intended for the illustration of formal engineering procedures to such a structure, and it is not claimed that the representation is realistic.

III.1. Design Example : Lateral Force Calculation

The overall dimensions of the structure are 9.5m by 6 m. Interior or exterior partition walls or structural appendages like patios or verandahs, if any, are assumed not to contribute to the lateral force resistance of the system. It is also assumed that the flexible roof rafters span in the N-S direction and thus the calculation of forces and stresses need be made only for the more critical E-W direction.

The weight of adobe brick is taken as 2.0 tons/m^3 The roof of the dwelling is taken to be typical of rural buildings with relatively thick earthen layering, giving a weight of 0.8 tons/m^2 of roof area.

The base lateral shear force V for the dwelling during an earthquake is given by the Uniform Building Code as

$$V = Z\ I\ K\ C\ S\ W$$

where

Z = numerical constant dependent on the seismic zone. Here a highly seismic zone (Zone 4) wi l be assumed, for which Z =

= occupancy importance factor

= 1.0 for non-essential installations.

K = system coefficient, depending on ductility and bracing characteristics of the structural systems.

The most unfavourable value (for shear walls without ductile frame) of 1.33 will be taken.

C = "spectral" coefficient

S = soil resonance factor

The Code gives the upper limit for the product of C and S as 0.14, which will be taken. Hence CS = 0.14

W = Dead load, taken as weight of the roof and half the weight of the walls.

No snow load is considered for this case.

Assuming 0.5 m overhangs for the roof in the N-S direction, the roof area is (9.5 + 0.5 + 0.5)(6.0) = 63 m^2 and the weight is 0.8 x 63 = 50.4 tons.

The wall area in plan is 12.26 m^2 and the height of the walls is 2.70 m. Using the adobe brick weight of 2 tons/m^3, half the weight of the walls is calculated as 33.1 tons.

For the present structure, therefore, W = 83.5 tons and

V = (1.0)(1.0)(1.33)(0.14)(83.5)

= 15.5

say V = 16 tons.

The structural properties of walls A, B, C and D are given in detail in the Appendix. For each wall, the centroidal distance, moment of inertia and critical section modulus have been calculated.

III.2. Design Example : Distribution of Lateral Force

The E-W lateral force shall be distributed only to those portions of the bearing walls A, B, C and D that span in the E-W direction. Because of the assumption of a flexible roof, the lateral force will be distributed to these bearing wall portions in accordance with their tributary areas. Furthermore because the E-W portions of walls A and D are equal in length, they will each carry 50% of their share of lateral load, but the E-W portions of walls B and C will divide their share of the lateral load in the ratio of their lengths. The total lateral load of 16 tons is thus distributed as shown in Table 2.

III.3. Design Example : Calculation of Vertical Loading on Each Wall and Stress Checks

The roof load of 50.4 tons has to be shared by the walls in proportion to their tributary areas. Assuming also a live load contribution of 150 kg/m^2 on the roof, the dead, live and total vertical loading on each wall may be calculated as in Table 3. Values for wall A (North) are equal to those for wall A (South) and values for wall D (North) to those of wall D (South); hence alculations need to be made for the four cases A, B, and D nly.

be checked for each wall consist of the axial stress (compressive), the shear stress and the compound axial and flexural stress. Furthermore the overall stability of the wall to the overturning moment caused by the application of the lateral force component horizontally at the top of each wall has to be assessed. The checks are carried out for the walls A, B, C and D in Table 4 and 5.

IV. DISCUSSION

Recalling from Table 1 that the allowable stresses for compression are 2 kg/cm^2 and for shear or tension in flexure are 0.53 kg/cm^2 (with special inspection) the values in Table 5 indicate that all walls are satisfactory from the viewpoint of compressive stress, tensile stress and shear stress. However it is observed that the compression created by the total dead load in wall B is 2.18 kg/cm^2 which is greater that the allowable value of 2.0 kg/cm^2. As the Code permits an increase in the allowable stresses by 33% for seismic loading this figure is not critical. Furthermore it is observed from Table 4 that wall B is also unsatisfactory when its overturning stability is considered. One solution might be in arranging for the E-W legs of walls B and C to be more nearly equal, by shifting the intermediate door into a central position. However, the calculations have been made on the basis of [illegible]umulativel conservative a[illegible]s, e.g. the wall portions ove[illegible] and under the [illegible] and window openings ha[illegible] been take[illegible] as contribu[illegible]ng [illegible] strength

to the structure. In a more exact analysis it is likely that wall B will not be critical.

The roof of the one-storey adobe dwelling has been considered flexible although it is heavy. This is because of its inability to prevent rotation and its lack of in-plane rigidity.

The analysis followed in the design example suffers from omissions and limitations but the steps constitute part of a design process. Increased knowledge of material properties and structural behavior will enable more detailed application of engineering calculations to adobe structures.

V. EXPERIMENTAL INVESTIGATION OF COMPONENT STRUCTURAL ELEMENTS

Much experimental research also needs to be carried out to assess the structural behaviour of adobe dwellings under service loads and also overloads such as seismic loads. Ideally, full scale single storey adobe houses should be tested in tne same manner as the masonry structures tested on the University of California, Berkeley shaking table by Gülkan, Mayes and Clough {20}. Initially, however, it is probably more feasible to test structural components such as walls and small panels because simple components are more amenable to analysis and because the number of tests on such elements can be increased.

For brick masonry, earlier tests on component structural elements have been reported in Sahlin. Static and cyclic tests on masonry walls under axial and shear loads and separately undei bending moments and axial forces in order to obtain information on the seismic behaviour of masonry are also being conducted by Anicic {21} in Yugoslavia.

On the basis of the above experimental investigations on brick masonry, the following preliminary tests on adobe wall panels may be proposed :

1) The loading of square adobe brick panels (each side measuring approximately 1 m) under different combinations of diagonal and normal loads as shown in Fig. 5 to study the shear strength and possible failure criteria.

2) An evaluation of the out-of-plane strength of rectangular panels (measuring up to 1.2 m by 2.5 m) under various combinations of eccentric axial loads and lateral pressure as indicated in Fig. 6. The objective of this type of "bulge" test would be to ascertain the suitability of a concrete-like (moment M-axial force N) interaction diagram for adobe.

3) The simulation of a frame enclosing an adobe filler wall may be accomplished most simply as shown in Fig. 7 where a reusable vertical steel column is used to apply lateral loads to adobe masonry walls. The effect of varying the height of the adobe nfill on the deflection of the steel column can give an ndication of the increase in the stiffness of the system

imparted by the ler wall. t is expected that over the next few years a series of tests along the above lines will be ~~planned and executed in the Civil Engineering Department of~~ Middle East Technical University in cooperation with appropriate government agencies in Turkey.

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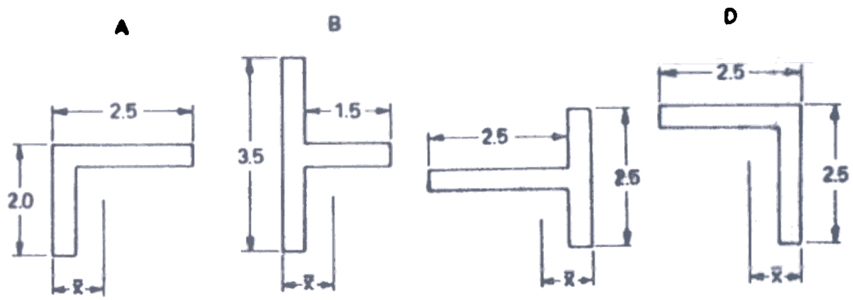
APPENDIX

Structural Properties of Walls E-W Direction



All dimensions in meters. Wall thickness 0.45 m.

Wall Type	Area m^2	Centroidal Distance $\bar{x}$ m	Moment of Inertia I m^4	Section Modulus S m^3
A	1.82	0.85	2.03	1.23
B	2.26	0.52	0.99	0.67
C	2.26	0.96	3.62	1.77
D	2.05	0.78	2.10	1.22

TABLE 1. ALLOWABLE WORKING STRESSES IN ADOBE MASONRY
{UNIFORM BUILDING CODE}

Type of Loading		Compression	Shear or Tension in flexure*	
Type of Mortar		M or S		
Allowable Working Stresses	kg/cm^2	2	With special inspection 0.53	Without Special inspection 0.26
	kilo-Pascals	207	55	27.5

* Value based on tension across a bed joint, i.e. vertically in the normal masonry work.

TABLE 2. DISTRIBUTION OF E-W LATERAL FORCE TO WALLS

WALL	PERCENTAGE OF E-W LATERAL LOAD	LOAD PER WALL (TONS)
A (North)	13%	2.1
D (North)	13%	2.1
B	18%	2.9
C	30%	4.8
A(South)	13%	2.1
D(South)	13%	2.1

TABLE 3. WALL VERTICAL LOADING (TONS)

WALL	DEAD LOAD	LIVE LOAD	DEAD + LIVE LOAD
A	7.2	1.35	8.55
B	9.0	1.69	10.69
C	10.2	1.91	12.11
D	8.4	1.58	9.98

TABLE 4. STABILITY CHECKS

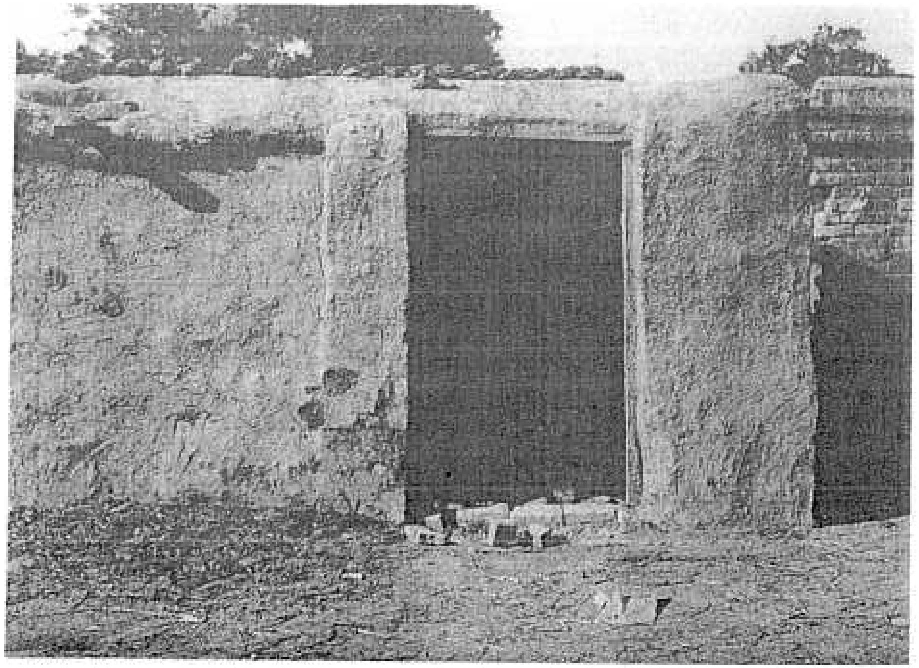
WALL	LATERAL FORCE V (TONS)	OVER-TURNING MOMENT M_o (T-M) $=2.70V$	DEAD LOAD RESISTING MOMENT M_R (WEIGHT OF WALL+DEAD LOAD) TIMES CENTROIDAL DISTANCE $\bar{x}$	$\frac{M_R}{M_o}$	REMARKS
A	2.1	5.67	14.47	2.55	>1.5 O.K.
B	2.9	7.83	11.03	1.41	<1.5 N.G.
C	4.8	12.96	21.51	1.66	>1.5 O.K.
D	2.1	5.67	15.19	2.68	>1.5 O.K.

TABLE 5. STRESS CHECKS

WALL	LATERAL FORCE V (TONS)	SHEAR STRESS* τ (KG/CM^2)	COMPRESSIVE STRESS** σ (KG/CM^2)	COMPOUND STRESS (KG/CM^2) $\sigma \pm \frac{M_o}{\text{SECTION MODULUS S}}$
A	2.1	0.19	1.01	1.01 + 0.46 = 1.47 1.01 - 0.46 = 0.55
B	2.9	0.32	1.01	1.01 + 1.17 = 2.18 1.01 - 1.17 = -0.16
C	4.8	0.36	1.08	1.08 + 0.73 = 1.81 1.08 - 0.73 = 0.35
D	2.1	0.19	1.03	1.03 + 0.46 = 1.49 1.03 - 0.46 = 0.57

* τ = V/ AREA OF E-W PORTION OF WALL

** σ = DEAD + LIVE LOAD/TOTAL WALL AREA



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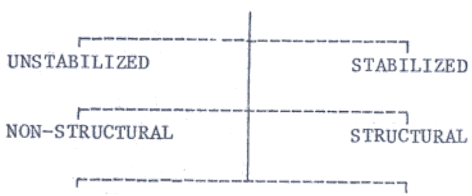

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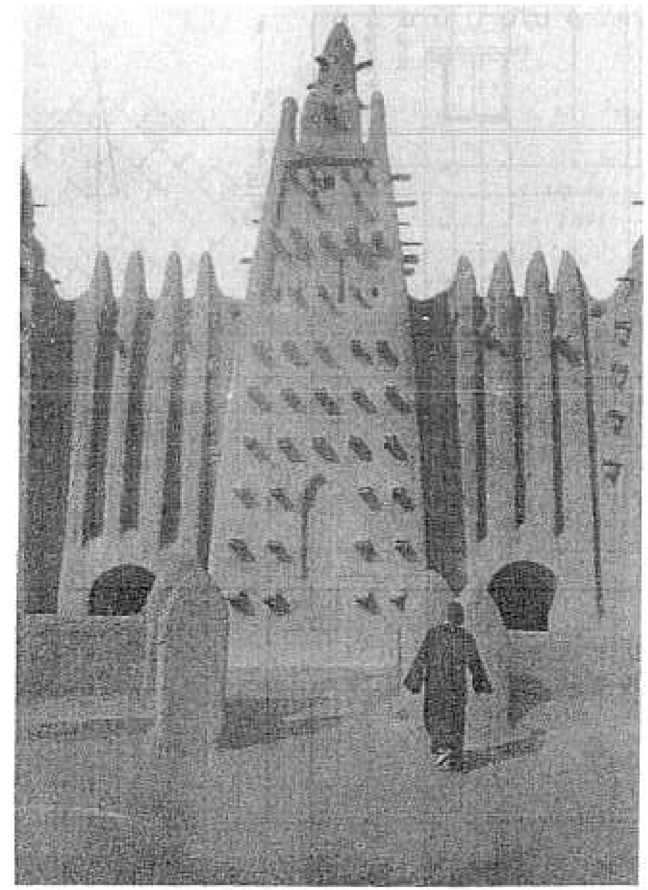

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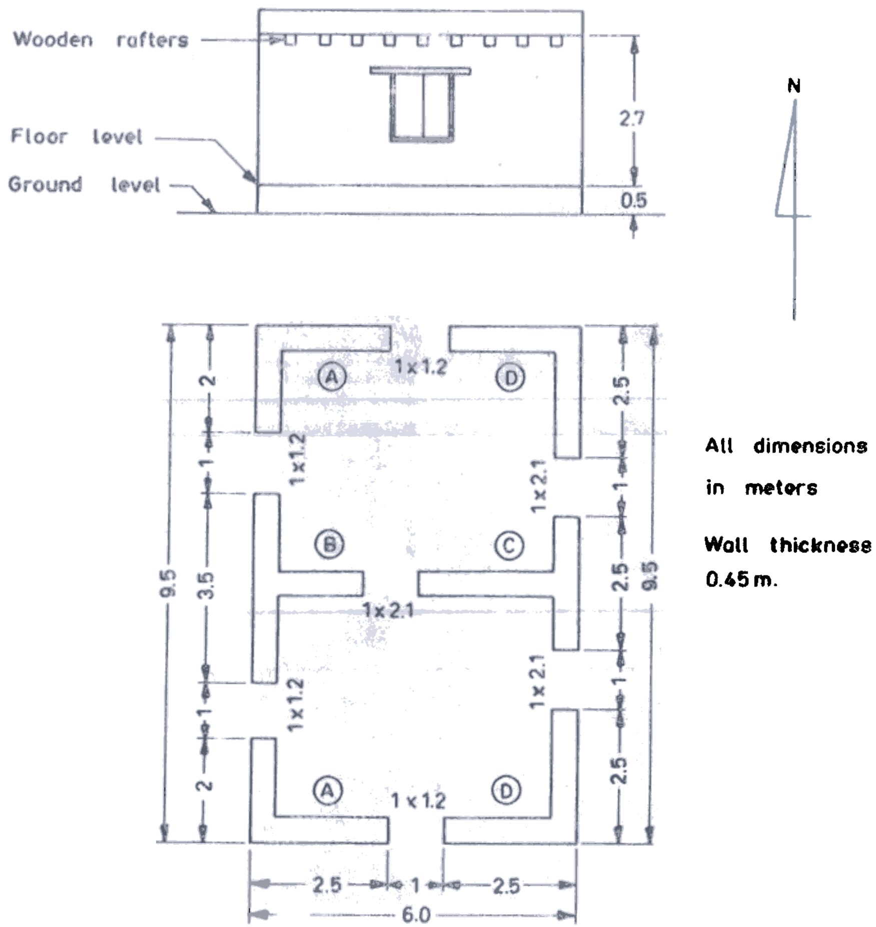

Fig. 4 Design Example

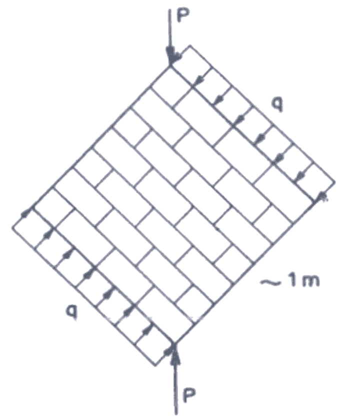

Fig. 5 Adobe Brick Panels

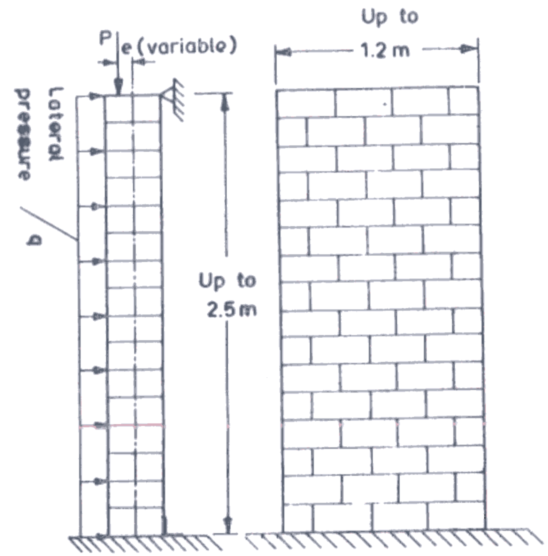

Fig. 6 Bulge Test on Adobe Walls

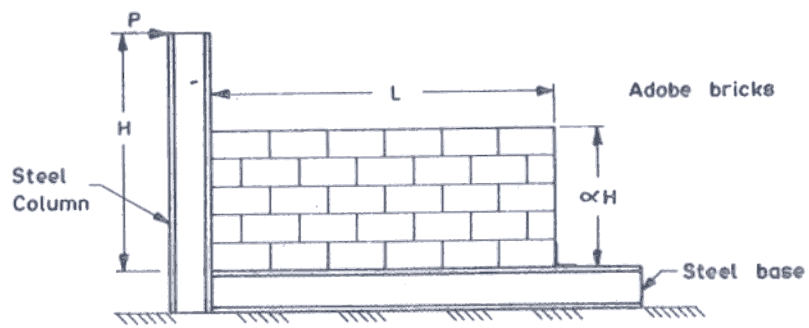

Fig. 7 imulation of Frame and Infill Wall