IV–7. Behaviour of Reinforced Grouted Cavity Beams

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ABSTRACT

The paper describes the results of an investigation carried out on reinforced grouted cavity beams of different shear arm: effective depth ratios. The brick strength and the % of steel were kept constant throughout the testing. The calculated allowable moments based on the British Standards CP 111 and CP 110 (Limit state) are compared with the test results in this paper and it appears that the design based on CP 111 is rather conservative. Design based on ultimate load philosophy appears more realistic.

The paper also describes an approximate method which predicts favourably the ultimate shear strength of the test beams.

INTRODUCTION

The behaviour of reinforced concrete suggests that the ultimate shear strength of reinforced brickwork or reinforced grouted cavity walls could be affected by the shear span/effective depth ratio, percentage of tensile reinforcement, the shear reinforcement and, to some extent, the brick strength. For "ordinary" reinforced brickwork (i.e. with thin reinforcement in bed joints only), the ultimate shear increases significantly with decreasing shear arm/effective depth ratios[1,2,3]. However, there is a wide scatter of experimental results and Suter et al.[4] have recently suggested characteristic shear stress of 0.3 N/mm². The suggestion is based on test results of beams very different from thin reinforced retaining walls. Further, this is very much less than the result obtained on reinforced brick grouted beams carried out at BRE[5] for Structural Clay Products Ltd. In the light of these results it became necessary to examine the effect of all factors mentioned above which could influence the ultimate shear strength and thus the load carrying capacity of thin reinforced brick grouted beams as used in retaining walls.

The investigation described in this paper is mainly concerned with the effect of shear span/effective depth ratio on the behaviour and strength of reinforced brickwork beams with a constant % of steel. Only one type of brick was used. The effects studied were deflection, cracking and ultimate strength.*

MATERIALS

Bricks

Perforated Downing bricks with average crushing strength of 71.32 N/mm² were used for all tests. The coefficient of variation was 7.8%. The average water absorption was 4.2%. The suction rate was 0.2 Kg/m²/min.

Cement and Lime

Ordinary Portland Cement to BS 12 "Portland" Cement (Ordinary and rapid hardening) was used for the construction of the test specimen. The lime used in the mortar conformed to BS 890 "Building Limes".

Aggregate

Fine Aggregate

The sand available in Scotland could not meet the grading requirement of BS 1200 for reinforced brickwork. It was therefore necessary to obtain special sand from Leighton Buzzard conforming to the Standard. Local sand conforming to the BS grading zone 2 was used for grout.

Mortar

1:¼:3 (cement:lime:sand) mix was used for mortar. A mortar mix with water/cement ratio of 0.6 was found workable and kept constant for all tests. For each specimen three 100mm cubes were cast, cured in water, and tested at 28 days. The average strength was 28.38 N/mm².

Grout

The constituents of the grout were mixed by weight to give 1:0.1:3:2 (cement:lime:sand:pea gravel) mix by volume. The water/cement ratio was 1.2 and the slump 275 mm. Three 100 mm cubes/wall were tested at 28 days. The average strength was 20.34 N/mm².

Reinforcement

Hot rolled high yield deformed bars were used for the reinforcement. Two steel specimens were tested under tension and the resulting strain was measured by electrical strain gauges mounted on the specimen. The data were analysed and a least square linear regression method was applied to obtain the value of initial modulus of elasticity. The correlation coefficient in both cases was 0.998. The average modulus of elasticity was 217.56 kN/mm² (213.78 kN/m² and 221.34 kN/mm²), and the average ultimate strength was 525 N/mm² (500 and 550 N/mm²). The 0.2% proof stress[11] was 476 N/mm².

DETAILS OF BRICKWORK TEST SPECIMENS AND ARRANGEMENTS FOR TESTING

Test Specimens

The test specimens (Fig. 1) were 2445 × 660 × 275mm (l × b × d). The brickwork was tied by strip ties to BS

* Since then (1973) a more comprehensive programme of research, investigating all factors, is being carried out at the University of Edinburgh under the sponsorship of the Building Research Establishment, U.K.

1243 spaced 400 × 300 mm and staggered. The reinforcement was seven 12 mm bars giving an area of 798 mm^3, or 0.88% of the effective area. The beams were tested to failure using symmetrical two point loading with loads 1000 mm apart.

The permissible bond stress for 20 N/mm^2 grade concrete is 1.7 + 30% = 2.2 N/mm^2. (CP 110: Part 1: 1972[6] Clause 3.11.6.2). Hence the anchorage length needed for 12 mm bars is

$$\frac{\pi r^2 . f_y}{2\pi r . f_{bs}} = \frac{6 \times 410}{2 \times 2.2} = 0.56 \text{ m} = 560 \text{ mm}$$

and the minimum specimen length is thus 1000 + (2 × 560) = 2120 mm. The distance between supports changed with changes in a/d ratios (where d = 138 mm) and when this was 5 this distance becomes 1000 + (2 × 690) = 2380 mm. All specimens were made this length—actually 2445 mm—irrespective of a/d ratio and minimum bond achorage.

Compressive Strength

Ten prisms each six courses high (Fig. 2) were tested to obtain the ultimate strength. The average compressive strength[11] was 33.9 N/mm^2 with a coefficient of variation of 17.8%.

Modulus of Elasticity

The strain was measured by demec gauge on four prisms to obtain the modulus of elasticity. The modulus of elasticity varied from 18.3 to 22 kN/mm^2 with an average of 20.5 kN/mm^2.

Modulus of Rupture (Flexural Tensile) Strength of Brickwork

Three 8-courses high two brick wide wallettes were built and tested as a beam subjected to a central point load to obtain the flexural strength at 28 days (Fig. 3). This was necessary to determine the moment at which 1st crack appears in the beams.

The test results are shown in Table 1.

Bond Shear Strength

Tests were carried out as shown in Fig. 4 to obtain the bond shear strength of the grout and brickwork interface. The test results are shown in Table 2.

Instrumentation and Testing

Line loading (Fig. 1) was applied by 4 hydraulic jacks fixed to a loading frame, the load from each jack being measured by the load cells connected to a pen-chart recorder. The lateral displacement of beams was measured by means of dial gauges reading to 0.002 mm. The load was applied incrementally and the deflection was recorded for each beam. The loading was continued till beam failure occurred. Wherever possible the loads at which first and subsequent cracks appeared were noted.

TEST RESULTS AND DISCUSSION

Mode of Failure

In all the tests the initial visible cracks started at the interface of brick and mortar in the tension zone. From the deflection results it is apparent that the actual cracking took place much earlier than it became visible since there was marked changes in the load-deflection relationship. Typical crack propagation (Fig. 5) shows that the sudden failure at the interface of grout and top brickwork was due to shear compression failure and shear failure. With a lower shear span/depth ratio the failure, in some instances, may have coincided with the yielding of the steel. The test results are shown in Table 3.

Deflection

The load-deflection relationship for various beams is shown in Figs. 6 to 9. The load-deflection relationship is bi-linear and it appears that there is sudden change in deflection when the resulting moment exceeds the brickwork cracking moment. The load at which this deviation in deflection takes place can very well be predicted as shown in Figs. 6 to 9 by using the flexural strength of brickwork (Sec. 3.1.3) and uncracked section (full cross-section) of the beam. The deflection of different beams under similar loading conditions is not the same, which may be due to differences in the modulus of elasticity, workmanship and presence of hair-cracks at the brick/mortar interface affecting the stiffness of the beams.

Moment of Resistance

Uncracked Moment of Resistance

The moment of resistance before the crack became visible was calculated by using the full uncracked section and the flexural strength of brickwork from section 3.1.3. The moment of resistance (6.5 kNm) was very much less than the ultimate moment of resistance (48.8 kNm). However, even before the appearance of the first crack at the interface of brick and mortar, moment was higher than the permissible moment according to CP 111:1970. The factor of safety will be in the range of 1 to 2.6, if the design is based on completely uncracked section. (Table 3b, ii).

Ultimate Moment of Resistance

The ultimate moment of resistance (48.8 kNm) of the test beams has been calculated by assuming a parabolic stress block[11] and taking into account the actual yield stress of steel. This compares favourably with 48.1 kNm, the average test results of beams 2, 3, 4 and 6 (Table 3) where failure was due to shear and flexural tension. Similar results[11] can be obtained by Whitney theory using a rectangular stress block.

With higher shear span/depth ratios, 4 & 5, the failure moment was 78 to 52% less, due to premature shear failure, than the theoretical moment of resistance. It may be possible to increase the moment capacity of these beams by using shear connectors so that failure at the interface of brick and grout can be delayed.

Comparison of Results with CP 111[7] and CP 110 (Limit State)

The calculated allowable moments based on CP 111 and CP 110 are compared with the test results (Table 3). The factor of safety varies from 4 to 18 for beams with a/d ratio

5 to 2 when the shear stress (and hence the load and moment) is limited by the appropriate clauses of CP 111. When these clauses are ignored the factor of safety reduces and becomes 2.7 to 4.7 with the steel stressed to a very low value (97.5 N/mm^2). Even then shear stress exceeds the allowable in CP 111 (Clause 321). The global safety factor varies from 1.1 to 1.92 if the design calculation for resistance moment is based on CP 110.

Ultimate Shear Stress

The ultimate shear stress increases with decreasing shear span/depth ratio (Table 4). As in most cases, the failure of the reinforced grouted beams was due to shear it is important to identify the parameters which affected the test results.

Shear Failure Theory

To calculate the ultimate shear stress, the brickwork beam can be treated as a tied arch, and the forces acting are shown in Fig. 11.

Hence,

$$H = \frac{M_{max}}{z} = \frac{Wa}{z} = \frac{Wa}{jd}; \quad M_{max} = \text{moment} \qquad \text{(i)}$$

The failure of arch[9] will take place if, (a) the compressive stress exceeds the compressive strength of brickwork; (b) the tie stress exceeds the tensile strength of steel; (c) the tie force H is greater than or equal to the ultimate shear strength of the brickwork and thus destroys the bond at the interface of brick and grout. In the present test the final failure is due to destruction of bond at the interface of brickwork and grout. Hence

$$H = V_{ult} \qquad \text{(ii)}$$

where V_{ult} is the ultimate shear force.

Between the support and loading point, i.e. within the shear arm, the brickwork and grout interface is subjected to precompression. Under such condition the ultimate shear strength[10] of brickwork can be represented by:

$$v_{ult} = t_b + \mu\sigma \qquad \text{(iii)}$$

where σ – compressive stress N/mm^2; μ – coefficient of friction; t_b – initial bond shear N/mm^2; v_{ult} – shear stress N/mm^2.

From equation (iii),

$$V_{ult} = t_b(a + l)b + \mu W \qquad \text{(iv)}$$

From equation (ii) and (iv),

$$\frac{Wa}{jd} = t_b(a + l)b + \mu W \qquad \text{(v)}$$

or,

$$\frac{Wa}{jd} - \mu W = t_b(a + l)\cdot b$$

or,

$$W\frac{a - \mu jd}{jd} = t_b(a + l)\cdot b$$

or,

$$\frac{W}{bd} = \frac{(a + l)t_b\cdot j}{a - \mu jd}$$

or,

$$v = j\cdot t_b\cdot\left[\frac{\frac{a}{d} + \frac{l}{d}}{\frac{a}{d} - \mu j}\right]$$

provided

$$\frac{a}{d} \geqslant 0.65 \qquad \text{(vi)}$$

where:

$j = \frac{z}{d} = \frac{\text{lever arm}}{\text{effective depth}} = 0.93$ from parabolic stress block—Appendix I

$\mu = 0.7$ (coefficient of friction between brickwork and grout or mortar)

$t_b = 0.49$ N/mm^2 (Initial bond shear: Section 3.14)

The theoretical ultimate shear stress was calculated from equation (vi) and compared with stress calculated from $\frac{W}{bd}$ and shown in Fig. 10.

From Fig. 10 it can be seen that there is very good agreement between the test results and theory. However, this needs to be conformed for $\frac{a}{d}$ values higher than 5 and also for other brick types.†

The shear stresses for brickwork reinforced in the bed joints were also calculated by this method, and the figures agreed closely with the results obtained by Suter and Hendry[4]. Since the initial bond strength for their case was not known, the initial bond strength of 0.354 N/mm^2 obtained in previous tests of Sinha and Hendry[8] on the same brick in 1:1:6 mortar was used.

Considering all these facts it would be reasonable to recognise the significant increase in nominal shear stress with decreasing $\frac{a}{d}$ values. Provision could be made in the Code to take this into account. For the present, the ultimate load design proposed in this report is an alternative for reinforced grouted cavity construction and the design moment and design shear stress can be obtained by dividing by a suitable factor of safety.

CONCLUSIONS

The ultimate shear stress increases significantly with decreasing shear span/depth ratio. Provision could be made in the Code to take this fact into account.

Design based on CP 111:1970:Part 2 is conservative for the type of brick and mortar used in tests because of low allowable flexural compressive stress and constant allowable shear stress. Design based on ultimate load philosophy as suggested in this report appears more reasonable.

† Recent work done by first author confirms this for other types of brick.

The theoretical shear stress calculated by the method suggested compares favourably with the present test results and also with results on "ordinary" reinforced brickwork.

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TABLE 1—Flexural Strength of Brickwork

No.	Flexural Strength N/mm^2	Average Flexural Strength N/mm^2
1	0.74	
2	0.70	0.78
3	0.90	

TABLE 2—Bond Shear Strength

Corresponding Wall No.	No.	Shear Stress N/mm^2	Average Shear Stress N/mm^2
12	1	0.473	
	2	0.287	0.49
6	1	0.630	
	2	0.550	

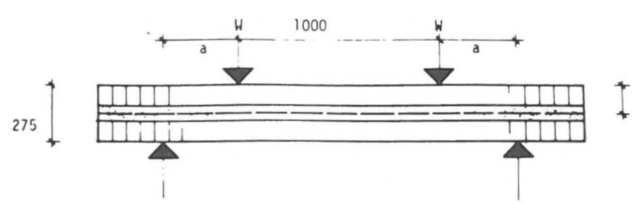

Figure 1. Test specimen and loading arrangement

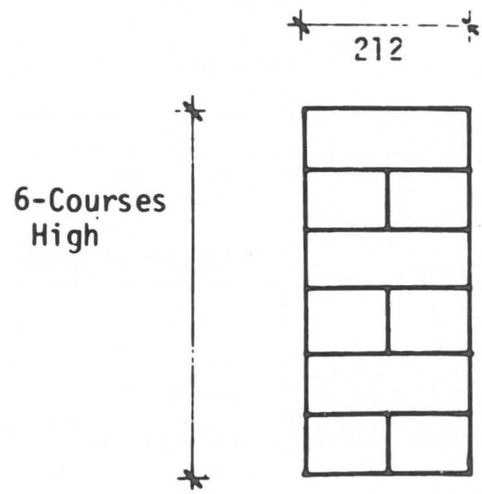

Figure 2. Test prism (dimensions in mm)

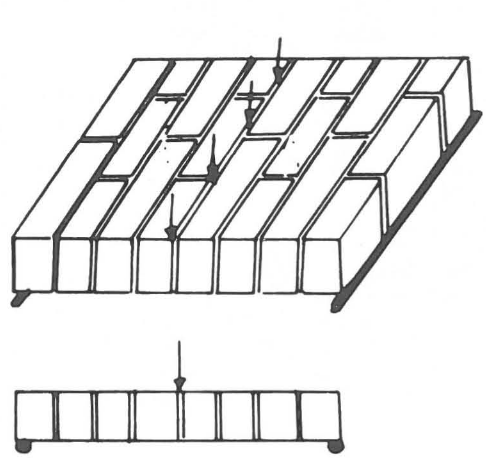

Figure 3. Test arrangement for determination of modulus of rupture.

TABLE 3—Comparisons on Test Results with Calculated CP.111 Performance (Elastic Design) & CP.110 Limit State

	a/d	2	3	4	5
Bending	(a) B.M. at Failure kNm	(1) 36.4 (2) 49.14 Av. 44.5 (3) 47.94	(4) 47.3 (5) 34.0 Av. 43.0 (6) 48.12	(7) 41.0 (8) 36.1 Av. 38.0 (9) 37.0	(10)35.0 (11)23.7 Av. 25.6 (12)18.0
	(b) Permissible* B.M. from CP.111 (kNm)	(i) 9.4 (ii) 2.5	9.4 4.13	9.4 5.0	9.4 6.23
	(c) Ratio (a)/(b)	(i) 4.7 (ii) 17.8	4.6 10.4	4.0 7.6	2.7 4.1
Nominal shear stress $v = W/bd$	(d) Average shear stress at failure	1.79	1.18	0.82	0.46
	(e) Actual shear stress from b(i) Permissible shear stress b(ii)	0.374 0.1	0.25 0.1	0.187 0.1	0.15 0.1
	(f) Ratio (d)/(e)	4.8 17.9	4.7 11.8	4.4 8.2	3.1 4.6
Bending	(g) Design moment $\gamma_f = 1.4$ (CP.110)	23.2	23.2	23.2	23.2
	(h) Global safety factor, ratio (a)/(g)	1.92	1.85	1.6	1.1

* NOTE: (i) ignoring the shear stress of CP.110, Clause 3.4.5.
(ii) based on allowable shear stress of CP.110, Clause 3.4.5.

TABLE 4—Ultimate Shear Test Results (Age at test 28 days)

Beam No.	Mortar Strength N/mm²	Grout Strength N/mm²	a/d	Failure Mode	Shear stress v_1 N/mm² (from test load)	Average shear stress v_1 N/mm²	Shear stress due to dead wt v_2 N/mm²	Average ultimate shear stress $v = v_1 + v_2$ N/mm²
1	23.0	15.2	2	Ssu	1.45			
2	29.7	27.0	2	Ssu/FL	1.94	1.76	0.03	1.79
3	26.7	19.8	2	Ssu/FL	1.90			
4	29.7	23.0	3	Ssu/FL	1.23			
5	31.0	18.0	3	Ssu	0.91	1.14	0.035	1.175
6	31.8	16.6	3	Ssu/FL	1.28			
7	27.9	22.4	4	Ssu	0.86			
8	27.3	23.5	4	Ssu	0.73	0.78	0.041	0.821
9	28.4	28.2	4	Ssu	0.74			
10	32.9	22.3	5	Ssu	0.38			
11	28.9	19.2	5	Ssu	0.56	0.41	0.045	0.46
12	29.2	14.0	5	Ssu	0.29			

Notes: Ssu — Sudden shear failure
FL — Flexural failure

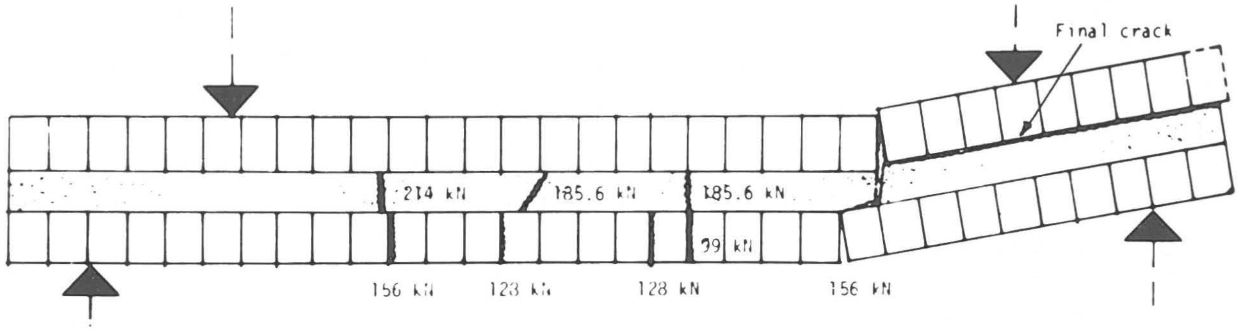

Figure 5a. Typical failure

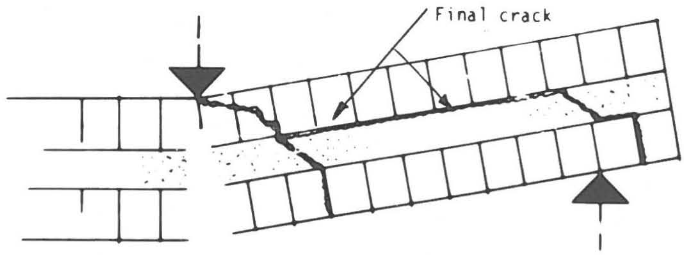

Figure 5b. Alternative failure pattern (e.g. wall 10: a/d = 5)

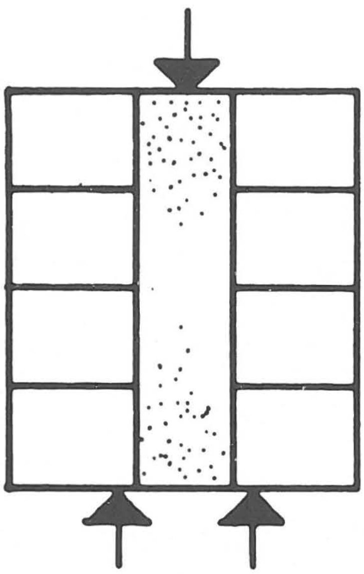

Figure 4. Bond shear test arrangement.

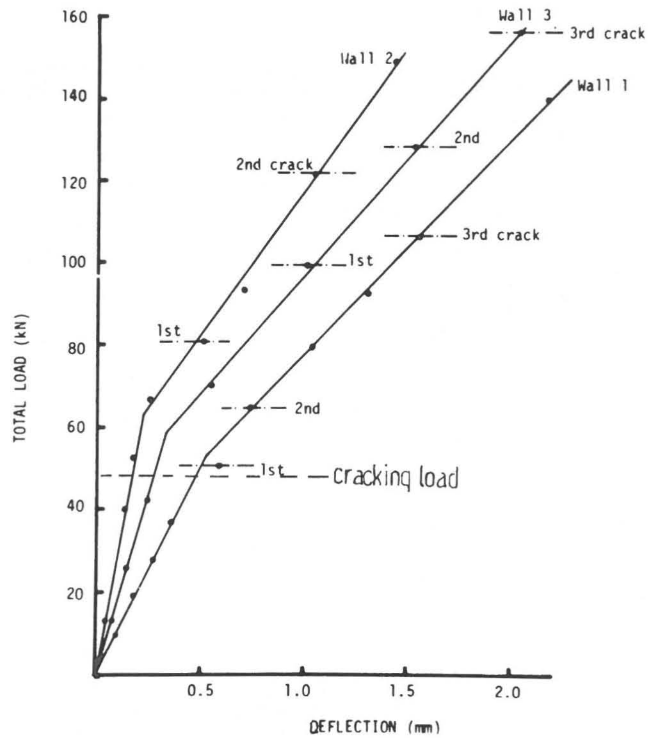

Figure 6. Load/deflection graphs for walls with a/d = 2

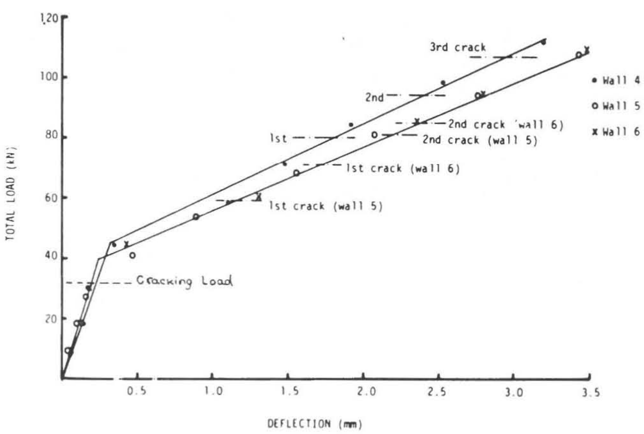

Figure 7. Load/deflection graphs for walls with a/d = 3

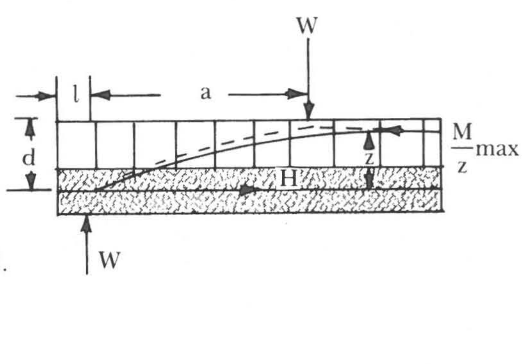

Figure 11.

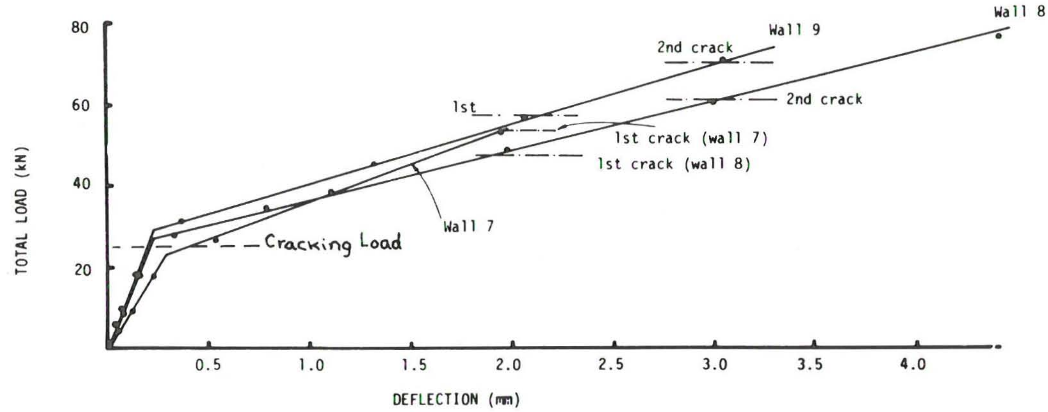

Figure 8. Load/deflection graphs for walls with a/d = 4

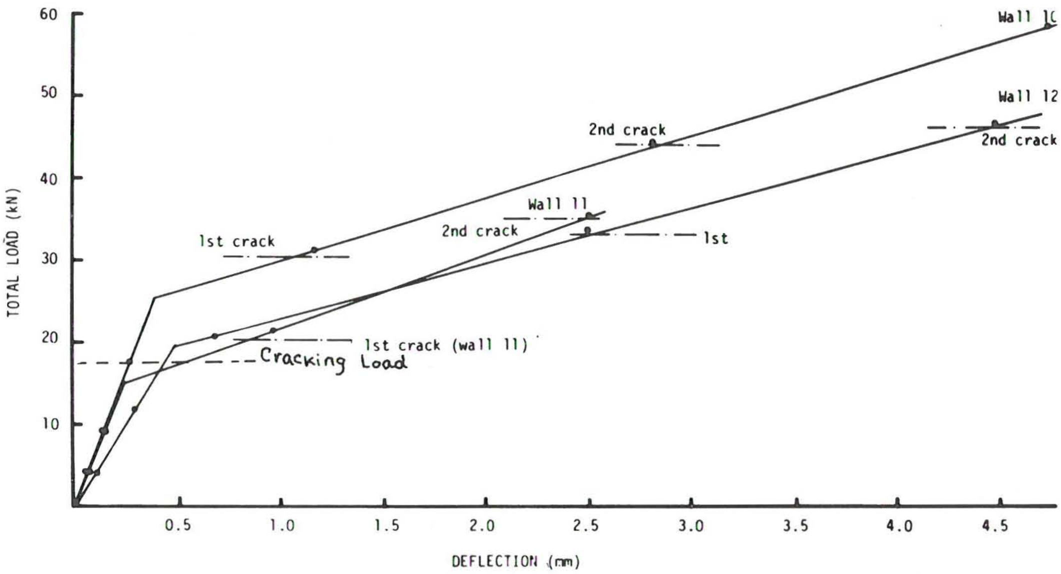

Figure 9. Load/deflection graphs for walls with a/d = 5

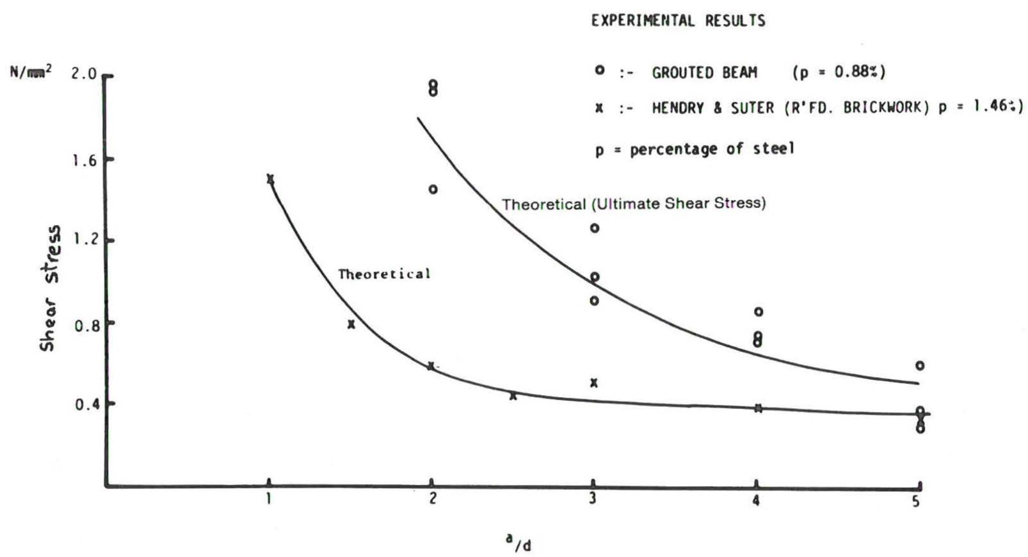

Figure 10. Influence of a/d on the shear strength of beams