TEST ON WALLS SUBJECTED TO UNIFORM LATERAL LOADING AND EDGE LOADING.

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ABSTRACT. The results of a programme of six transverse lateral loading tests on vertical spanning masonry walls with a stiff return at one end and a line loading along a free vertical edge at the other end are given and compared with three similar walls without edge loading. The edge loaded walls were repaired by injecting epoxy resin into the failed joints and re-tested.

The analysis of the wall strengths using yield line formulae and four derivations of flexural stress are compared with the ultimate strengths of the test walls.

1. INTRODUCTION

Prior to undertaking the programme of tests on walls with edge loading a series of lateral loading tests on single leaf and cavity walls had been tested to assess the effect of returns on the strength of vertical spanning walls. The walls had a variety of lengths and a range of return lengths at one or both ends, a series of strip walls without returns was also included (1) (2). The tests showed that if the length of returns was not less than 1/3 of the vertical span then failure did not occur in the returns and the wall panel could be assumed to have a fixed edge at its junction with the return.

The tests to investigate the effect of the edge loading were therefore carried out on walls with a return longer than 1/3 of the vertical span.

As well as comparing the strength of walls with different magnitudes of edge loading on the free vertical edge the programme was used to investigate the suitability of various methods of assessing the moment of resistance of the masonry.

2. DETAILS OF THE TEST WALLS.

All the walls had a vertical span of 3m and they fell into two groups with wall panel lengths of 2.5 m and 4.5 m as shown in Table 1.

The technique for applying lateral loading to walls tested at the Polytechnic of the South Bank is a mechanical system of beams and wires pulled by a single jack. The system which is often referred to as a "christmas tree" or "wiffle tree" is usually used for applying a series of equal loads to simulate uniform wind loading. In this programme the technique was modified to apply an additional series of eight point loads along the free edge of the wall to simulate wind load transferred from an adjoining horizontal spanning panel. Fig. 1 shows the loading situation simulated in the tests and a plan view of the loading system used.

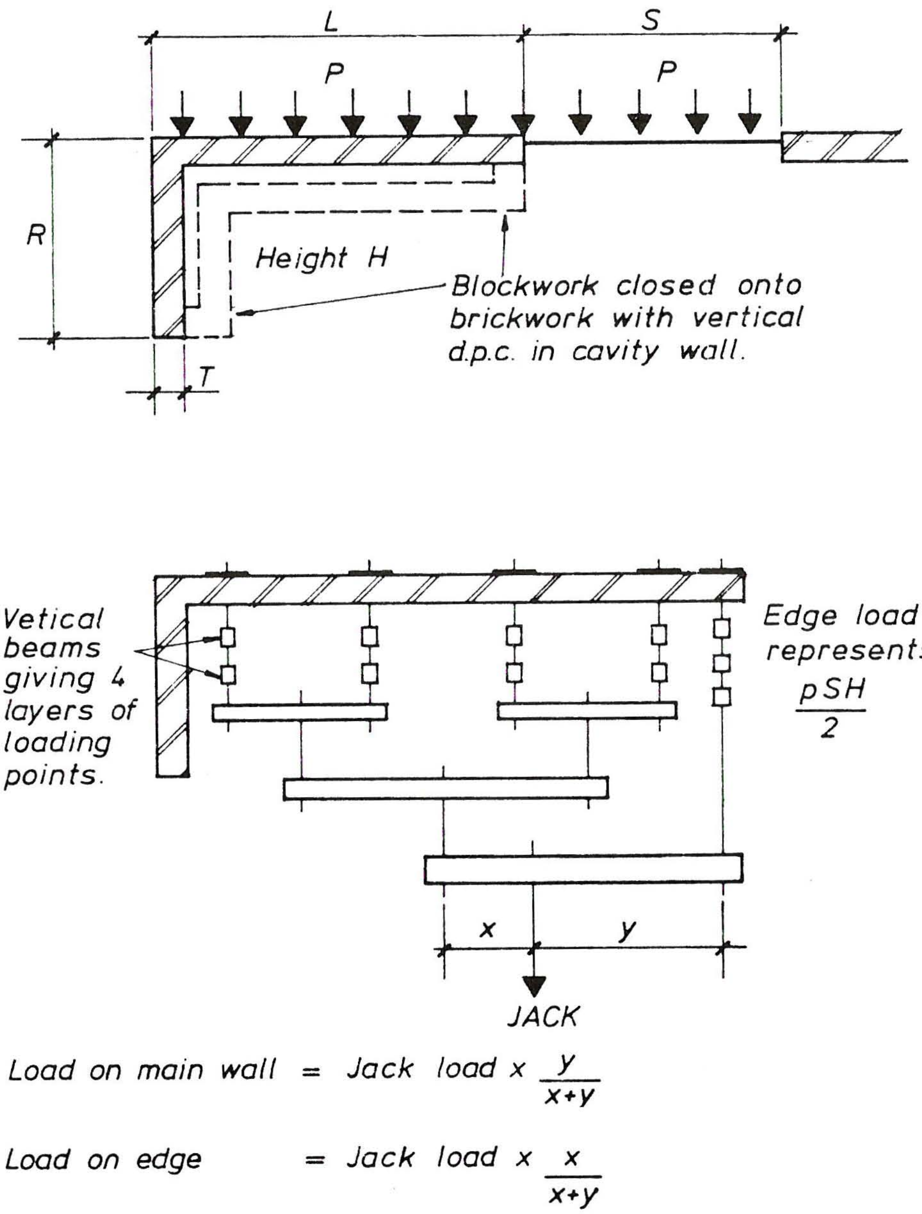


Fig. 1 Configuration and Loading System for Walls

As wall tests of this type are expensive and time consuming it was decided to investigate the possibility of repairing a failed wall and re-testing it with a different load distribution. The repairs were carried out by applying a proprietory resin injection technique to the cracks. The first wall repaired in this way was of brickwork and it was retested with the same load distribution and an identical ultimate load was obtained in the two tests so subsequent walls were retested with a different load distribution to increase the range of test results in the series.

The dimensions of the test walls and the load distributions applied are shown in Table 1.

All the walls were built directly onto a concrete strong floor with a mortar joint which included a bituminous felt d.p.c.

Table 1 Dimension of Test Walls

TEST No	MATERIAL	L m	R m	T mm	S m	Propn. of total load on wall	Propn. of total load on edge
8/1A	Brick	4.5	1.36	102.5	4.50	2/3	1/3
8/1B		4.5	1.36	102.5	4.50	2/3	1/3
8/2B	Block	4.5	1.36	100	2.25	4/5	1/5
8/2A		4.5	1.36	100	4.50	2/3	1/3
2/5		4.5	1.13		0	1	0
8/3B	Brick+	4.5	1.51	102.5	2.25	4/5	1/5
8/3A	Block	4.5	1.51	+100	4.50	2/3	1/3
2/12		2.5	1.13		0	1	0
8/4A	Brick	2.5	1.36	102.5	2.50	2/3	1/3
8/4B		2.5	1.36		5.00	1/2	1/2
8/5A	Block	2.5	1.36	100	2.50	2/3	1/3
8/5B		2.5	1.36	100	5.00	1/2	1/2
2/7		2.5	1.13		0	1	0
8/6A	Brick+	2.5	1.51	102.5	2.50	2/3	1/3
8/6B	Block	2.5	1.51	+100	5.00	1/2	1/2

3. MATERIALS

Extensive measurements of the properties of the materials were taken but space only permits the following to be quoted in this paper.

3.1 Bricks

Deep frogged clay bricks with work size 215mm x 102.5mm x 65mm with compressive strength (BS 3921(3)) of 28.4N/mm^2 and water absorption of 20.7%

3.2 Blocks

Lightweight aggregate (PFA pellets) concrete blocks with work size of 440mm x 215mm x 100mm with mean compressive strength (BS 6073(4)) of 12.4N/mm^2 and moisture content 12-16% by weight.

3.3 Mortar

A 1:1:6 cement, lime, and sand mortar in volume proportions but weigh batched and mixed to a consistency given by a dropping ball number of 13 ± 0.5mm (BS 4551(5)). Walls were tested at ages of 20-23 days, the mortar cube strengths at the time of the tests were in the range 2.9-3.8 N/mm^2 for walls 8/1 - 8/6 and in the range 5.8 - 6.2 N/mm^2 for walls 2/5, 2/7 and 2/12.

3.4 Wall Ties

Galvanised wire, butterfly type (to BS 1243(6)) at 900mm centres horizontally and 450mm vertically were used in the main wall and returns of the cavity walls.

4. CONSTRUCTION AND TESTING OF WALLS

Walls were built in 2 or 3 lifts. The top edge of the walls reacted onto a horizontal steel beam supported outside the wall length by triangulated frames.

The end of the returns were built up against the upright of a triangulated reaction frame securely bolted to the strong floor. A hardwood batten was inserted in the cavity at the level of the top beam as it was assumed that each leaf of such cavity walls would be adequately supported in practice. The walls were covered in polythene sheeting for approximately 10 days before preparations for the test commenced. Holes were drilled through the walls for the loading wires which were locked off by grips bearing onto cushioned loading pads. Deflections of the loaded wall were measured at 5 vertical sections by a travelling bar carrying 7 LVDT's.

For the walls with edge loading a rigid stop fitted with a load cell was used to prop the bottom corner at the "free edge". The tests were carried out with the servo-hydraulic jack in displacement control, load being applied in increments and the wall being held at a fixed displacement while the deflections were recorded by data logger, strains in joints on the "free end" measured by Demec gauge and the rotation of the base measured by dial gauges. After ultimate load was reached the walls with edge loading had epoxy resin adhesive injected into the cracks and the walls were re-tested 2 days later. Failure cracks in the re-tested walls occurred either in different joints or on the other interface of the joints which failed in the first test.

Sets of 10 wallettes for determining the orthogonal flexural properties of the masonry across the bed joints and perpend joints were built and tested at the same age as the test walls.

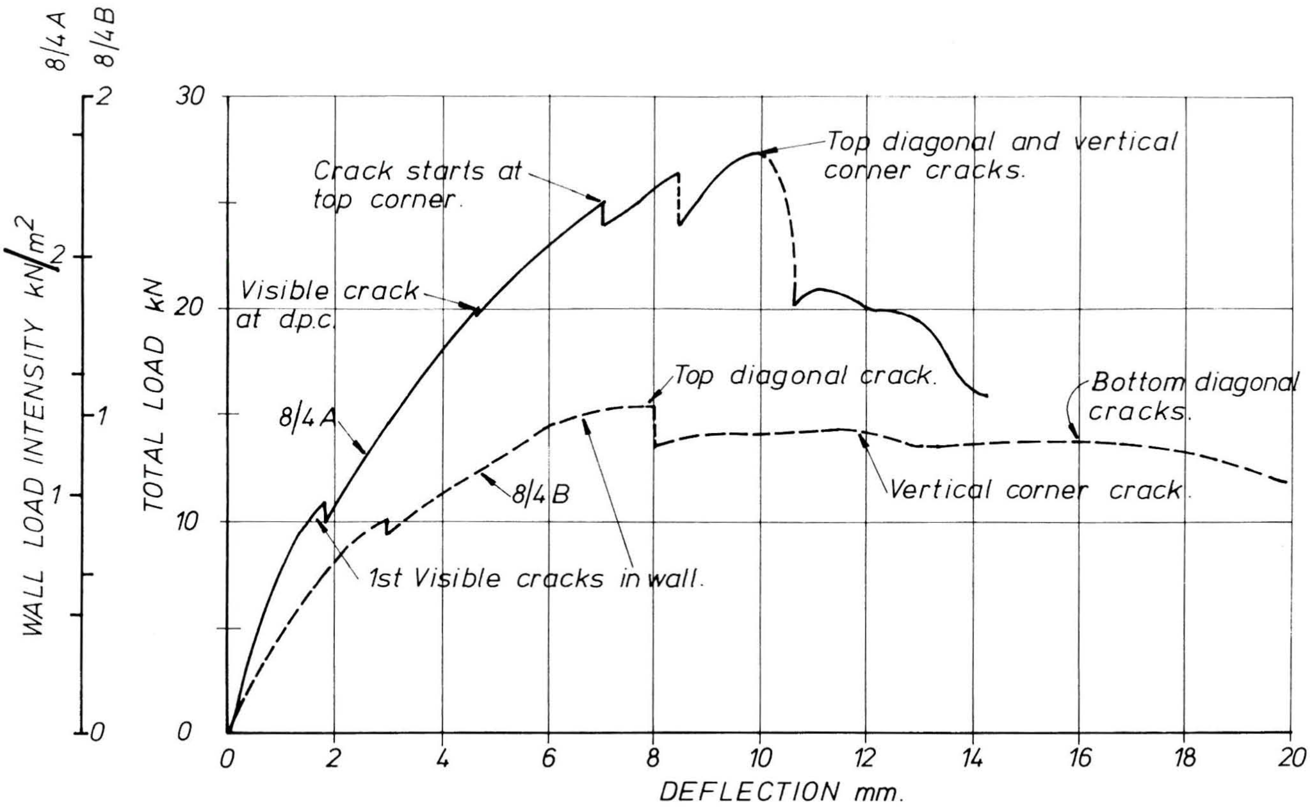
5. RESULTS

A summary of the main test results is given in Table 2. Note that the first cracks were observed in the walls at loads roughly of the order of half the ultimate load. A typical plot of load v max. deflection in the wall is shown in Fig. 2.

6 ANALYSIS OF WALLS

6.1 Flexural Analysis

The yield line method was used in the theoretical analysis of the strength of these walls using unified formulae developed by C. Morison of the P.S.A. These formulae are set out in full in a paper describing 80 wall tests carried out at the Polytechnic (2) and they are based on the simplest forms of yield line which give a minimum strength. The walls were also analysed with yield lines approximating to the positions of the actual cracks in the walls. The unified, minimum strength formulae generate the BM coefficients given in BS 5628 Part 1(7). Four different sets of stresses were used to calculate moments of resistance and orthogonal ratios for the test walls as follows.



PSA WALL TESTS - PHASE 8 - WALL No. 8/4 TESTS A & B
LOAD v DEFLECTION OF GRID POINT E4 Figure 2

Table 2 Summary of Test Results

Test No	Masonry Types	L m	S m	At First Crack: Total Load kN	p kN/m²	Edge Load kN/m	Max. Defl. mm	At Ultimate Load: Total Load kN	p kN/m²	Edge Load kN/m	Strut Load kN	Max. Defl. mm	Crack Pattern Type
8/1A	Brick	4.50	4.50	10.4	0.51	1.16	1.8	24.0	1.19	2.67	7.06	16.6	A2
8/1B			4.50	13.9	0.69	1.54	3.8	24.0	1.19	2.67	7.34	11.7	A2
8/2B	LWA	4.50	2.25	11.8	0.70	0.79	2.4	20.0	1.19	1.33	4.27	15.8	A2
8/2A			4.50	12.0	0.59	1.33	2.4	25.0	1.23	2.78	6.70	20.7	B2
2/5	Brick + LWA	4.50	0	24.8	1.84	0	2.3	52.2	3.87	0	-	13.5	A2
8/3B			2.25	19.0	1.13	1.27	2.1	57.5	3.40	3.84	10.03	18.9	B2
8/3A			4.50	22.0	1.08	2.44	2.5	58.0	2.84	6.44	9.62	16.4	B2
2/12	Brick	2.5	0	10.0	1.33	0	1.1	28.5	3.80	0	-	8.0	A2
8/4A			2.5	10.9	0.97	1.21	1.8	27.4	2.43	3.04	7.35	9.9	B2
8/4B			5.0	15.0	1.00	2.50	6.6	15.3	1.02	2.55	3.89	7.5	B2
8/5A	LWA	2.5	2.5	11.8	1.05	1.31	2.4	24.0	2.13	2.66	5.76	11.4	B2
8/5B			5.0	7.0	0.47	1.17	2.2	19.9	1.33	3.32	7.48	12.0	B2
2/7	Brick + LWA	2.5	0	14.7	1.96	0	1.0	53.8	7.17	0	-	8.2	B2
8/6A			2.5	17.5	1.56	1.95	1.3	53.4	4.75	5.93	10.76	10.7	B2
8/6B			5.0	25.1	1.67	4.18	3.5	45.2	3.01	7.53	13.06	13.7	B2

Stress case (a). Characteristic flexural stresses from Table 3 of BS 5628:Part 1 with the bed joint stresses increased by γ_m times the self weight stress at mid-height of the wall.

Stress case (b). Mean flexural stresses obtained from the wallette tests with the bed joint stress increased by the unfactored self weight stress.

Stress case (c). 1/0.9 (Characteristic flexural stresses obtained from wallette tests in accordance with BS 5628:Part 1 with the bed joint stresses increased by γ_m times the self weight stress at mid-height).

Stress case (d). Characteristic flexural stresses from wallette tests with bed joint stresses increased by unfactored self weight stress.

Cases (a) and (c) assess the recommendations given in BS 5628:Part 1, the 1/0.9 in (c) is introduced for comparison purposes as the partial safety factors can be reduced by 10% if wallette tests have been carried out.

Cases (b) and (d) enable the suitability of wallette test results to be assessed.

The stresses derived by these principles and used in the calculation of the moments of resistance are given in Table 3.

Measurements of the deformation at the base of the wall suggested that partial fixity was occurring due to the self weight of the wall acting at an eccentricity of 0.45 x leaf thickness. A base fixity factor ($\not>1$) was calculated from the ratio of this eccentricity or stability moment and the full flexural moment of resistance across the bed joints.

Table 3 Stresses Used in Analysis of Walls

Masonry Type	Stress Case	Limit State Stresses N/mm^2				Modified Orthog' Ratio
		across perp' joints	across bed joints	self weight allowance	total bed joints	
Brick w.a.> 12%	a	0.90	0.30	0.11*	0.41	0.46
	b	1.41	0.59	0.03	0.62	0.44
	c	1.38	0.46	0.11*	0.57	0.41
	d	1.24	0.41	0.03	0.44	0.35
Block (12.4 N/mm^2)	a	0.83	0.25	0.07*	0.32	0.39
	b	1.11	0.71	0.02	0.73	0.66
	c	0.97	0.58	0.07*	0.65	0.67
	d	0.87	0.52	0.02	0.54	0.62

* based upon $\gamma_m = 3.5$

The results of analysing the strength of the walls using stress case (b) with the yield lines in the positions of the cracks in the test and to give the minimum strengths are shown in Table 4. In both cases the strength of the cavity walls was obtained by adding the strength of the individual leaves.

Table 4 Effect of Crack Pattern on Wall Strength

Calculations based on stress case (b)

Wall Test No.	L m	S m	Masonry	Calculated p kN/m^2		Test Load kN/m^2	Test/Theory	
				Actual Cracks	Min.		Actual Cracks	Min.
8/1A	4.50	4.50	)Brick	1.54	1.32	1.19	0.77	0.90
8/1B		4.50	)	1.54	1.32	1.19	0.77	0.90
8/2B		2.25	)Block	1.96	1.64	1.19	0.61	0.73
8/2A		4.50	)	1.49	1.30	1.24	0.83	0.95
2/5		0	)Brick	4.79	4.48	3.87	0.81	0.86
8/3B		2.25	) +	4.50	3.33	3.40	0.76	1.02
8/3A		4.50	)Block	3.46	2.62	2.84	0.82	1.08
for 4.5m long walls						(Mean	0.77	0.92
						(C of V %	9.7	12.3
2/12	2.5	0	)	4.90	3.75	3.80	0.78	1.01
8/4A		2.5	)Brick	2.03	2.02	2.43	1.19	1.20
8/4B		5.0	)	1.39	1.31	1.02	0.73	0.78
8/5A		2.5	)Block	1.90	1.88	2.13	1.12	1.13
8/5B		5.0	)	1.30	1.29	1.33	1.02	1.03
2/7		0	)Brick	8.29	7.18	7.17	0.86	1.00
8/6A		2.5	) +	3.54	3.90	4.70	1.33	1.21
8/6B		5.0	)Block	2.80	2.60	3.01	1.08	1.16
for 2.5m long walls						(Mean	1.01	1.07
						(C of V %	20.6	13.4
for all walls						(Mean	0.90	1.00
						(C of V %	22.4	14.6

The table demonstrates that the test strengths compared with the predicted strengths are more consistent for the 4.5m long walls but the use of mean wallette stresses overestimates the strength of the 4.5m long walls. On average the mean wallette stresses give a good prediction of strength for the shorter walls but the variability is considerable. Lawrence (8) has reported similar findings concerning the aspect ratios for panel walls without edge loadings.

Table 5 shows the results of analysing all the walls with yield lines to give minimum strength using moments of resistance derived from the four stress cases.

Table 5 Effect of Stress Case on Wall Strength

Wall Test No	L m	S m	Calculated p kN/m^2 For Stress Case a	b	c	d	Test Load kN/m^2	Test/Theory a	b	c	d
8/1A	4.50	4.50	0.88	1.32	1.23	1.03	1.19	1.35	0.90	0.97	1.16
8/1B		4.50	0.88	1.32	1.23	1.03	1.19	1.35	0.90	0.97	1.16
8/2B		2.25	0.89	1.64	1.46	1.25	1.19	1.34	0.73	0.82	0.95
8/2A		4.50	0.69	1.30	1.16	0.99	1.24	1.80	0.95	1.07	1.25
2/5		0	2.72	4.48	4.09	3.49	3.87	1.42	0.86	0.95	1.11
8/3B		2.25	2.01	3.33	3.03	2.57	3.40	1.69	1.02	1.12	1.32
8/3A		4.50	1.57	2.62	2.39	2.02	2.84	1.81	1.08	1.19	1.41
							Mean C of V %	1.54 14.3	0.92 12.3	1.01 12.2	1.19 12.5
2/12	2.50	0	2.45	3.75	3.52	3.01	3.80	1.55	1.01	1.08	1.26
8/4A		2.50	1.33	2.02	1.90	1.62	2.43	1.83	1.20	1.28	1.50
8/4B		5.00	0.91	1.31	1.30	1.10	1.02	1.12	0.78	0.78	0.93
8/5A		2.50	1.08	1.88	1.66	1.44	2.13	1.97	1.13	1.28	1.50
8/5B		5.00	0.74	1.29	1.14	0.99	1.33	1.80	1.03	1.17	1.34
2/7		0	4.45	7.18	6.56	5.64	7.17	1.61	1.00	1.09	1.27
8/6A		2.50	2.41	3.90	3.56	3.06	4.70	1.95	1.21	1.32	1.54
8/6B		5.00	1.65	2.60	2.44	2.09	3.01	1.82	1.16	1.23	1.44
							Mean C of V %	1.71 16.3	1.07 13.4	1.15 15.2	1.35 14.8
			for all tests				Mean C of V %	1.63 15.9	1.00 14.6	1.09 15.1	1.28 14.8

The comments above on Table 4 also apply to Table 5 but in addition it can be seen that the flexural stresses given in BS 5628 for the materials used in this programme give very conservative strengths for the walls. Although the mean wallette stresses give the best overall correlation between tests and theory they cannot be considered suitable for design use due to the aspect ratio influence referred to previously which would make the longer walls unsafe. The results using stress case (c) show that use of characteristic wallette strengths and the 10% reduction in the partial safety factor for materials are justified for the range of walls tested. The ratios of test load to predicted load are lowest for walls 8/2B and 8/4B which are tests carried out after repairing failed joints so it is possible that the repairs may not have been entirely satisfactory in these walls which included the porous no fines type of blocks which allowed the adhesive to disperse through the block without spreading so effectively along the joint.

6.2 Reaction at base of free edge

The calculation of the reaction at the base of the free edge was determined from the shaded trapezium shown in Fig.3. These calculated reactions when compared with the measured loads on the load cell showed that the assumptions were conservative and safe for design.

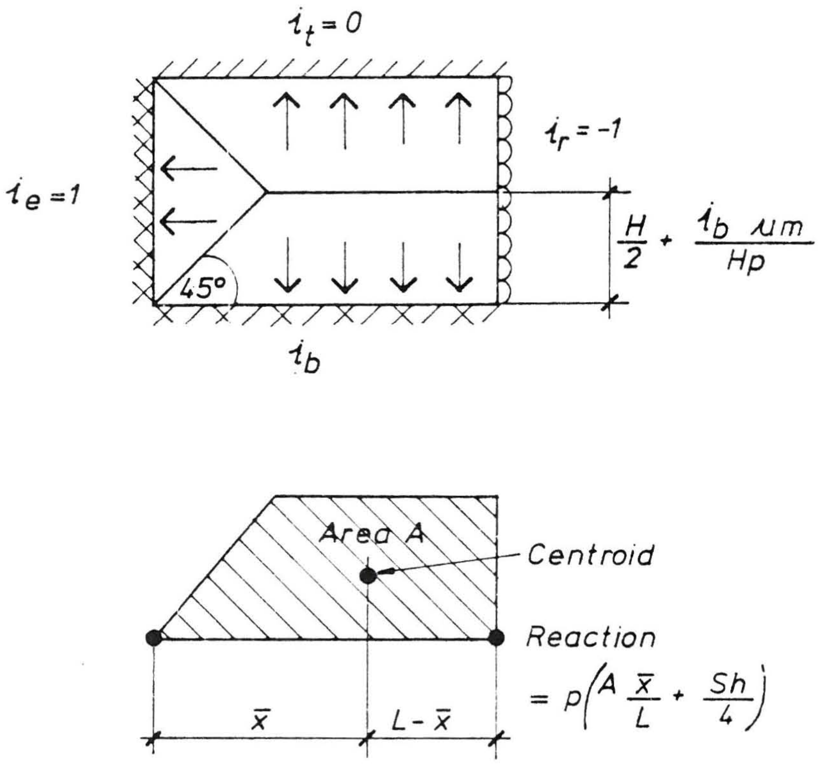


Fig 3 Distribution of Loads to Reactions

7 CONCLUSIONS

The main conclusions from the results of this series of tests are

7.1 The use of yield line theory is a satisfactory method for analysing walls with line loading on one free vertical edge although on the evidence of these tests it should be used with caution for storey height walls longer than 5m.

7.2 For the masonry materials used in this series of tests the characteristic flexural strengths given in Table 3 of BS 5628: Part I are very conservative.

7.3 The use of mean wallette flexural strengths for the appropriate materials in association with yield line theory gives good general agreement between analysis and test results with some strengths over-estimated and some under-estimated. This suggests that wallette tests are a satisfactory way of determining the properties of full size walls for use in the yield line method analysis for the walls reported here. The use of the characteristic wallette flexural strengths and yield line theory generally under-estimate the strength of the walls and hence give conservative designs. It should be remembered however that the mean and characteristic values from a set of bed joint wallettes (usually 10) is not the true mean of all the joints as only one test result is taken for each specimen. This problem is discussed by Anderson (9) and Lovegrove and

de Vekey (10). The fact that the wallette results are probably well below the corresponding strength of the masonry in an actual wall is a factor contributing to the apparently good agreement between test load and prediction.

7.4 The use of characteristic wallette strengths, enhanced by γ_m x the self weight stress across the bed joints, and a γ_m reduced by 10% are justified by the results of these tests.

7.5 Adding the strength of the individual leaves to determine the strength of cavity walls with butterfly ties is justified by these tests, but it must be remembered that the cavity was closed at the vertical edges by returning one leaf on to the other and that closure of the cavity at the top support was prevented. It is particularly important that designers of masonry cavity walls realise the importance of carrying the loads from each leaf into the supporting beams, columns or cross walls at the edges of the panels assumed supported in the analyses. This will often require the use of extra ties where a cavity continues past a support.

7.6 Failure of the d.p.c. by sliding does not appear to be a problem provided that "strong points" are provided at the ends of the wall to carry the shear from the panel area and line load shown in Fig 3.

7.7 Deflection at first cracking does not seem to be affected by the panel length and loading distribution but the maximum deflection at ultimate load does appear to be a function of the wall length.

7.8 An eccentricity factor of 0.45xT at the fracture line and base of the walls is confirmed by these tests. The use of yield line theory is often criticised as being inappropriate for a brittle unreinforced material which cannot carry a moment after it has cracked. This criticism does not allow for the secondary effects due to in-plane membrane action, self weight effects and partial arching action from supports which can induce eccentric compression forces across the cracks.

These factors and those discussed in 7.3 suggest that a new approach from first principles to the analysis of masonry walls in flexure would be justified but in the mean time the combination of wallette testing and yield line analyses does seem to be a reasonable basis for design of a wide range of walls. Anderson (2) has shown however that the strength of walls with continuity over two vertical edge supports can be unsafe using yield line theory. Ma and May (11) attribute this to the inability of walls of this type to carry the same horizontal moment across the supports and in the span simultaneously as assumed by the yield line theory.

7.9 The use of a resin injection technique for repairing cracks in masonry is capable of restoring flexural strength.

8 ACKNOWLEDGEMENTS

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