Factors affecting the Shear Strength of Reinforced grouted Brickwork Beams and Slabs

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The paper describes the statistical analysis carried out on the test results to identify the factors which affect the shear strength of the reinforced grouted beams and slabs. It appears from this analysis that the shear strength of the reinforced grouted cavity brickwork beams and slabs is strongly affected by:

i) shear arm/effective depth ratio
ii) % of tensile reinforcements
iii) shear reinforcements
iv) thinness of section

The grades of mortar ($1 : \frac{1}{4} : 3$ - cement : lime : sand) and ($1 : \frac{1}{2} : 4\frac{1}{2}$ - cement : lime : sand) slightly affect the strength, but not very significantly. The brick strength does not affect the shear strength of reinforced brickwork.

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INTRODUCTION

Reinforced brickwork has been used to a limited extent during the past. The failure of reinforced brickwork is almost invariably due to shear and it is very difficult to provide shear reinforcement in brickwork. Further, the necessity to put the main reinforcement in the bed joint limits the size of reinforcement to less than the joint thickness. These limitations of reinforced brickwork can be overcome by the use of brick grouted cavity construction. Basically, it consists of two skins of brickwork as used in an ordinary cavity wall; the cavity being used to accomodate the main and shear reinforcements. The cavity is finally grouted to form a monolithic construction and also to give an additional protection to the reinforcements from the weather. This form of construction would have a wide field of application and may prove economical because of elimination of formwork. Although, reinforced brickwork was the subject of investigation (1,2,3) in the past, no comprehensive (4,5) tests were carried out in case of grouted cavity construction. Because of this lack of experimental data relating to grouted cavity construction a comprehensive programme of research was undertaken.

This paper describes very briefly the experimental work done to investigate shear strength of grouted cavity reinforced brickwork beams and analyses the results statistically to establish the factors which affect the strength. The major variable considered in this programme were:

i. Shear span/effective depth ratio: The investigation covers a wide range of a/d ratio varying from 1:5 to 10.

ii. Brick strength: Three types of bricks, low (21.55 N/mm^2), medium (59.38 N/mm^2) and high strength (88.33 N/mm^2) were used for the construction of the beams and slabs.

iii. Mortar Grade: Two grades of mortar 1:$\frac{1}{4}$:3 (cement:lime:sand) and 1:$\frac{1}{2}$:4$\frac{1}{2}$ (cement:lime:sand) were used.

iv. % tensile reinforcement: Three different percentages of the tensile reinforcements varying from 0.88 to 1.68 were used for the beams. The percentages of tensile reinforcements used for the walls were 0.9 and 2.54.

v. Effect of extra ties: In case of the walls, the failure was always noticed at the interface of the grout and the brickwork. The normal spacing (900mm horizontally and 400mm vertically staggered) of the wall ties were used originally. The number of ties were increased with the idea to stop the interface failure and thus to establish the effect of the extra number of ties.

vi. Shear reinforcements: The variable considered was the spacing of the vertical stirrups and its effect on shear strength of beams built with various types and strength of bricks.

DETAILS OF THE TEST SPECIMENS AND TEST ARRANGEMENTS

Two types of specimens, a beam and a thin slab, as shown in Fig. 1 were used for the tests. The two leaves of the cavity wall forming both sets of specimens were 80 - 90mm apart and were tied by galvanised fish tail ties spaced at 450 - 300mm staggered. In the case of the slab the reinforcement was in the centre of the cavity. For every specimen, full anchorage length for the reinforcements were provided as per concrete code (6). A 1:0.1:3:2 (cement:lime:sand:pea gravel) mix by volume was used for the grout with a constant water cement ratio of 1.2.

Both types of specimens were tested under two point loading in a specially designed loading frame providing a pin and a roller support as shown in fig. 2. The load was applied by means of two hydraulic jacks operated by a pump, the load being measured by the load cells connected to a pin chart recorder and a digital voltmeter. The load was applied at stages till failure.

The majority of the test specimens for investigating the effect of shear arm/effective depth ratios on the ultimate shear strength were made from low strength bricks. Since this variable has no significant effect on the shear strength after $a/d > 5$, the effects of all other variables were investigated by keeping this constant at 6.

METHOD OF STATISTICAL ANALYSIS

Fully replicated analyses of variance were carried out on the results in Tables 1 to 6 as follows:-
One way analysis of results in Table 1 with the shear arm/depth ratio as the variate.
Two way analysis with brick strength as one variate and the other variates being beams versus walls (Table 2), percentage steel (Table 4), effect of extra ties (Table 5) and effect of shear reinforcement (Table 6).

Lastly, a three way analysis of the variates mortar strength, brick strength and 'beam versus wall' was carried out on the results in Table 3.

RESULTS AND DISCUSSION

The test results are given in Tables 1 to 6 and the results of the statistical analyses in Table 7. They are listed as either significant at the 95%, 99% or 99.9% probability level or not significant (NS), i.e. less than 95% probability. For data on physical engineering properties it is seldom of value to consider probabilities lower than 95% and to look carefully at these at 95% especially interactions. The results demonstrate clearly, as expected, the effect of shear arm/depth ratio and the improvements resulting from increasing the percentage of steel and adding shear reinforcement.

The analysis also indicated that it was possible to develop a higher shear stress in walls than in beams of the same a/d ratio and materials. This is probably because the shear plane in walls does not pass through the brickwork but will be at the interface between brick and concrete or concrete and steel.

The result that brick strength had little overall effect on shear strength is also reasonable since few of the specimens failed by shearing or crushing of bricks most by interfacial shear. The interaction terms indicate, however, that there is a significant but small effect of brick strength on walls as opposed to beams and that with shear reinforcement in a beam it is possible to exploit higher brick strengths.

The significant effect of the mortar strength was probably due to its influence on the shear resistance of the brickwork in beams and on the crushing resistance of the brickwork in walls.

CONCLUSIONS

On the basis of the statistical analysis the following conclusions can be drawn from the test results:

i) Shear strength is affected strongly by shear arm/depth ratio and by percentage of tensile reinforcements.

ii) Shear strength is strongly affected by addition of shear reinforcement to beams.

iii) For the same shear arm/effective depth ratio of 6 and for approximately same % of steel the walls were significantly stronger than the beams.

iv) The shear strength is affected by the difference between grade i and ii mortars, prepared in laboratory condition, albeit weakly. This does imply, however that good quality - control of the mortar used on site will be necessary.

v) The use of stronger bricks will not improve the strength of simple beams designed to fail in shear although it can result in small improvements in the strength of walls of similar design. Higher brick strengths may be exploited in designs where the shear strength is also increased by some form of shear reinforcement.

vi) The addition of extra wall ties did not enhance the strength significantly.

ACKNOWLEDGEMENTS

The work described in this paper has been sponsored by the Building Research Establishment, Department of Environment, U.K. and carried out in the Department of Civil Engineering and Building Science, University of Edinburgh.

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TABLE 1: Effect of $\frac{\text{shear span}}{\text{Effective depth}}$ ratios on the shear strength of reinforced grouted brickwork beam and slab (wall)

Type of Specimen	Brick Strength N/mm^2	No of Specimens	Shear span ratio / Effective depth	1:1/4:3 Mortar Strength N/mm^2	1:0.1:3:2 Grout Strength N/mm^2	Nominal Ultimate Shear Stress N/mm^2 V/bd	Average Shear Stress N/mm^2	Coeff. of variation in %	Remarks
SLAB or WALL	Low Strength flat : 21.55; % of steel 0.9	1	2	18.7	11.6	1.76	1.51	16.0	Shear failure at the interface of brick and grout
		2	2	21.5	11.6	1.46			
		3	2	24.9	10.0	1.38			
		4	2	24.0	10.0	1.25			
		5	2	20.0	10.9	1.37			
		6	2	21.0	10.9	1.86			
		1	4	20.6	11.7	0.72	0.785	9.8	
		2	4	21.55	11.7	0.69			
		3	4	21.67	16.5	0.86			
		4	4	21.22	16.5	0.86			
		5	4	21.22	16.5	0.84			
		6	4	19.78	17.37	0.74			
		1	6	20.46	14.18	0.52	0.61	-	
		2	6	20.46	14.18	0.63			
		3	6	25.0	18.02	0.69			
		4	6	25.0	18.02	0.58			
		1	8	22.14	17.37	0.405	0.43	7.87	Yielding of steel & Subsequent Compressive failure of b.w.
		2	8	18.86	13.04	0.44			
		3	8	20.86	13.04	0.47			
		4	8	19.66	13.56	0.43			
		5	8	19.66	13.56	0.38			
		6	8	20.46	14.18	0.46			
	High Strength flat: 88.33	1	10	22.7	22.1	0.50	0.48	12.6	Shear failure
		2	10	22.7	22.1	0.50			
		3	10	22.7	22.1	0.54			
		4	10	19.2	19.2	0.46			
		5	10	19.2	19.2	0.38			
BEAM	Low Strength on bed: 21.55; on edge: 16.10; % of steel 0.88	1	1.5	22.14	17.37	1.28	1.26	12.99	shear failure
		2	1.5	18.86	13.04	1.38			
		3	1.5	20.80	13.04	1.43			
		4	1.5	19.66	13.08	1.35			
		5	1.5	19.25	13.08	1.12			
		6	1.5	21.96	14.18	1.01			
		1	3.0	20.6	11.7	0.68	0.64	14.8	"
		2	3.0	21.55	11.7	0.63			
		3	3.0	21.67	16.5	0.49			
		4	3.0	21.22	16.5	0.61			
		5	3.0	19.78	17.37	0.66			
		6	3.0	22.14	17.37	0.78			
		1	4.5	18.7	11.6	0.49	0.53	4.4	"
		2	4.5	21.5	11.6	0.51			
		3	4.5	24.3	10.0	0.53			
		4	4.5	24.0	10.0	0.53			
		5	4.5	20.0	10.9	0.53			
		6	4.5	21.0	10.9	0.56			
		1	6.0	22.20	14.0	0.59	0.63	3.4	"
		2	6.0	22.20	14.0	0.64			
		3	6.0	19.96	16.86	0.64			
		4	6.0	19.96	16.86	0.63			
		5	6.0	19.96	17.24	0.65			
		6	6.0	22.86	17.24	0.64			
		1	6.8	19.3	17.5	0.53	0.56	-	Explosive Failure
		2	6.8	22.5	14.0	0.55			Explosive compressive at top
		3	6.8	23.3	14.0	0.60			Slow compressive at top

TABLE 2. Effect of brick strength on the shear strength of Reinforced brickwork beams and slab (wall)

$\frac{\text{Shear span}}{\text{effective depth}}$ (a/d) = 6

Type of Specimen	Brick Strength N/mm²	No of tests	1:1/4:3 Mortar strength N/mm²	1:0.1:3:2 Grout strength N/mm²	Nominal Ultimate shear stress N/mm²	Average shear stress N/mm²	Coefficient of variation in %
BEAM with % High Yield steel = 0.88	Low strength	1	22.2	14.0	0.59		
	flat 21.55	2	22.2	14.0	0.64		
		3	19.96	16.86	0.64	0.63	3.4
	on edge 16.10	4	19.96	16.86	0.63		
		5	22.86	17.24	0.65		
		6	22.86	17.24	0.64		
	Medium strength	1	24.58	15.61	0.60		
	flat 59.40	2	20.80	16.10	0.66		
		3	26.85	19.20	0.63	0.60	7.2
	on edge 31.92	4	23.50	15.61	0.53		
		5	20.80	16.10	0.60		
		6	21.73	15.58	0.60		
	High strength	1	21.59	15.0	0.59		
	flat 88.33	2	21.59	15.0	0.64		
		3	21.17	12.64	0.56	0.61	5.3
	on edge 26.4	4	21.17	12.64	0.59		
		5	19.04	17.68	0.62		
		6	19.04	17.68	0.64		
SLAB or WALL % of High Yield steel = 0.9	Low strength	1	20.46	14.18	0.52		
	flat 21.55	2	20.46	14.18	0.63		
	on edge 16.10	3	25.0	18.02	0.69	0.61	-
		4	25.0	18.02	0.58		
	Medium strength	1	21.66	15.58	0.62		
	flat 59.40	2	23.51	11.93	0.74		
	on edge 31.92	3	23.51	11.93	0.62		
		4	21.66	15.58	0.78	0.71	10.28
		5	21.66	15.8	0.76		
		6	23.51	11.93	0.76		
	High strength	1	21.53	16.11	0.59		
	flat 88.33	2	21.53	16.11	0.72		
	on edge 26.40	3	21.53	16.11	0.69		
		4	26.85	19.18	0.65	0.71	13.3
		5	24.0	15.61	0.72		
		6	24.0	15.61	0.87		

TABLE 3: EFFECT OF MORTAR GRADES ON THE SHEAR STRENGTH OF REINFORCED GROUTED BEAMS AND SLABS (wall)

$\frac{\text{Shear span}}{\text{Effective depth}}$ a/d = 6

Type of Specimen	Type & Strength of brick N/mm^2	No of Specimens	Shear Strength N/mm^2 Mortar Grade 1:1/4:3		1:½:4½	
	Low Strength	1	0.59			
	Flat:21.55	2	0.64		0.63	
	Edge:16.10	3	0.64	0.63	0.65	0.62
		4	0.63		0.59	
		5	0.65			
BEAM		6	0.64			
	Medium Strength	1	0.60			
	Flat:59.40	2	0.66		0.52	
	Edge:31.92	3	0.63	0.60	0.59	0.57
		4	0.53		0.61	
		5	0.60			
		6	0.60			
	High Strength	1	0.59			
	Flat: 88.33	2	0.64		0.53	
	Edge: 26.4	3	0.56	0.61	0.53	0.53
		4	0.59		0.54	
		5	0.62		0.53	
		6	0.64		0.53	
	Low Strength	1	0.52			
	Flat: 21.55	2	0.63		0.60	
	Edge: 16.10	3	0.69	0.61	0.72	0.68
		4	0.58		0.73	
	Medium Strength	1	0.62		0.60	
	Flat: 59.40	2	0.74		0.64	0.67
	Edge: 31.92	3	0.62	0.71	0.78	
		4	0.78			
		5	0.76			
		6	0.76			
SLAB	High Strength	1	0.59		0.71	
or	Flat: 88.33	2	0.72		0.55	
WALL	Edge: 26.40	3	0.69		0.66	
		4	0.65	0.71	0.62	0.63
		5	0.72		0.53	Coeff. of variation = 9.4%
		6	0.87		0.67	

Note: % of High tensile steel for

Beam = 0.38

Slab = 0.9

TABLE 4: EFFECT OF % OF STEEL ON THE SHEAR STRENGTH OF REINFORCED GROUTED BRICKWORK BEAMS AND WALLS

$\frac{\text{Shear span}}{\text{Effective depth}}$ a/d = 6

No of Specimen	Type and strength of brick N/mm^2) / % of steel	Shear Strength N/mm^2 BEAM 0.88		1.38		1.68		WALL 0.9		2.54	
1	Low Strength	0.59		0.82		0.69		0.52		0.55*	
2	Flat: 21.55	0.64		0.64	0.73	0.90	0.82	0.63		0.96	0.87
3		0.64	0.63	0.74		0.86		0.69	0.61	0.77	
4	On edge: 16.10	0.63						0.58			
5		0.65									
6		0.64									
1	High Strength	0.59		0.71		0.77		0.59		0.82	
2		0.64		0.67	0.68	0.76	0.73	0.72		0.87	0.82
3	Flat: 88.33	0.56	0.61	0.65		0.67		0.69	0.71	0.76	
4	on edge: 26.40	0.59						0.65			
5		0.62						0.72			
6		0.64						0.87			

* very inexperienced bricklayer from outside

TABLE 5: EFFECT OF EXTRA TIES ON THE SHEAR STRENGTH OF GROUTED REINFORCED BRICKWORK WALL (SLAB)

$$\frac{\text{Shear span}}{\text{Effective depth}} \quad \frac{a}{d} = 6$$

No of Specimens	Type and strength of brick (N/mm²)	Normal spacing of ties		Extra number of ties	
1	Low Strength	0.52		0.69	
2		0.63	0.61	0.65	0.65
3	Flat: 21.55	0.69		0.61	
4		0.58			
1		0.59		0.81	
2	High Strength	0.72		0.82	0.84
3	Flat: 8033	0.69	0.71	0.89	
4		0.65			
5		0.72			
6		0.87			

NOTE: % of steel : 0.9

TABLE 6. SHEAR STRENGTH OF REINFORCED GROUTED BRICKWORK BEAMS WITH AND WITHOUT SHEAR REINFORCEMENTS

$\frac{\text{shear span}}{\text{effective depth}}$ a/d = 6

No of Specimens	Type and Brick Strength (N/mm^2)	% Steel	Shear Strength N/mm^2					
			No Shear reinforcements		with shear reinforcements			
					8mm @ 360mm		8mm @ 90mm	
1	Low Strength		0.59		·0.72		0.67	
2			0.64	0.63	0.67	0.66	0.65	0.65
3	Flat: 21.55	0.88	0.64		0.59		0.63	
4			0.63					
5	On edge: 16.10		0.65					
6			0.64					
1	Medium strength		0.60		with shear reinforcements 12mm @ 110mm			
2			0.66					
3	Flat: 59.40	0.88	0.63	0.60	0.74			
4			0.53		0.71	0.73		
5	On edge: 31.92		0.60		0.73			
6			0.60					
1			0.59		0.78	0.76		
2			0.64		0.75			
3	Flat : 88.33		0.56	0.61				
4		0.88	0.59					
5	On edge: 26.4		0.62					
6			0.64					

TABLE 7 <u>RESULTS OF VARIANCE ANALYSES</u>

Table No.	Experiment	Variates and interactions	Degrees of freedom	Variance ratio	Significance %
1)	Effect of shear arm/ depth ratio				
1a)	wall	a/d	4/22	70	99.9
1b)	beam	a/d	4/18	69	99.9
2)	Effect of brick strength all at same a/d ratio	Brick strength	2/28	1.3	NS
		Beam/wall	1/28	11.2	99
		interaction	2/28	3.6	95
3)	Effect of mortar grades all at same a/d ratio	Mortar strength	1/45	4.4	95
		brick strength	2/45	0.8	NS
		beam/wall	1/45	23	99.9
		beam/wall v brick	2/45	3.6	95
		All other interaction			NS
4)a)	Effect of % steel-	% steel	2/18	16.3	99.9
	beams	Brick strength	1/18	4.3	NS
		interaction			NS
b)	Effect of % steel-	% steel	1/11	12.62	99
	walls	Brick strength	1/11	1.25	NS
		interaction			NS
5)	Effect of extra ties on walls	ties	1/12	4.2	NS
		Brick strength	1/12	11.4	99
		interaction			NS
6)	Beams with and without shear reinf.	Shear reinf.	1/20	40	99.9
		Brick strength	2/20	0.04	NS
		Interaction	2/20	6.5	99

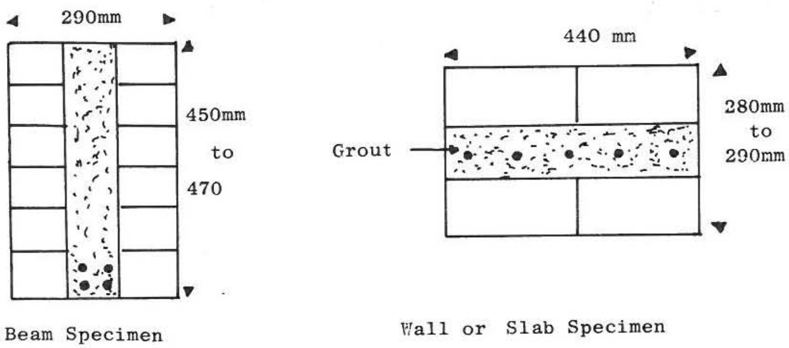

Fig. 1 Cross-sectional dimension of the test specimens

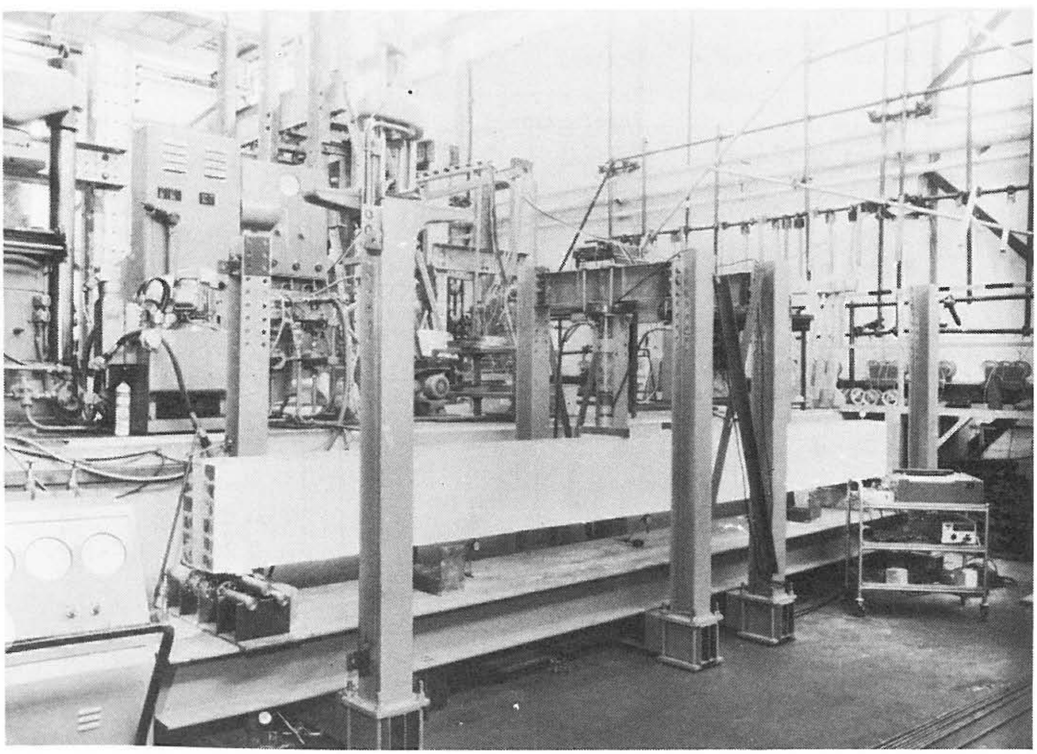

Fig.2 Showing the test arrangement and a beam of 6.3m span under test.