STRENGTHENING OF BRICK BUILDINGS
AGAINST EARTHQUAKE FORCES

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SYNOPSIS

Strengthening of brick buildings against earthquake forces is of immediate consequence to many seismic countries using this form of construction. This paper includes information about significant properties of brick masonry in different mortars, strength of shear walls and the single storeyed brick house models. Different methods of reinforcing them have been examined.

INTRODUCTION

Many countries are faced with the problem of earthquakes destroying many buildings from time to time. The problem is more acute in such areas where steel, reinforced concrete or timber construction cannot be taken up extensively for want of materials and finance. The usual mode of construction consists of brickwork in mortars of different kind without any reinforcement against earthquake forces. The construction practices in these countries have developed with the experience gained by the inhabitants over the ages keeping the requirements of weather, availability of materials and the cost in view but not so much the earthquakes. It is not possible to change it into steel, concrete or timber construction immediately. In course of time, with the industrial development and improvement in the economic position of people this may be feasible. Till such time, it is essential to study the present form of construction strengthening them so that they can resist earthquakes better even though they may not equal the strength of construction with other materials. This itself will be a gain and cut down the loss of life and property. This paper presents the study that has been taken up at the Earthquake Research School, Roorkee with this end in view, and suggest different methods of strengthening brick houses.

Some work on brick walls has been done in Canada, U.S.A.[1] and the experience gained there as well as here brings forth 'Workmanship' as the most important factor which affects the strength of brickwork. Since it is very difficult to take this into account in either analytical or experimental work, the results obtained are

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bound to show considerable scatter. They however, give qualitative indications of strength and weakness and offer adequate guidance in comparing the relative merits of different methods of strengthening.

The study undertaken has been divided up as follows:

I. Determination of the Strength for Brickwork in different mortars in compression, tension(bending), direct tension (bond), and Elastic modulus. (For purpose of keeping the factor of workmanship uniform, the same bricklayer was utilized throughout the work. Overall dimensions have been adjusted to ensure the same quantity and thickness of mortar in different models. These steps cut down the scatter between the strength of differant specimens of the same kind to a considerable extent.)

II. Damping of brick columns in different mortars and at various stages of stress.

III. Analytical and experimental study of the positioning of openings in walls.

IV. Relative strength of single room brick house models built in 1:6 cement sand mortar when reinforced as follows:

a) Normal construction without any reinforcement.
b) Providing a lintel band.
c) Providing lintel and plinth bands.
d) Providing vertical steel at corners only.
e) Providing vertical steel at Jambs only.
f) Providing vertical steel at corners as well as at Jambs.
g) Lintel band in combination with (d),(e) and (f).

In the following paragraphs the work done under above headings is presented.

I - STRENGTH AND ELASTIC MODULUS OF BRICKWORK

Various strength properties of brickwork in different mortars were determined. They are (i) Tensile Strength (ii) Compressive strength and (iii) Strength under combined stress conditions. For this purpose brick mortar couplets were prepared and tested under various stress conditions. Fig. 1 shows the various angles of testing brick couplets. Table-1 gives the results obtained.

TABLE - 1

MORTAR	Ultimate load in lbs			
	0°	90°	120°	135°
1:3 Cement Sand	-	-	740	1075
1:6 Cement Sand	32	53	327	692
1:12+ Cement Sand	23	40	80.5	213
1:2 Lime Surkhi ++	47	98	258	358
1:2 Cinder	36	74	128	269
Mud	9	48	89.5	128

The 0° test revealed that the pure tensile strength obtained from this test gave considerable scatter from specimen to specimen and that it is very sensitive to test procedure. Hence it was decided to find it by some other method also. For this purpose 18in. high brick columns 3 in. x 3 in. and 3in. x $6^1/2$ in in section were tested as vertical cantilevers and bending tension was calculated from the load that caused the first appearance of crack in tension. The results are shown in table 2 along with other properties of brickwork that were determined.

The tensile strength obtained from the column test is more consistent for the group of columns constructed in the same mortar. This may be because the unknown and variable eccentricity in the 0° test led to greater scatter. As such, the tensile strength obtained by the column test is recommended for use in analytical work particularly because the main resistance offered by a brickhouse against horizontal forces is through the tensile strength, of the mortar.

For compressive strength, brick cubes of 6 in. size were tested. The results obtained for different mortars are included in Table 2. The results indicate that the variation in compressive strength for different mortars is comparatively small whereas the tensile strength changes over a wide range(See Table 2).

ELASTIC MODULUS

The elastic modulus (E) for brickwork was determined both for static and dynamic conditions.

+Machine mixing of mortar will improve the strength. The results here indicate what may be expected with manual work.
++Surkhi is powdered brick having puzzuolanic properties.

For the static tests, brick columns of section 5 in. x 5 in. and height 28.5 in. were tested as vertical cantilevers[2]. Horizontal deflections were measured and E was calculated. Fig. 2 shows the arrangement of loading.

Load deflection curves for columns in different mortars are shown in Fig.3. The initial straight line portion of the curve is used for calculation of E. These values are shown in Table 2.

The dynamic modulus of elasticity (E') was calculated from the free vibration records of brick columns. If A is the area of cross section of the vibrating column, I the moment of inertia of column section about the bending axis, γ the density of material, the frequency of vibration for a uniform cantilever of length l is given by

$$f = \frac{1}{2\pi} \cdot \frac{3.516}{l^2} \sqrt{\frac{E' I g}{A \gamma}} \qquad \text{.........(1)}$$

which gives

$$E' = \frac{4\pi^2 f^2 l^4 . A \gamma}{(3.516)^2 \; I . g.}$$

The values of E' are included in Table 2. A comparison of values of E and E' will show that the dynamic value of elastic modulus is consistently higher than the static value. This of course, is well known for concrete and sems to be reasonable for brickwork.

TABLE 2

MORTAR	Tensile Strength p.s.i.	Comp Strength p.s.i.	E x 10^6 p.s.i.	E′ x 10^6 p.s.i.
1:3 Cement Sand	100.4	1340	0.24	0.33
1:6 Cement Sand	35.4	870	0.17	0.24
1:12 Cement Sand	5.1	765	0.11	0.21
1:2 Lime Surkhi	13.5	834	0.14	0.14
1:2 Lime Cinder	8.5	752	0.10	0.15
Mud	4.5	675	0.06	0.07

II - DAMPING CHARACTERISTICS

Damping was determined from the free vibration records of brick columns in different mortars and assuming viscous damping. The transducer used was a system of strain gauges mounted on the column. This was specially useful in determining the effect of strain conditions on the damping characteristics. The results confirm that damping increases appreciably with strain. It varies as follows:

MORTAR	Damping as % of critical damping rising with the increase in strain.
1:3 Cement Sand	1.8% to 5.5%
1:6 Cement Sand	2.2% to 6.2%
1:12 Cement Sand	3.8% to 7.5%

These results have been shown in Fig.4.

III - ANALYSIS OF BRICK STRUCTURES FOR EARTHQUAKE FORCES

As a first step towards analysis of brick building, shear walls by themselves were analysed for earthquake forces and the results were verified through experiments on models[3].

For analysis, the horizontal shear has been distributed among the participating constituents in the ratio of their stiffness. The wall analysed had one opening only. The following variable parameters were studied.

(i) b/h - length to height ratio of the shear wall.

(ii) m - which determines the vertical placing of opening (being the distance from the bottom of wall to the centre of opening expressed as fraction of 'h')

(iii) n - which determines the horizontal placing of the opening (being thedistance from the left end of wall to the centre of opening expressed as fraction of 'b')

(iv) x - a fraction of 'b' determining half the width of opening.

(v) y - a fraction of 'h' determining half the height of opening.

The wall is shown in Fig.5.

In the theoretical analysis, expressions were derived for the lateral load carrying capacity of the wall. Taking C as the coefficient of lateral force(expressed as percentage of gravity)the following inequalities determine the strength of the wall. The least value of C from equation 2 to 6 gives the maximum value of lateral force coefficient which the wall is capable of withstanding.

1. $C \leq \frac{I}{b} \cdot f_1 + p_1$ ... ... (2)

2. $C \leq \frac{I}{b} \cdot f_2 + p_2$ ... ... (3)

3. $C \leq \frac{I}{b} \cdot f_3 + p_3$ ... ... (4)

4. $C \leq \frac{I}{b} \cdot f_4 + p_4$ ... ... (5)

5. $C \leq \frac{I}{b} \cdot f + p$ ... ... (6)

where ,

$$f_1 = \frac{1 \cdot 8\,(n-x)}{\varepsilon_s} \quad ; \quad p_1 = \frac{n-\theta}{\varepsilon_s}$$

$$f_2 = \frac{1 \cdot 8\,(n-x)}{\rho} \quad ; \quad p_2 = \frac{n+\theta}{\rho}$$

$$f_3 = \frac{1 \cdot 8\,(1-n-x)}{T} \quad ; \quad p_3 = \frac{\psi-\phi}{T}$$

$$f_4 = \frac{1 \cdot 8\,(1-n-x)}{\varsigma} \quad ; \quad p_4 = \frac{\psi+\phi}{\varsigma}$$

$$f = \frac{1 \cdot 2}{4/(b/h) + 3/(b/h)^2} \quad ; \quad p = \frac{1/3 + 1/(b/h)}{4/(b/h) + 3/(b/h)^2}$$

and

$$\varepsilon_s = -P + Q + W \quad ; \quad \rho = P + Q + W$$

$$T = -P + R + W \quad ; \quad \varsigma = P + R + W$$

Also,

$$P = \frac{4 \cdot 5\, y^2}{(b/h)^2} \quad ; \quad Q = \frac{6\,\gamma\, y}{(b/h)(n-x)}$$

$$R = \frac{6\,\delta\, y}{(b/h)(1-n-x)}$$

$$w = \frac{1}{(1+2x)(b/h)} \left[2(1-m) + \frac{1.5}{(b/h)} \left\{ (1-m)^2 - 2xy^2 \right\} \right]$$

and

$$\gamma = \alpha \left[1 + \frac{1.5}{(b/h)} \left\{ 1 - m - 1.25\, y (0.3 + x) \right\} \right] + \frac{0.562\, y (n-x)}{(b/h)}$$

$$\delta = 1 + \frac{1.5}{(b/h)} (1 - m - 2xy) - \gamma$$

where

$$\alpha = \frac{1}{1 + A} \quad \text{with}$$

$$A = \frac{1-n-x}{n-x} \; \frac{\left[\frac{y}{(b/h)} \cdot \frac{1}{n-x} \right]^2 + 0.6}{\left[\frac{y}{(b/h)} \cdot \frac{1}{1-n-x} \right]^2 + 0.6}$$

Again,

$$\psi = \frac{1-n-x}{1+2x} \left\{ 0.5 + \frac{1.5}{(b/h)} (1-m-y) \right\} + \frac{1.5\, y}{(b/h)} (1-n-x)$$

$$\eta = 0.5 + \frac{1.5}{(b/h)} (1 - m - 2xy) - \psi$$

$$\theta = \frac{1.5}{(b/h)} \cdot y (n-x)$$

$$\phi = \frac{1.5}{(b/h)} \cdot y (1-n-x)$$

Thus we see that the independent variables in the above five inequalities are:

1. 'T' the tensile strength in bond.

2. 'b' the length of wall

3. 'b/h' ratio

4. 'x', 'y'.

5. 'm' and 'n'.

The variation of 'b/h', 'x', 'y', 'm' and 'n' has been studied. The length 'b' and 'T' have been kept constant. The following conclusions are drawn on the basis of this study.

(i) Strength of wall increases with the tensile strength of bond of brick masonry which would suggest the use of richer mixes of mortar in seismic zones.

(ii) Strength of wall increases as (b/h) increases.

(iii) (b/h) remaining fixed.

(a) 'x', 'y' and 'm' remaining same, strength of wall increases as 'n' $\rightarrow$ 0.5.

(b) 'x', 'y' and 'n' remaining same, strength of wall increase as 'm' increases.

(c) 'm' and 'n' remaining same the strength of wall increases as size of opening decreases.

These were confirmed by experimental study of unbonded shear wall models under horizontal loads. During the wall tests it was found that failures were by splitting at the brick mortar contact surface due to tension and there was no slipping from which it is concluded that failure of brick masonry begins due to tensile failure of brick mortar bond, shear stresses not being critical. The ultimate failure or collapse conditions combines in it tensile failure due to bending as well as shear.

THEORETICAL ANALYSIS OF ONE STOREY BRICK BUILDING

Fig.6 shows the building chosen for the purpose of study. The building has two shear walls and two cross walls. One of the shear walls has a door and a window while the other one has two windows only. The behaviour of the building could be of one of the following types:

I. Shear wall action with sections through openings as the critical sections.

II. Vertical cantilever action with the four walls forming the box section of the cantilever. This assumes full bonding effect of the cross walls.

III. Vertical cantilever action with only the shear walls providing the moment of resistance. This neglects the effect of cross walls.

Type I: The structure is treated as follows:

(i) The shear (F) is distributed among the piers in proportional to their shear stiffness(I/L^3). For convenience, putting (I/L^3) as S, we get

$S_1 : S_2 : S_3 = 8 : 101.6 : 1$ where the subscripts refer to the pier number as indicated in fig. 7

Distributing shear in proportion to shear stiffness, we get,

$$F_1 = 0.072\ F, \quad F_2 = 0.920\ F, \text{ and } F_3 = 0.009\ F \quad \ldots\ldots.(7)$$

(ii) The vertical reactions (R's) at the piers are calculated by assuming that the elongation of piers is proportional to the distance from the neutral axis. If $\bar{x}$ is the distance (Fig. 7) we get,

$$R_1 = \frac{-K\bar{x}A_1E}{L_1} \quad \ldots\ldots.(8)$$

$$R_2 = \frac{K(a-\bar{x})A_2E}{L_2} \quad \ldots\ldots.(9)$$

$$R_3 = \frac{K(a+b-\bar{x})A_3E}{L_3} \quad \ldots\ldots(10)$$

Also, $R_1 + R_2 + R_3$ = Total vertical load = Roof slab + wall upto mid height of piers
= 37 lbs ....(11)

Putting the values of R in equation 8,9 and 10 we get

$90\,K - 11.5K\,\bar{x} = 92.5$ ....(12)

and $237K - 46.8\,K\,\bar{x} = 8.55\,F - 352$ ....(13)

which give the values of K and $K\,\bar{x}$, and hence the vertical reaction at the piers.

Knowing the reactions and shears, stresses on the sections around jambs are calculated by superimposing direct and bending stresses. This approach indicates that a building in 1:6 cement sand mortar will fail at the Pier III when the horizontal load F is about 850 lbs.

Types II and III

This method assumes that the building is a vertical cantilever fixed at the plinth level.

Bending Moment $M = F \times L$. see Fig. 7 ....(14)

I_1 = moment of inertia(considering full bounding effect)

$= 9600\ in^4$

I_2 = moment of inertia(considering no bounding effect)

$= 3460\ in^4$

Maximum Tensile stress(bending) $T = (M/I)\,y$ ....(15)

If T is equated to the ultimate tensile strength of particular mortar, the strength of the building in terms of shear force 'F' is obtained. Thus

$F_1 = 2300$ lb and $F_2 = 800$ lb

It can be seen that the strength of the building(when the effect of cross walls is neglected)is much less than what it would be if the walls are fully bonded. In an actual construction the condition may be somewhere in between the two cases since the side walls may not offer 100% fixity but would do so to a great extent.

An average of the two will perhaps be closer to realistic condition.

Experiments also indicated that the actual behaviour of structure lies in between the types II and III as discussed above.

STRENGTHENING OF BUILDINGS

So far we have been analysing unreinforced brick buildings only. As such the lateral force which a building can stand is very small. To increase this some strengthening methods have been tested. These methods consist of providing horizontal and vertical steel at various positions as mentioned earlier. It was proposed to study the effect of each type of reinforcement on the lateral strength of the brick building.

For this purpose models of the house under study were constructed and tested for lateral loads as shown in Fig.8. The ultimate strength of the house with different methods of strengthening was determined. Table 3, gives an idea of the strength that various types of reinforcements provide.

TABLE 3

	Average Ultimate load in lbs.
1. House unreinforced	610
2. With Lintel Band	610
3. With lintel and plinth bands	750
4. Vertical steel at corners only	1800
5. Vertical steel at Jambs only	800
6. Vertical steel at Jambs and corners	2500
7. Vertical steel at corners + lintel band	2000
8. Vertical steel at Jambs + lintel band	1000
9. Vertical steel at Jambs + corners + Lintel band	2700

An examination of table 3 reveals that

1. Horizontal steel alone at lintel level does not

contribute to strength as the failure occurs at the plinth level, with the steel at lintel level not playing any part. The overall stiffness against cantilever action is, however, increased and would certainly delay the actual collapse of the structure. The result here only shows that the ultimate load carrying capacity against extensive cracking is not increased by the provision of a lintel band.

2. Vertical steel at corners is very effective and increases the strength of the structure considerably. It will delay the initial cracking and take much more load before final collapse.

3. Vertical steel at jambs only does not prevent the initial failure of the structure but does increase the overall resistance of the structure since corners near jambs are vulnerable to failure due to diagonal tension.

4. Combination of horizontal steel at lintel level and vertical steel at corners is still stronger a combination and of course, if vertical steel at jambs is also present, the effect is very much pronounced. The relative importance of each type of reinforcement is shown in Table 3.

Further work on such buildings is in progress.

REFERENCES

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3. Agnihotri, V.K., "Strength of Single Storeyed Brick Shear Walls Against Earthquake Forces", Master of Engineering Thesis, University of Roorkee, Roorkee, August 1962.

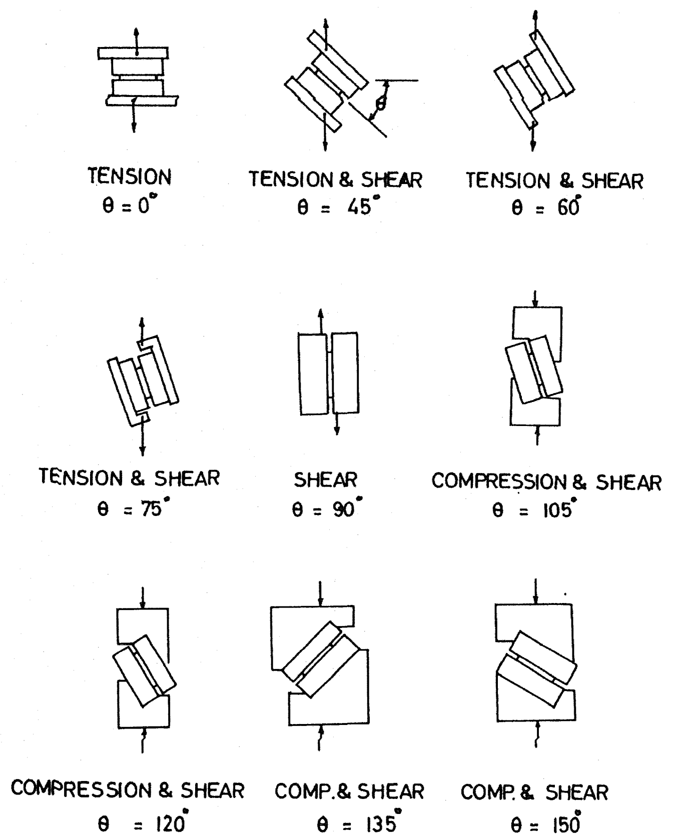


FIG.1_ARRANGEMENTS FOR COMBINED STRESS TESTS FOR MORTAR JOINT.

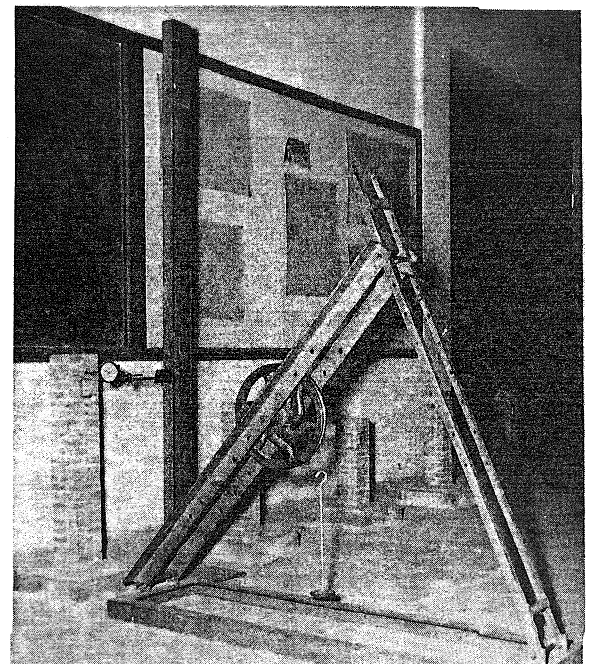


Fig. 2 - SET UP FOR TESTING BRICK COLUM[N] UNDER HORIZONTAL LOAD

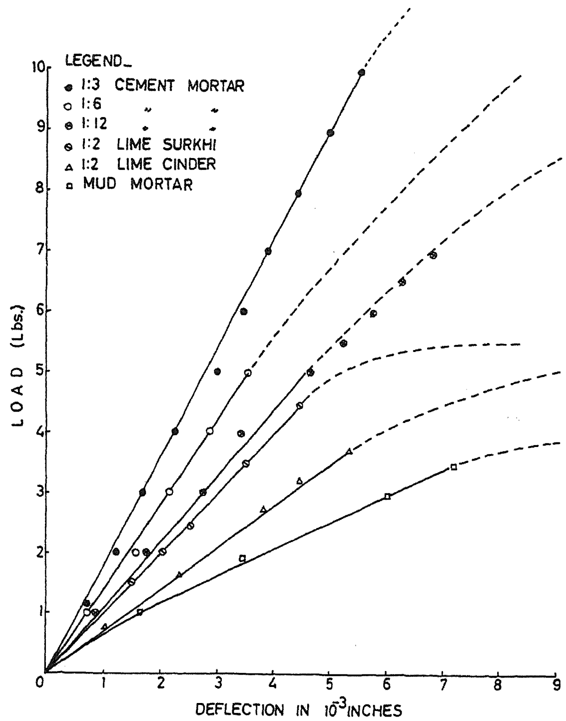


FIG.3_ LOAD DEFLECTION CURVES FOR BRICK COLUMN IN DIFFERENT MORTARS

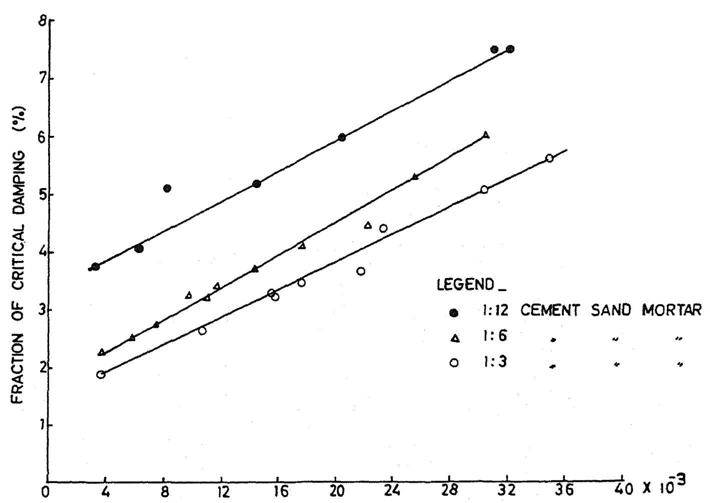


FIG.4_VARIATION OF DAMPING FACTOR WITH THE INCREASE OF STRAIN IN THE COLUMNS BUILT IN DIFFERENT MORTARS.

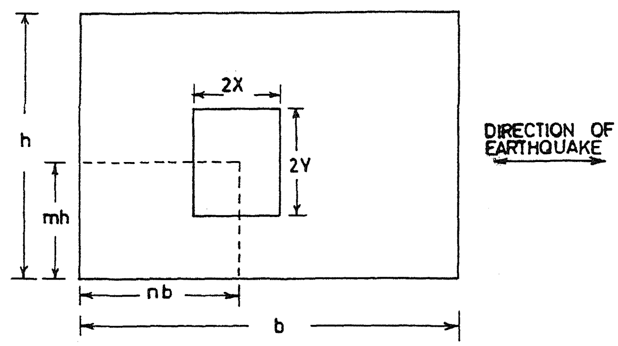


FIG.5_ THE SHEAR WALL

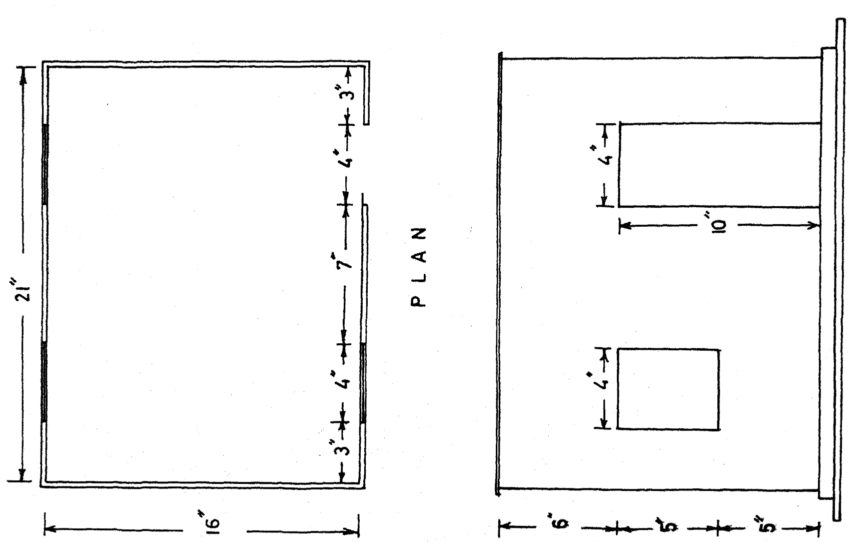


FIG.6_ EXPERIMENTAL BUILDING

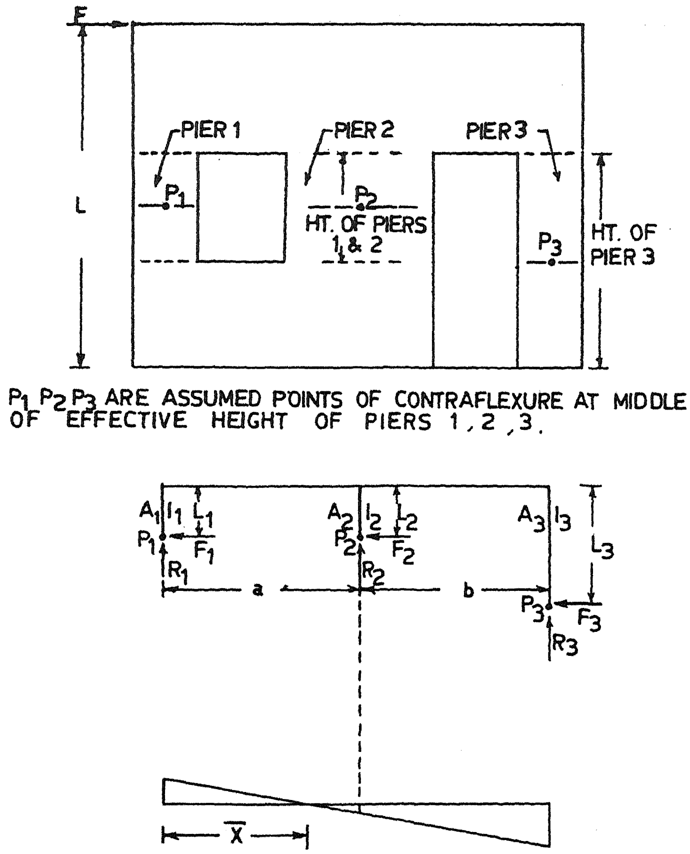
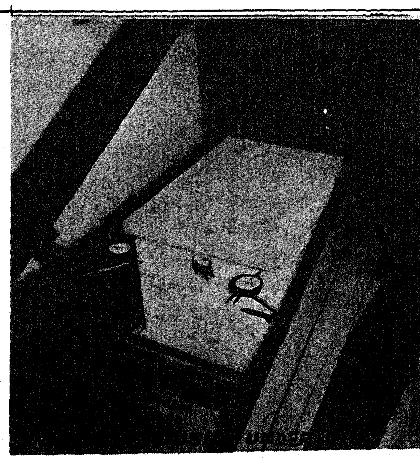


FIG. 7_ EQUIVALENT STRUCTURE



STRENGTHENING OF BRICK BUILDINGS AGAINST EARTHQUAKE FORCES

BY J. KRISHNA AND B. CHANDRA

QUESTION BY: I.L. HOLMES - NEW ZEALAND

I would refer to the interesting results of Table 3. This illustrates the type of framing that can be applied to masonry to achieve the framing effect to improve ductility in earthquake such as referred to by Dr. Borges in discussion this morning. Steel at the corners greatly increases the strength and this steel need not be provided as a separate frame material such as reinforced concrete or structural steel. In fact, if it is provided within the masonry a multiple framing effect is obtained because the steel at jambs and lintels further increases its strength.

A further problem is illustrated, and that is the question of how much shear steel, uniformly distributed in the body of the wall is necessary to assist the ductility. It is a question that concerns us in New Zealand. Has Dr. Krishna any comment on the usefulness of shear reinforcing?

QUESTION BY: L.F. KENNA - NEW ZEALAND

1. Can ductility be regarded as a function of steel content?
2. Would the author comment on the importance of mortar and brick characteristics?

AUTHOR'S REPLY: Unreinforced brickwork is a brittle material and its energy absorbing capacity is limited by the elastic strains it could develop before failure. In order to increase this capacity, therefore, steel is recommended to be introduced in appropriate positions. It was observed that steel bars were most effective at corners and the "lintel bands", though useful, did not contribute additional strength per unit weight to the same extent. Work is now in hand to determine the optimum percentage of steel in various positions.

Just like other structures, the shear reinforcement in the case of brickwalls also, plays its part after considerable flexural deformation has taken place. It delays the ultimate failure if used with corner steel, and would serve a useful purpose particularly for short duration earthquake forces. Without corner steel, however, their utility will be very limited.

As regards the question raised by Mr. L.F. Kenna, about the importance of mortar and brick characteristics it can be said that the initial shock of the earthquake is borne by the brick mortar composite only. The stronger the mortar, therefore, the higher the total resistance of the structure.