The Behaviour of Concrete Block Masonry Units under Vertical Loads

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SUMMARY

Due to sudden failures which occur when testing full size masonry walls, the exact conditions of stress, deformation and failure propagation are not easily determinable. A method has therefore been developed for testing a single block/mortar joint under controlled conditions. The loading arrangement and instrumentation permits the position of the centre of compression relative to the mortar under compression to be defined and gives an indication about the stress distribution within the joint. Various combinations of applied stress, mortar mixes and block specification have been investigated in order to obtain a greater understanding of the block/mortar joint under variable eccentric loading.

1. INTRODUCTION

The work described in this paper has been performed at the Cement and Concrete Association over the past 12 months and is part of a much more extensive investigation into the behaviour of concrete block masonry subjected to vertical loading.

The programme of work started approximately ten years ago when a testing frame was built [1] to enable full size wall panels to be tested under vertical load. These wall panels, measuring 2.6m high and 1.8m wide, were tested to failure in a fixed-ended condition in order to obtain values of the characteristic compressive strength of concrete masonry [2]. The influence of mortar type, workmanship and bond pattern on the strength of concrete masonry was also investigated [3]. The compressive strengths were found to be generally independent of mortar type, workmanship, and bond pattern and gave values of the order of 0.8 of the strength of the block being used where the blocks were solid and rather less for hollow units.

Recently the programme has proceeded to tests to assess the influence of eccentricity of the applied load and slenderness on the performance of walls. The initial results from these tests have been reported by Cranston and Roberts [4]. In all the tests the walls were strain gauged on both faces and deflections measured over the full height. However, because of the explosive failures being experienced from the walls it was not possible to observe exactly where failure propagated or the actual mode of failure.

To overcome this problem and obtain a more detailed understanding of the behaviour of masonry under ultimate load conditions, Cranston adapted a test rig which had originally been used to study the moment-rotation characteristics of the compression zone of concrete beams [5]. Instead of concrete, two half concrete blocks with a mortar joint between (couplet) was used to obtain moment-rotation relationships for blockwork. A larger test rig has since been built which enables full size blocks with one, two or three joints to be tested under controlled condition. This paper gives details and results from the tests, performed in the new test rig, on couplets constructed of various combination of mortar type and block specification, subjected to different levels of stress.

2. MATERIAL PROPERTIES

In the test programme five different types of concrete block have been used. These blocks, manufactured by Forticrete Ltd, were chosen to give as wide a range of block types as possible. Table 1 gives details of size, type, specified strength and the compressive strength obtained using the method given in BS 6073 Pts 1 and 2 [6].

A range of mortars covering the most common mixes used with concrete blocks was chosen. The mix proportions, target strengths and BS 5628 [7] mortar designations are given in Table 2.

Sufficient water was added to the mixes to give a workability suitable for block laying. This workability was found to be equivalent to a dropping ball [8] number of between 9 and 11. For each combination of mortar and block type, six couplets were made. The blocks were laid dry and sufficient mortar was used (approx. 15mm thickness) to give a final joint thickness of between 10 and 12mm after removing the excess material. Cubes (100 x 100mm) were also cast from the mortar and cured together with the couplets under polythene for 7 days. The polythene was then removed and the specimens left in constant temperature conditions until being tested at a minimum age of 28 days.

Four average stress levels were applied to each set of couplets. These cover a range which could be expected from the loading of different numbers of storeys.

Block designation used in this paper	Dimensions l x h x w mm x mm x mm	Type of manufacture	Specified strength N/mm^2	Measured strength [6] N/mm^2	
				Gross	Net
No-voids solid block - NVS	390 x 190 x 140	Dense concrete	21	29.9	29.9
Hollow block (40% voids) - HB	390 x 190 x 140	Dense concrete	21	31.6	54.1
Solid block (20% voids) - SB	390 x 190 x 140	Dense concrete	11	21.6	27.7
No voids solid block - DB	390 x 190 x 90	Dense concrete	14	21.6	21.6
Beslite block (20% voids) - BB	390 x 190 x 90	Lightweight agg	3.5	8.05	9.9

TABLE 1 - CONCRETE BLOCK SPECIFICATIONS

Type	Proportions by volume c : l : s	Target strengths N/mm^2
i	1 : 1/4 : 3	15+
ii	1 : 1/2 : 4 1/2	10
iii	1 : 1 : 6	5
iv	1 : 2 : 9	2.5

TABLE 2 - MORTAR SPECIFICATIONS

The average stresses envisaged were : - 12.5, 10.0, 7.5, 5.0 N/mm^2 and equivalent loads, based on gross cross-sectional area, to the nearest 5 kN adopted. It was not possible to use these stresses on the low strength block (Beslite) and here two stress levels of 5.0 and 2.5 N/mm^2 were used.

3. TEST RIG AND INSTRUMENTATION

The test frame used in the eccentrically loaded tests is shown in diagrammatical form in Figure 1 below. The arrangement of the loading system allows the position of the resultant load to be defined.

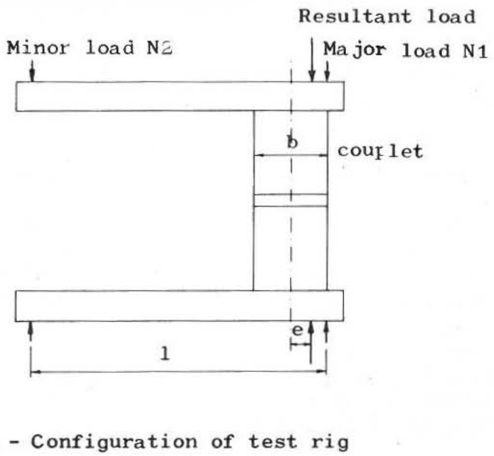

Fig. 1 - Configuration of test rig

The resultant load - N - is the sum of the two loads N = N1 + N2. Its position relative to the centre line of the block is given by :

$$e = \frac{b}{2} - \frac{l.\ N2}{(N1+N2)}$$

where :

e	is distance from centre line of block to position of resultant load
b	is width of block
l	is distance between loading points
N1	is major load
N2	is minor load

Therefore by altering the ratio of the two loads but not their sum, the line of action of the applied load can be altered without changing the average stress applied to the overall section.

The whole arrangement is contained within a testing frame which applies the major load through rollers. The minor load is applied via a small jack and cable. Figure 2 shows the complete arrangement. Axial load tests were also performed in the machine with the eccentric loading arms removed and the load applied directly through the machine platens.

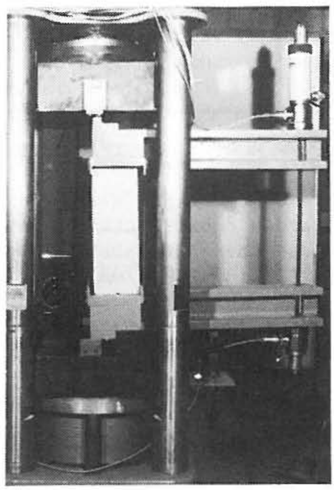

Fig 2 - Complete eccentric load test frame arrangement

The loads applied to the test frame were obtained using load cells which were connected directly into a data logger. The loads were also shown on a digital display from which the applied load was controlled.

Strains from the couplet were measured by two methods. The first was by 200mm strain transducer gauges which spanned both the joint and part of each block.[9] These gauges were developed at the Cement and Concrete Association and consist of a flexible aluminium strip which when bent, by a change in length, causes resistance gauges attached to the strip to alter the electrical output from a strain-gauge bridge, thus enabling the strain to be measured. Four of these gauges were used, two on both the tension and compression faces, and the outputs fed to the logger. The second gauge was used to measure the strain across the joint only and because this distance was small and no proprietary gauge was available, a hand held gauge, with a dial gauge measuring the movement between two closely spaced studs, was developed. Depending on the thickness of the block, 90 or 140mm, 4 or 6 pairs of studs respectively were placed on each end of the couplet.

Measurements of the amount of spalling of the compression face of the mortar were

taken during the test with a vernier depth gauge.

4. TEST PROCEDURES

To eliminate high spots on the blocks the couplets being used for the axial tests were capped using a rapid hardening non shrinking plaster. The couplets were gauged up before being placed in the testing machine. For the axial tests, load was applied in increments of roughly 50 kN. A full set of readings was taken at each load increment and the tests continued until failure of the couplet occurred.

In the eccentrically loaded tests, each couplet was placed in the testing frame on a bed of plaster. The couplet was also clamped to the frame to prevent any rotation occurring between the blocks and the machine platens. Again, the couplet was pre-gauged. The two loads were first increased in stages in such a way that the resultant load remained axial until the required average stress level was reached. After reading the required total load and checking that the couplet had compressed uniformly, the major load was increased in stages of 2 kN and the minor load decreased by the same amount. This had the effect of moving the resultant load towards the compression face and causing rotation of the joint. Readings were taken at every load stage and the test continued until one of three things happened :

1. failure of the block occurred
2. the rotational capacity of the test frame was reached, or
3. the peak moment had been exceeded, preventing the minor load to be reduced any more.

If the latter occurred the couplet was allowed to rotate by slightly altering the loads but returning them to the required total load before the readings were taken.

5. RESULTS

The results from the axial tests are given in Table 3. It can be seen that data from the no-void solid blocks (NVS) are not given apart from the maximum applied stress for a 1 : 1/4 : 3 mortar. This was because insufficient blocks were available to perform the tests. The value given is an average of 20 tests obtained from axial couplet tests performed in conjunction with the wall test programme. The table gives the maximum stress corresponding to each block type-mortar type combination together with the appropriate mortar cube strength and the maximum recorded strains from both the 200mm (total) and hand held (joint) gauges. When it was not possible to take a set of the joint readings near the end of the test (denoted by * in Table 3), the corresponding stress at which the last joint strain was taken is given. It can be seen from this table that the failure strength of the couplet is not greatly influenced by the type of mortar used but more related to the strength of block (see Table 1). The ultimate strains in the joints are, however, influenced by both the mortar and the block type. Generally larger joint strains were recorded with decreasing mortar strength. Block type (more specifically % voids) has an effect in that a thinner shell/web thickness produces greater strains.

A typical stress strain graph is shown in Figure 3 from one of the axial tests. It shows that the couplet behaves non-linearly and that if it is unloaded from the preset stress levels a permanent strain will result. Although this permanent strain is not significant over a large length, the permanent joint strains can be as much as 40% of the failure strain.

The results from the eccentrically loaded couplets are summarised in Table 4. In the axial tests mortar type plays no significant influence. However, in these tests it has a significant effect since the amount of rotation and subsequent moment is largely related to the deformation of the joint. As would be expected the lower

stress levels produces the highest rotations but not the highest moment since this value is largely dependent upon the magnitude of the applied load. In the majority of cases the type (i) mortar (1:1/4:3) gave the largest rotation and accompanying moment for each particular stress level before failure occurred.

A typical moment-rotation graph is shown in Figure 4. Here again a difference in the joint and total values can be seen at low rotations. This difference is most noticeable at the lower stress levels when large joint rotations are possible.

Mortar			Block type				
			BB	DB	HB	SB	NVS
1:1/4:3 type (i)	Max stress N/mm^2		7.9	19.3	26.7	18.3	21.9
	Max strain $\times 10^{-3}$	Total	2.85	3.32	3.28	2.50	
		Joint	12.10* (7.2)	11.14* (17.9)	13.71	8.09* (17.0)	
	Cube strength N/mm^2		18.6	26.1	18.6	22.2	
1:1/2:4 1/2 type (ii)	Max stress N/mm^2		7.9	18.5	20.3	20.3	
	Max strain $\times 10^{-3}$	Total	2.06	3.59	4.86	2.75	
		Joint	6.25	9.40* (17.1)	32.40	13.42* (19.5)	
	Cube strength N/mm^2		16.0	13.0	10.5	10.7	
1:1:6 type (iii)	Max stress N/mm^2		6.4	21.4	23.2	17.7	
	Max strain $\times 10^{-3}$	Total	3.41	3.85	5.53	3.97	
		Joint	16.77* (5.69)	17.49* (20.02)	37.91	26.93	
	Cube strength N/mm^2		5.9	5.8	3.9	4.2	
1:2:9 type (iv)	Max stress N/mm^2		7.1	18.6	15.4	17.5	
	Max strain $\times 10^{-3}$	Total	3.16	3.64	7.83	4.29	
		Joint	10.67* (6.45)	25.71	63.00	22.99* (16.0)	
	Cube strength N/mm^2		2.1	3.0	0.5	2.1	

* Maximum joint strain not taken, value given corresponding to last stress reading in brackets.

TABLE 3 - AXIAL COUPLET TEST RESULTS

Mortar type			1 : 1/4 : 3 (i)			1 : 1/2 : 4 1/2 (ii)			1 : 1 : 6 (iii)			1 : 2 : 9 (iv)		
	Load	Equiv. stress level N/mm^2	Moment kNm	Rotation $\times 10^{-3}$ rads	Cube strength N/mm^2	Moment kNm	Rotation $\times 10^{-3}$ rads	Cube strength N/mm^2	Moment kNm	Rotation $\times 10^{-3}$ rads	Cube strength N/mm^2	Moment kNm	Rotation $\times 10^{-3}$ rads	Cube strength N/mm^2
BB	90	2.5	3.53	54.53	18.6	3.39	39.04	16.0	3.54	49.43	5.9	3.39	24.38	2.1
	175	5.0	2.97	14.66		4.54	7.10		4.31	8.96		2.32	12.01	
	175	5.0	5.68	103.99		6.0	116.05		5.48	104.56		5.55	88.07	
DB	265	7.5	7.98	75.02	26.1	7.11	53.33	13.0	6.98	69.62	5.8	5.54	42.98	3.0
	350	10.0	8.07	40.00		8.12	20.48		7.09	33.40		6.74	41.30	
	440	12.5	8.35	26.36		7.80	14.96		7.41	39.95		7.30	23.48	
	280	5.0	18.14	96.80		14.89	70.90		15.87	41.59		11.91	26.88	
HB	410	7.5	21.09	41.21	18.0	21.33	29.98	10.5	19.79	24.07	3.9	18.31	28.05	0.5
	560	10.0	24.31	6.32		17.88	4.25		21.61	9.12		2.01	1.32	
	690	12.5	32.25	9.02		17.20	6.23		11.82	3.41		6.59	4.56	
	280	5.0	16.18	40.17		14.90	53.52		13.99	29.80		15.14	61.55	
SB	410	7.5	19.81	19.37	22.2	19.21	15.52	10.7	17.60	11.88	4.2	17.94	19.03	2.9
	560	10.0	24.61	7.42		23.38	7.77		12.78	6.01		14.00	4.13	
	690	12.5	16.00	4.84		21.26	7.52		10.84	4.16		14.63	4.39	
	280	5.0	11.80	7.83		14.08	80.92		13.12	38.00				
NVS	440	7.5	19.96	45.02	11.9	18.30	25.08	8.0	17.15	28.01	4.3	16.39	40.13	2.1
	560	10.0	23.93	10.41		22.29	28.29		20.83	9.55		20.88	33.17	
	690	12.5							13.12	17.58		18.40	15.71	

TABLE 4 - ECCENTRICALLY LOADED COUPLET TESTS - MAXIMUM RECORDED VALUES

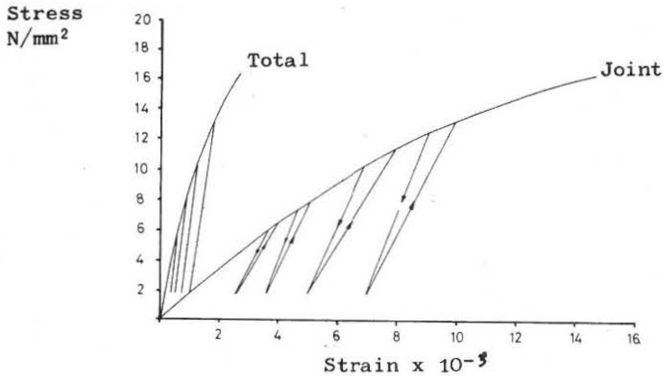

Fig 3 - Stress strain graph for SB couplet with a 1:1:6 mortar

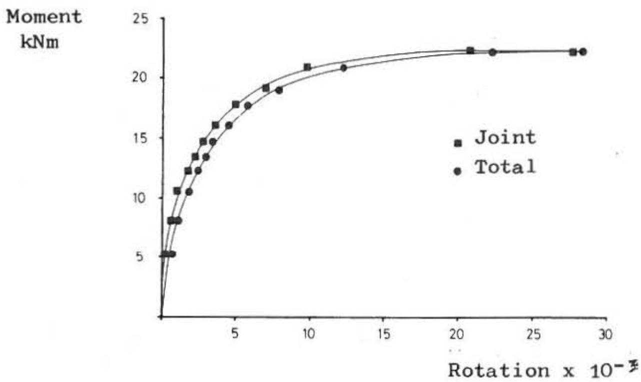

Fig.4 - Moment rotation plot for NVS couplet with a 1:1/2:4 1/2 mortar and 10 N/mm² stress level

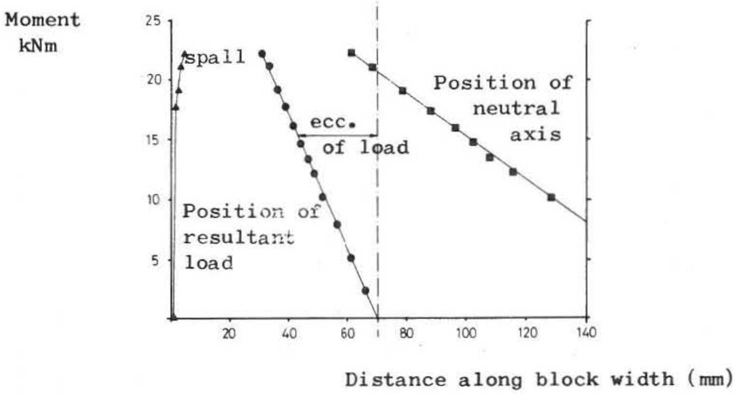

Fig.7 - A moment interation diagram for NVS couplet, 1:1/2:4 1/2 mortar and 10 N/mm² stress level

6. MODES OF FAILURE

Two distinct modes of failure have been observed :

a) The mortar spalls to such a depth that the centroid of the load passes into a spalled area. If this happens the blocks would flip giving a sudden increase in rotation. However, this could not occur since the maximum rotation allowed by the test frame was below the value at which this flip would happen. Figure 5 shows the large amount of spalling and a clearly defined crack. These types of failures were obtained from the low strength mortars with a low stress level being applied.

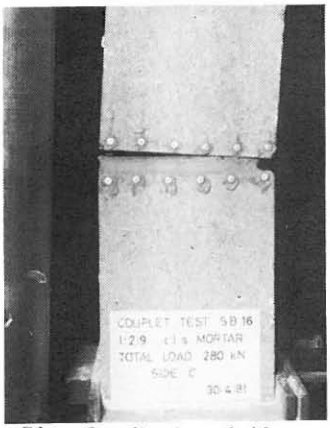

Fig. 5 - Mortar failure

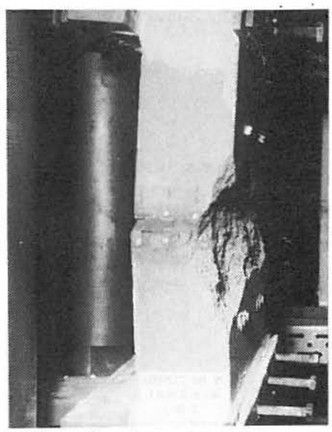

Fig. 6 - Block failure

b) The blocks fail in compression on either side of the joint as shown in Figure 6. This type of failure is analogous to the failure of the compression zone of a concrete beam and was obtained from the higher strength mortar and stress level tests. The type of block also influences the failure shape. For the solid blocks (NVS and DB), failure was similar to that shown in Figure 6. However, with the other blocks, splitting along the web face was common and at the highest loads, where the rotations were small, splitting occurred in the centre of the block.

7. DISCUSSION

The instrumentation allows the position of the neutral strain axis to be defined at each load stage. This is obtained by relating the rotation of the joint and the amount of compression due to the pre-loading to the condition of zero stress. It is assumed that the mortar in compression is bounded by the neutral axis on the one side and the limit of any spalling on the other; it is possible, by considering the position of the line of action of the load within the compressed mortar, to draw some conclusions about the distribution of compressive stress within the joint, the position of the centre of compression relative to the position of the neutral axis and the extent of spalling as a function of applied moment. A typical diagram is shown in Figure 7 which was obtained from the same couplet used to produce Figure 4.

It is not possible to show every interaction diagram obtained but generally it is unlikely that the neutral axis will come within the section of higher average stress levels since only small rotations occur before a critical stress situation is reached. It is therefore the lower stress levels that give an indication of the stress distribution.

To obtain the type of stress distribution through the joint it is necessary to determine the amount of mortar under compression and consider the position of the applied load within the mortar. For solid blocks, if its position is at the third point, then it can be assumed that the section is behaving elastically, if it is in the middle of the loaded section then a rectangular distribution could be assumed.

The no-voids solid blocks (NVS and DB) gave results which suggested an approximately elastic distribution. However, the analysis of the non-solid blocks has not yet progressed to the stage where any firm conclusions can be reached upon the type of stress distribution that should be assumed. Taking the NVS blocks and calculating the maximum stress that would be obtained using a triangular stress distribution, shown in Figure 8, a value is obtained, shown in Table 5, that is independent of, and substantially greater than, the mortar strength.

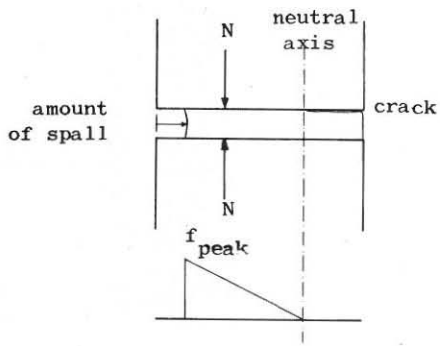

Fig. 8 - Conditions within a joint

This suggests that the mortar is being subjected to triaxial rather than the uniaxial forces obtained in a compression cube test. This triaxial stress can arise due to the restraint provided by the blocks to the lateral expansion of the water mortar.

Mortar type	Cube strength N/mm²	Type of failure	Stress level N/mm²	Peak stress N/mm²	$\frac{f_{peak}}{f_{cu}}$
(i) 1:1/4:3	11.9	Block	10.0	43.0	3.6
		Block	7.5	59.4	5.0
		Joint	5.0	28.1	2.4
(ii) 1:1/2:4 1/2	8.0	Block	10.0	59.3	7.4
		Block	7.5	48.6	6.1
		Joint	5.0	62.0	7.7
(iii) 1:1:6	4.3	Block	12.5	42.4	9.8
		Block	10.0	32.5	7.6
		Joint	7.5	29.1	6.8
		Joint	5.0	38.8	9.0
(iv) 1:2:9	2.1	Block	12.5	29.8	14.2
		Block	10.0	49.7	23.7
		Joint	7.5	47.6	22.7

TABLE 5 - COMPARISON OF MAXIMUM STRESS FROM TRIANGULAR STRESS DISTRIBUTION WITH CUBE STRENGTH FOR NVS BLOCKS

The moment-rotation relationships can also be used to predict the behaviour of walls. Beeby [10] has used the data from early tests on solid blocks to obtain the deflected shape of the wall by numerical integration. Using an iterative procedure, it is possible to produce a load-deflection curve for the wall and predict its ultimate strength. Figure 9 compares calculated and experimental ultimate loads for walls of varying heights and with varying eccentricities. It can be seen that good agreement is obtained.

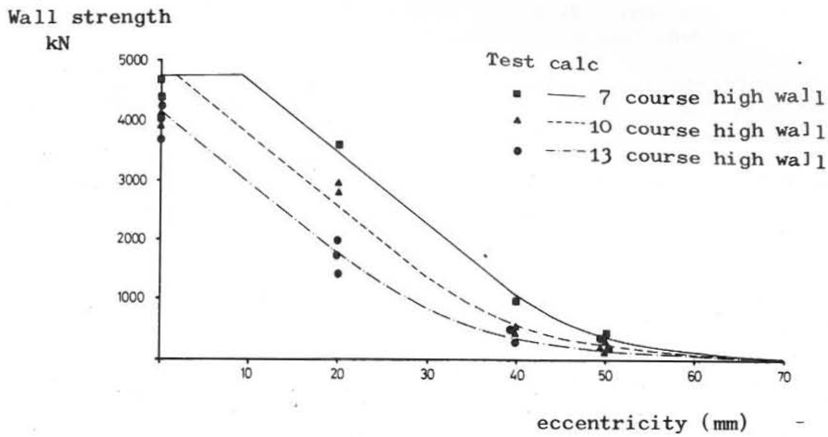

Fig. 9 - Comparison of experimental and calculated wall strengths

8. CONCLUSIONS

Although the test programme on the couplets has been completed, a full analysis has not yet been finished and the implications of the results have not, at this stage, been fully assessed. However, from the results given in this paper the following points are evident :

1. Mortar strength/type is not a factor when considering the ultimate strength of axially loaded masonry. However, joints strains can be related to the mortar type and also the cross-sectional layout of the block.

2. In the eccentrically loaded couplets it was the type (i) mortar (1:1/4:3) that generally produced the largest strength and stiffness properties of the couplets.

3. Two distinct modes of failure have been observed :

   a) failure by gradual spalling of the mortar

   b) failure by crushing of the blocks.

4. The mortar stress at failure obtained from an assumption of an elastic stress distribution is not directly related to the mortar cube strength.

5. The moment-rotation characteristics of a couplet can be used to predict the failure of full size concrete block wall panels.

Finally, it can be seen that the controlled conditions which are possible in a couplet test allow the detailed behaviour of masonry to be examined in a way that is impossible on full sized walls. Also, since a couplet test is quicker and cheaper than a wall test and allows many more variables to be considered, it is a useful method for obtaining a greater understanding of masonry behaviour.

REFERENCES

[1] READ J B and CLEMENTS S W : The strength of concrete block walls. Phase 1 : construction and proving of a suitable test frame. Technical Report 42.461, Cement and Concrete Association, London, January 1972.

[2] READ J B and CLEMENTS S W : The strength of concrete block walls. Phase 2 : under uniaxial loading. Technical Report 42.473. Cement and Concrete Association, London, September 1972.

[3] READ J B and CLEMENTS S W : The strength of concrete block walls. Phase 3 : effect of workmanship, mortar strength and bond pattern. Technical Report 42.518, Cement and Concrete Association, London, November 1977.

[4] CRANSTON W B and ROBERTS J J : The structural behaviour of concrete masonry - reinforced and unreinforced. The Structural Engineer, November 1976, No. 1, Vol. 54.

[5] CLEMENTS S W, CRANSTON W B and SYMONS M G : The influence of section breadth on rotation capacity. Technical Report 42.533, Cement and Concrete Association, London, September 1980.

[6] BRITISH STANDARDS INSTITUTION : BS 6073, Pt 1 and Pt 2 : Precast concrete masonry units, 1981.

[7] BRITISH STANDARDS INSTITUTION : BS 5628, Structural use of masonry, Part 1 unreinforced masonry, 1978.

[8] BRITISH STANDARDS INSTITUTION : BS 4551, Methods of testing mortars and specification for mortar testing sand, 1970.

[9] COOK C F : An electrical demountable strain transducer, Strain, 16, 113, 1980

[10] BEEBY A W : Private communication.