IN-PLANE BENDING OF CLAY BRICK WALLS

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ABSTRACT Five brick walls have been tested in in-plane bending simulating the action which would occur under a vertical wall when the support settles. The tests were carried out in the 'hogging' mode using a single central support. This paper examines the brick tensile failure mode. Strain readings were taken on bricks and joints and from the deformations observed a model of the failure mechanism was developed.

1. INTRODUCTION

Cracking of stretcher bonded brick walls due to support movements is common and this movement produces a bending failure of the wall either in the hogging or sagging mode. Such walls fail either by shear bond failure of the bed joints producing a stepped failure pattern or by brick tensile and perpend joint tensile bond failure. Previous authors (1) have investigated brickwork bending by carrying out tests and establishing a theory at 'working loads'. Abu-El-Magd and MacLeod (2) investigated the bed joint shear failure. The present paper reports a series of tests aimed at producing the brick tensile type of failure. This type of failure is the one observed in recent brickwork construction with the use of strong mortars.

2. MATERIALS TESTS

2.1 Bricks

The bricks used were 'New Aberdare Class B Engineering', an extruded wire cut brick with three 37 diameter (mean) holes. The properties of the bricks are given in Table 1.

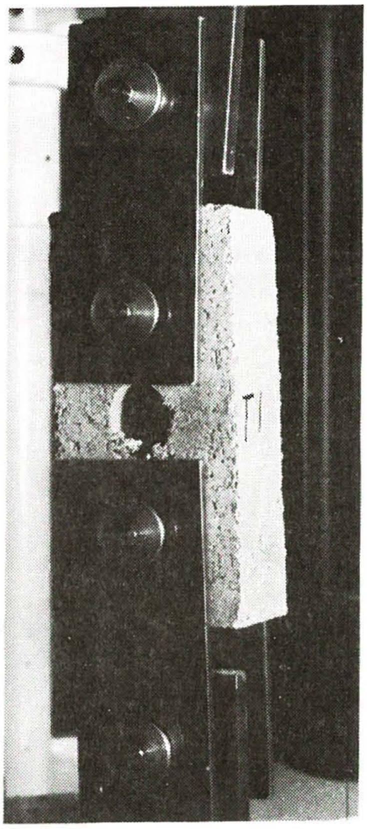
Table 1 Properties of Bricks

Test	Mean Strengths (MPa)	% Coeff. of Variation	No. Tested
Tranverse	6.45	13.2	12
Compressive	47.6	-	

Dimensions (mm)	B	L	D	Mass (kg)
Mean	103.3	218.3	67.2	
% Coeff. of Var.	1.7	1.2	1.6	

Initial Rate of Absorption (kg/m^{2}min) 0.86.

To provide input to the wall analysis tensile tests were carried out. The testing set-up is shown in Fig 1. Two steel pins faced with 5 mm wide flexible packings were threaded through the holes in the bricks and locked onto side plates. The pins were grooved to receive the plates and the whole set up was self centreing.



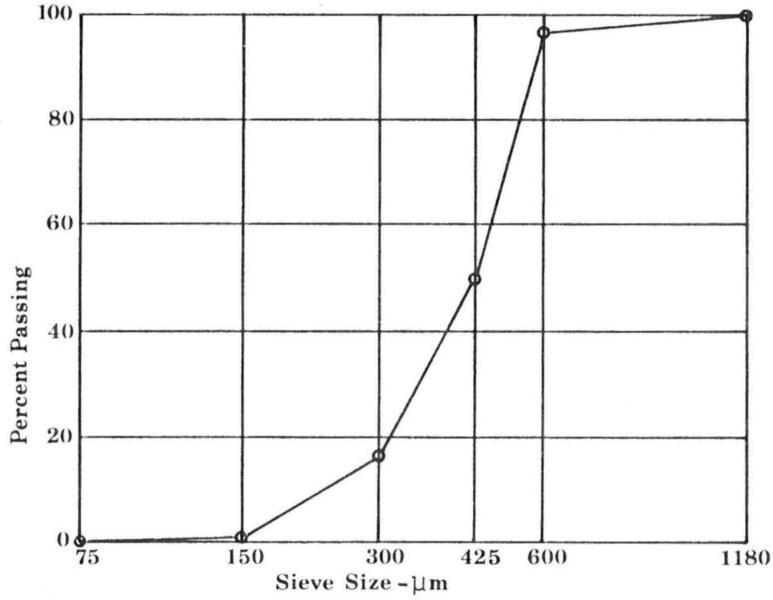


Fig 1 Tensile Testing Set-up

Fig 2 Sand Sieve Analysis

2.2 Mortar

The mortar mix used was developed from a nominal 1:1:4½ by volume and converted to mass for a trial mix. This rather strong mix was chosen to ensure (in conjunction with bricks of comparatively high tensile strength) that failure would be in the desired mode. All mortar used to construct the walls was weigh batched giving a mix (by mass) of 1 part normal portland cement: 0.5 hydrated lime: 5.7 of dry sand. The sand used was dredged from the Bristol Channel and washed. The sieve analysis is given in Fig. 2. The properties of the mortar used are given in Table 2.

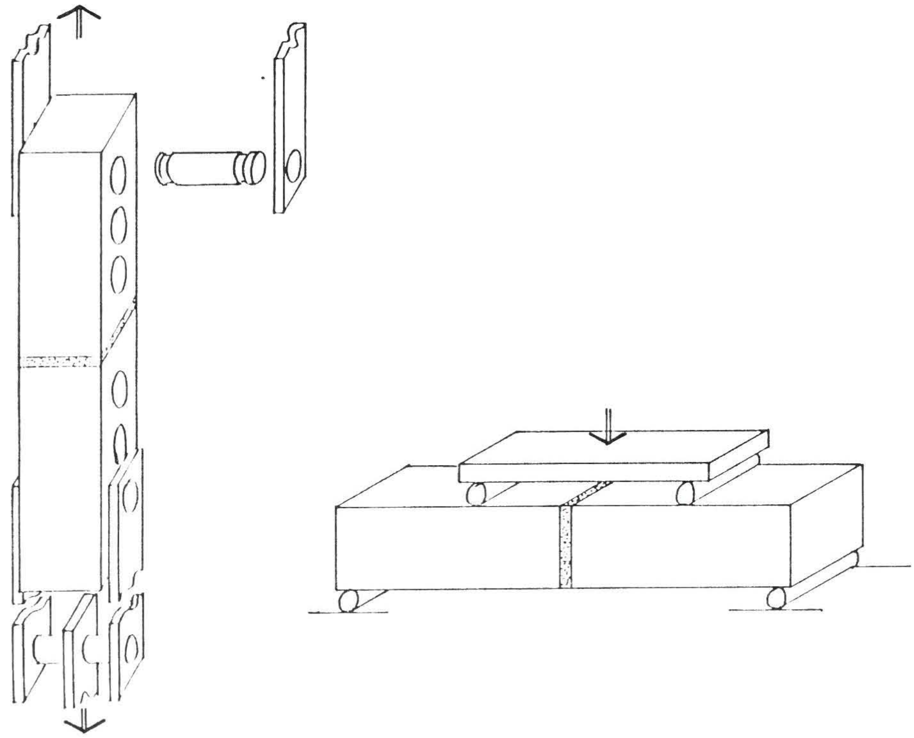
Table 2 Properties of Mortar

Test	Mean
Dropping Ball (BS 4155)	12.4 mm
Flow (BS 4155, AS 1316)	104 %
Air Content (Pressure Method)	9.2 %
Cube Strength (BS 4155)	10.5 MPa

Sufficient water was added to the mix to give the required workability.

3. CONTROL TESTS

In order to establish the contribution of perpend mortar bond to the bending strength a series of test specimens were made and tested as shown in Fig 3.



Tensile   Bending

Fig 3 Perpend Bond Strength Tests

Twenty four specimens were made with a steel rod inserted in the centre of the joint to investigate the effect on tensile strength of a restraint against free shrinkage of the mortar in the joint. Another twenty four were made with no restraint. Half of the specimens were tested in direct tension and the other half in bending. Six of the specimens were fitted with electric resistance strain gauges on each face and strain readings were taken to failure.

Pushout specimens to assess the bed joint bond strength were made and tested to ensure that the bond strength was greater than the brick tensile strength. The specimens were the same as those used by Sinha and Hendry (Test 5 of Ref 3).

4. WALL TESTS

Five walls were constructed in stretcher bond to the dimensions given in Table 3.

Table 3 Wall dimensions

Dimension	L	D
Wall A	6840	932 (12 courses)
Wall B	6864	932
Wall C	6867	920
Wall D	6848	924
Wall E	6817	920

The walls were built on screw pads which could be released leaving the walls supported as shown in Fig 4.

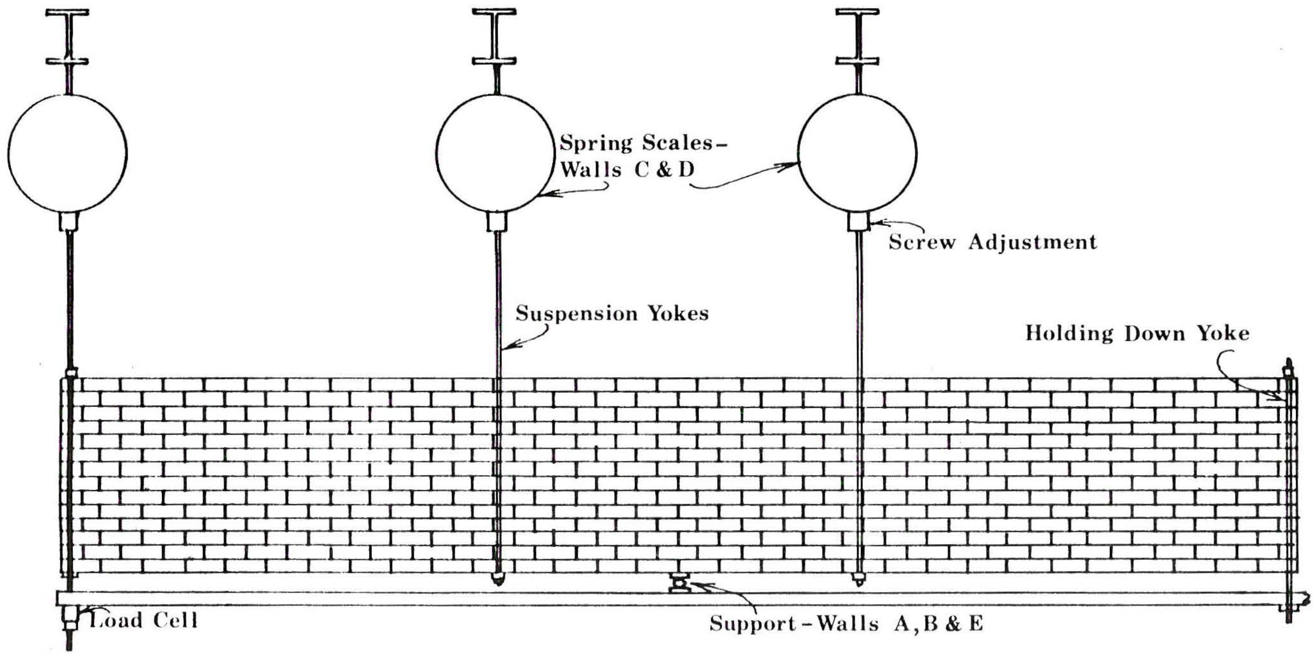


Fig 4 Wall Bending Test Set-up

After construction the walls were sealed in polyethylene sheet for seven days and then left a further fourteen days in a temperature controlled atmosphere. Testing was carried out at twenty one days. All the walls were tested in the hogging mode. A two point loading was applied to two of the walls (C and D) and a single end load to the other walls. The first load was applied by releasing in stages one end of the wall which was supported by a yoke and spring scale. When the walls were cantilevered fully under dead load further load was applied by a screw arrangement in conjunction with a precision load cell.

Deflections were measured at eight points along the wall and strains were measured across perpend joints and on the faces of selected bricks near the point of maximum moment. Demec gauge points were set and monitored so that post cracking behaviour could be measured.

One wall (D) was constructed with no mortar in the perpend joints to see if a significant reduction in bending strength resulted.

5. TEST RESULTS

5.1 Tensile tests on bricks

The mean stress on the nett area of thirteen tests was 4.21 MPa with a C.V. of 18.2%. Due to the shape of the brick perforations and the method of loading this is, of course, only a nominal value. A finite element analysis was performed on a model of the test giving a peak stress of 9.80 MPa at a point on the edge of one of the perforations corresponding closely with the observed fracture point on the test specimens.

In a wall there are several bricks at which facture may initiate as the moment is near maximum for some distance either side of the support point and fracture may occur in the top or second top courses. For the walls loaded at two points the weakest brick in the constant moment region will initiate

fracture. Due to the steep strain gradient the moment cannot be carried by the remaining structure after the first fracture although this could be the case for deep walls. A Monte Carlo analysis of the tensile results was undertaken to find the mean tensile stress at fracture for a set of three and eight bricks in a series giving the results shown in Table 4.

Table 4 Mean Tensile Strengths of Bricks

No. of bricks in tension	Mean strength (Nominal) MPa	Mean Peak Stress MPa
1	4.21	9.80
3	3.58	8.33
8	3.14	7.31

Three and eight bricks were chosen as being the number of bricks in the potential failure zones for the single and two point loadings.

5.2 Perpend joint tensile and bending tests

There was no significant difference between the tensile and bending strengths of the specimens made with and without shrinkage restraint. The mean tensile strength was 0.68 MPa (C.V. 33%) and the bending strength (modulus of rupture) was 1.52 MPa (C.V. 34%). Both of these values are well below the tensile and transverse strengths of the bricks and it was found in the wall tests that the perpend joints failed well before the ultimate load was reached. Strains at fracture varied from 35 to 110 μ strain, the higher values corresponding to the higher stress values.

5.3 Wall tests

5.3.1 Deflections. The load deflection curves were slightly non linear indicating some change in properties during the tests. At loads up to about half the ultimate the Modulus of Elasticity values were close to those given in structural brickwork codes.

5.3.2 Strains. Strains in the bricks were measured across the depth of the walls and at three levels in the top and second top courses for two walls. The strain increases were approximately linear with increasing distance from the neutral axis. As the modulus of elasticity of individual bricks was not known and the actual strains being measured were extremely small the strains give an indication of structural action only. Some interesting observations emerge; the neutral axis is well below the centre of the wall as tensile strains were recorded as far as two thirds of the depth from the top; in the top brick the maximum tensile strain occurs at the bottom of the brick and the strain decreases towards the top. In two of the walls where gauges were located close to the final failure crack compressive strains were recorded at the top of the top course.

The joint strains followed the same general pattern as brick strains but proved much more erratic. Sudden increases in strain were recorded at joints near the point of maximum moment with a small load increment indicating cracking of the perpend joints. Up to the point where perpend joint cracking commenced the strains increased in a linear fashion but beyond this point redistribution of stress was taking place. However even at failure in a region of constant moment there were some uncracked perpend joints in tension zones. Two strain distributions on the faces of bricks are shown in Fig 5.

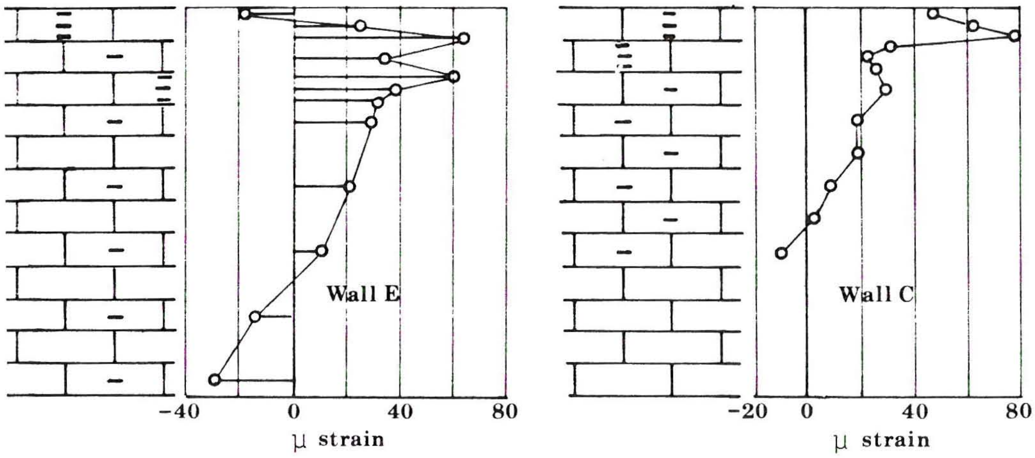


Fig 5 Strain Distributions in Bricks

5.3.3 Crack patterns at failure. The failure of two walls was initiated by tensile cracking of a brick in the top course and three walls by failure of a brick in the second top course (Fig 6). The cracks ran almost vertically through the walls for three failures. A step half a brick long occurred three and four courses from the top in the other two walls.

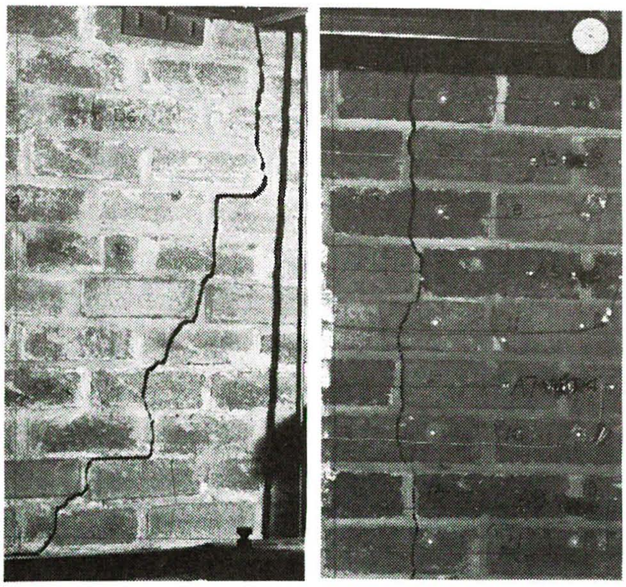


Fig 6 Crack Patterns at Failure

6. THEORETICAL PREDICTIONS

6.1 General

The analyses that follow make use of the following assumptions;

(a) The neutral axis can be found by assuming that perpend joints are cracked in tension giving the effective cross sections shown in Fig 7. Two sections are possible depending on the failure modes which can occur.

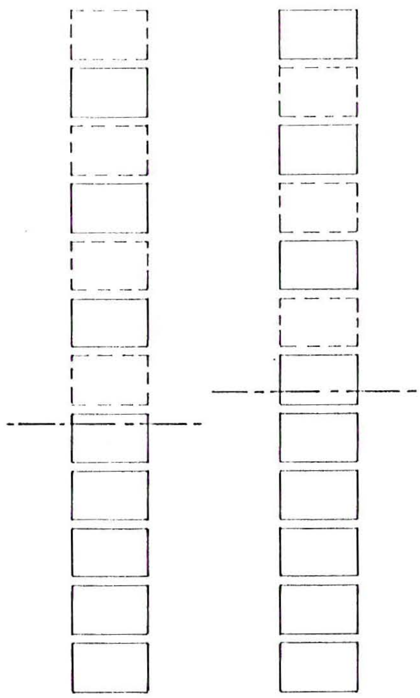


Fig 7 Effective Cross Sections in Bending.

(b) The force carried by each brick is proportional to the distance from the neutral axis.

6.2 Finite element analysis

An elastic analysis of a portion of the wall was made to find the stress distribution in the top four courses of bricks using the finite element method. Alternate bricks were assigned a force distribution compatible with the stress pattern revealed by analysis and giving a moment in the wall equal to that at failure. The stress values for the top two courses of one of the walls are shown in Fig 8.

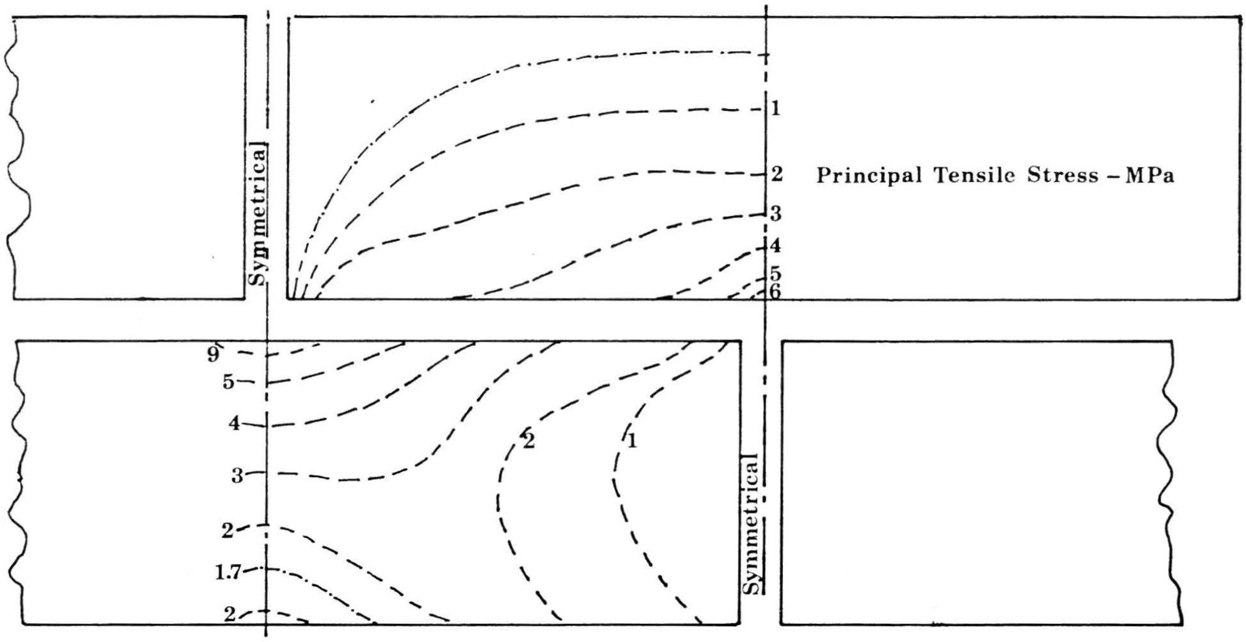


Fig 8 Principal Stress Contours

It can be seen that high values exist at two points; the centre top of a brick in the second top course and in the centre bottom of a brick in the top course. The values of stress in the top course echo the strain distribution revealed in the tests. For each of the walls the stresses at these critical points are compared in Table 5 with the mean tensile test results given in 5.1 above.

Table 5 Wall Stresses from Analysis and Brick Tensile Test Results

Wall	Stress at Failure (MPa) Top Brick	Second top brick	Mean Tensile test failure stress (MPa)
A	7.70*	10.87	8.33
B	6.79	9.59*	8.33
C	6.10	8.61*	7.31
D	8.86*	12.50	7.31
E	7.29	10.28*	8.33

*Denotes the location of the failure.

The different values for tensile test failure stress for walls C and D are a result of the larger number of bricks in the longer potential failure zone resulting from the two point loading.

6.3 Simplified Analysis

Using the section properties calculated from the cross sections of Fig 7 a nominal stress may be calculated simply. This is compared with the nominal stress obtained from the tensile tests in Table 6.

Table 6 Nominal Wall Stresses and Brick Tensile Test Results

Wall	Stress at Failure (MPa) Top Brick	Second top brick	Mean Nominal Tensile test failure stress (MPa)
A	3.34*	4.68	3.58
B	2.94	4.11*	3.58
C	2.65	3.70*	3.14
D	3.84*	5.38	3.14
E	3.16	4.43*	3.58

*Denotes the location of the failure

7. DISCUSSION OF RESULTS

7.1 General

From observation of the strains a model of wall bending has been developed. For small bending moments the walls acted as a unit of mortar and bricks. For larger moment the perpend joints begin to progressively crack and the moment is carried by a different mechanism. A similar mechanism has been previously reported by Lawrence (4). This cracking is to be expected when the joint values obtained from the tests reported in 5.2 are compared with brick tensile strength. The tensile stresses in the bricks are carried to the next brick by horizontal shear in the bed joints. This leads to a shift in the neutral axis towards the compression zone as all the perpend joints and hence all the bricks will act in compression. The bending strength result from wall D also verifies this model. The ultimate moment reached was not significantly different to the strengths of walls with filled perpend joints. Examination of the cross sections through the centre of top and second top bricks gives a different position of the neutral axis but whether this really takes place could not be experimentally determined due to the exceedingly small strains involved.

7.2 Failure Crack Pattern

An examination of the calculated stresses for both the refined and simplified methods indicates that failure ought to occur by fracture of the top of the brick in the second top course. This was not the case however in two of the walls. The difference in calculated stresses is larger than the variation in brick tensile strength. The finite element analysis produces large peak stresses at discontinuities which could be relieved by local cracking in the walls which may provide an explanation. The failures all occurred virtually instantaneously after the first crack occurred in a brick.

7.3 Correlations

The stresses calculated from the actual failure moments using the proposed model agree reasonably with the stresses calculated at the actual points of failure. However the higher stresses calculated at the alternative failure locations lie outside the 99% confidence limits on the mean tensile test strength. At the design stage of course it will not be known whether failure

will be through a top course or second course brick. The accuracy of all predictions depends on a knowledge of the tensile strength of the bricks. The method used to find tensile strength was a convenient one for a brick with large perforations but a centrifugal method is proposed for future work. (Ref. 5). The tensile test used measured the ceramic strength at the outside perforation. The ceramic strengths may not be the same at both locations although a sawn section of the brick revealed no marked difference in structure. The actual distribution of stress in the wall bricks is also far from uniform and is a tensile and superimposed bending stress pattern.

8. ACKNOWLEDGEMENTS

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