INVESTIGATION OF THE STRENGTH OF FLAT ARCHES IN BRICKWORK

DR.K.FISHER (Redland Bricks Ltd.)
MR.B.A.HASELTINE (Jenkins & Potter)
MR.H.R.HODGKINSON (British Ceramic Research Association)

ABSTRACT

Increasing interest is being shown by architects in the use of brickwork arches particularly in face work. Limited structural design information is available in the literature, with only a relatively small number of practical test results reported. The paper summarises results of a series of tests carried out to examine the strength and mode of failure of flat and shallow brick arches built using low strength bricks.

Arches were tested to failure under a uniformly distributed load, with spans of 2.0m. Results are presented for unreinforced arches of both types, and also lightly reinforced flat arches. Cracking patterns and failure mode are discussed, and data is presented on resultant brickwork stresses and arch deflections. Comparisons are made with previously reported data.

1. INTRODUCTION

Architectural design of facing brickwork has increasingly utilised the arch format to provide an attractive aesthetic appearance, this interest being supported by the requests received by brick manufacturers for design assistance. Simple forms of construction have often incorporated reinforcement in the form of flat steel bars in the joints or merely used the brickwork as a facade over a concrete or steel beam. Further structural design information is necessary to enable this brick application to be used to its full potential.

Nilsson(1) reported research on 21 flat arches, of which 16 were unreinforced and 5 reinforced. Spans varied between 1.0, 2.0 and 3.0m. More recently Hulse and Ambrose (2) described results obtained on 11 arches with spans of 1.8m, 2 of which were unreinforced and 9 reinforced. Both these papers suggested that reinforcement does not increase the failure strength of the arch, but does contribute to control of crack formation, and prevention of sudden and total collapse.

This paper reports the results of a series of arch tests carried out as part of a continuing programme using medium strength bricks. All the arches were built and tested at the British Ceramic Research Association, Stoke-on-Trent. The future test programme will be based on the results reported in this paper.

2. TEST METHOD

All of the arches tested in the programme to date were built using shallow-frogged soft mud stock bricks. 6 of the arches used a brick of mean compressive strength $31.7 N/mm^2$, and water absorption 11.9%; the seventh arch used a lower brick strength, $19.6 N/mm^2$ and water absorption 30.1%.

Arches were 3.38m overall length with a clear span of 2.03m and were built in single skin, stretcher bond brickwork, with a soldier-course over the opening. Mortar was 1:1:6 Portland cement:lime:sand.

Table 1 summarises the format of each arch. In Arch 2 a single 50 x 6.5mm mild steel bar was used; in Arch 3 60mm wide galvanised Murfor bed joint reinforcement was used.

TABLE 1 Programme of Arch Tests.

Arch.Test No.	Configuration	Reinforcement
1	Flat	Nil
2	Flat	M.S.bar under soffit.
3	Flat	Prefabricated bed joint reinforcement above soldier course.
4	Segmental	Nil
5	As 1 but no abutment	Nil
7	As 1 but with low strength brick	Nil
8	As 1 but with third load cell.	Nil

Note, Arch test No.6 has yet to be carried out.

Specimens were built on building paper on the strong floor of the structural laboratory in such a manner that they could be tested insitu by moving the loading apparatus to each wall in turn. In all but one test (No.5) the two ends of each wall were restrained by steel buttresses bolted to the strong floor, the space between the abutment and the buttresses being filled with massive blocks of brickwork. All the vertical surfaces were grouted to ensure full horizontal restraint. At one end of each arch, load cells were interposed between the end of the abutment and the restraint, to measure the horizontal thrust generated. Initially two load cells were used, at the top and bottom, but the final two tests incorporated a third load cell at the mid height position. The arch in test No.5 was completely free at each end.

Load was applied by a servo-controlled hydraulic jack through a system of eight subsidiary hydraulic rams, all of which were connected in parallel in a sealed system, and which were mounted on a main beam carried on the servo-controlled jack. This ensured equal load application to each of the eight spreaders. In all cases load was applied in 25kN increments up to failure.

Deflections and strains under load were measured using transducers and Demec points respectively. Eight linear transducers were positioned along the top of each arch. Eight pairs of Demec points (at 225mm) centres were placed horizontally at the mid-span. A number of 60^{o} (star) rosettes of Demec points (at 150mm centres) were arranged at specific points to determine the magnitude and direction of the principal compressive strains.

In the case of those arches containing horizontal reinforcement, pairs of electrical strain gauges were bonded to the longerons to monitor the horizontal tensions produced. The arrangement of the arch and apparatus is shown on Plate 1.

Stress-strain determinations were also carried out on a 225mm gauge length of 2 bricks completely bonded header to header to give an apparent E value in compression.

It is usual in the U.K. to form flat brickwork arches with a soldier course (vertically bedded bricks) for appearance reasons. Thus all the arches tested so far have been of this form although future tests will be carried out on normally (stretcher) bonded brickwork. For comparison purposes one test was carried out on a shallow segmental arch.

3. RESULTS

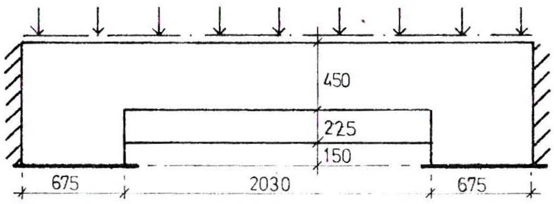
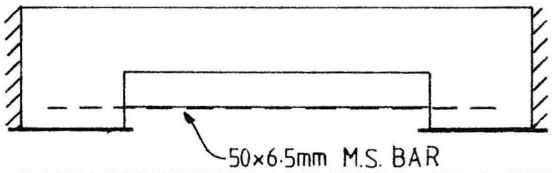
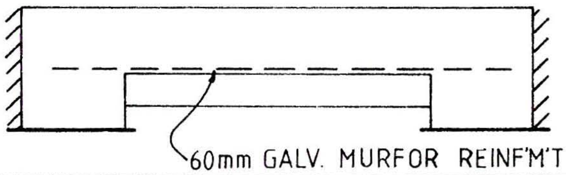
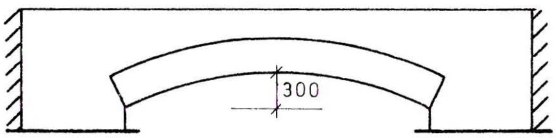
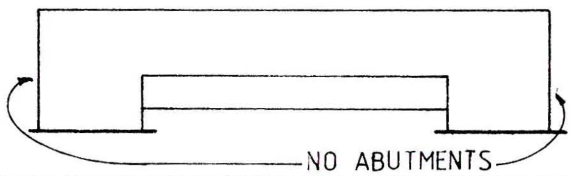
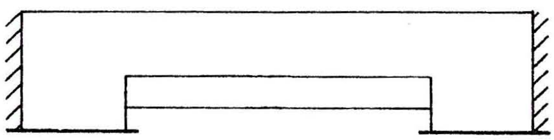
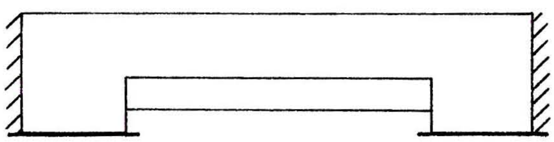
Table 2 gives details of the arches tested together with their first crack load (inferred from demec gauge readings), ultimate loads and the respective deflections at these loads. Table 3 gives details of the load/deflection behaviour of the arches during the tests and Table 4 gives the depths of the mid span compression zones at approaching ultimate loads, based upon demec gauge readings. A typical mid span strain distribution is illustrated in Figure 1.

The apparent E value in compression was 6800 N/mm^2.

TABLE 3 Load/Deflection behaviour during Arch Tests.

Arch	Deflection (mm) at a load/metre (kN/m) of				
No.	15	30	45	60	75
1	0.5	1.0	1.5	2.0	3.5
2	0.8	1.2	1.8	2.7	4.2
3	0.8	1.4	2.0	2.6	3.8
4	0.3	0.6	0.9	1.2	1.4
5	0.8	2.2	3.4	-	-
7	0.5	1.1	1.7	2.5	9.0
8	0.3	1.0	1.8	2.5	3.4

TABLE 2 - ARCH TEST WALL DETAILS AND RESULTS

	ARCH WALL DETAILS	FIRST CRACK*		ULTIMATE	
		LOAD [kN/m]	DEFLECTION [mm]	LOAD [kN/m]	DEFLECTION [mm]
1		14·8	0·4	85·8	6·5
2		44·4	1·8	88·8	9
3		14·8	0·75	81·4	5·6
4		29·6	2·0	142·0	24
5		14·8	0·8	53·3	21·5
7	 REPLICATE OF FIRST TEST with low strength brick	14·8	0·5	79·9	10·0
8	 REPLICATE OF FIRST TEST	14·8	0·2	82·8	32·5

* INFERRED FROM STRAIN GAUGE READINGS

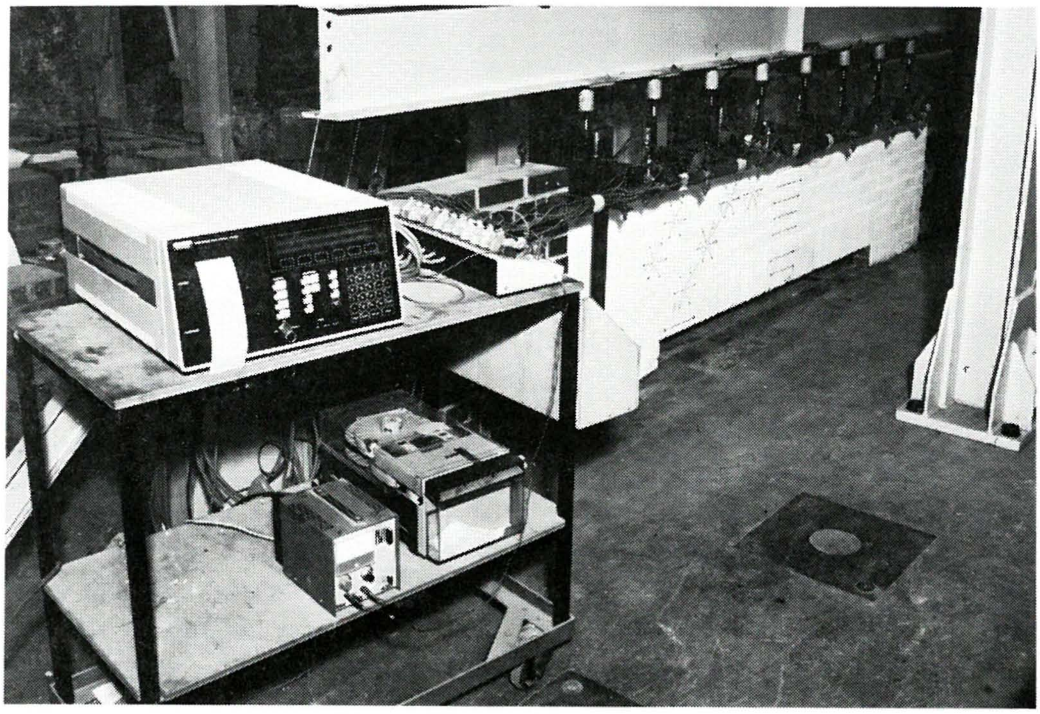


PLATE 1 Arrangement of Arch Test and Apparatus

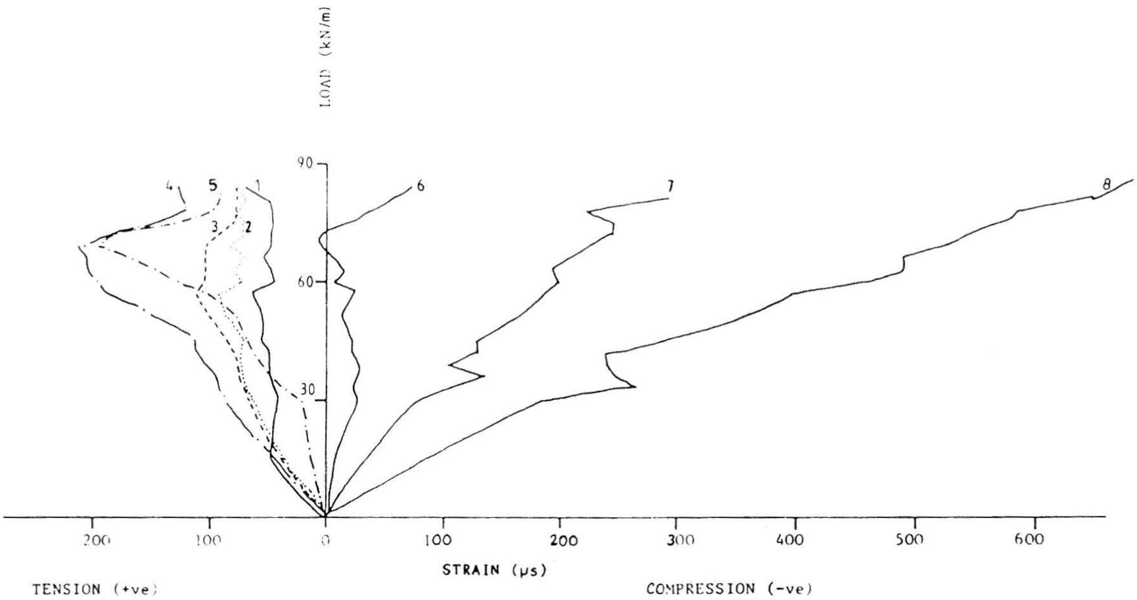


FIG. 1 Arch 1 - Horizontal Strains at Mid Span

TABLE 4 Depth of mid span compression zone from strain readings.

Arch No.	Load (kN/m)	Depth (mm)
1	82.8	225
2	74.0	225
3	66.6	190
4	103.6	150
5	41.4	225*
7	66.6	225
8	76.9	150

* Markedly non-linear.

4. DISCUSSION

4.1 Background

The use of masonry arches was one of the earliest applications of engineering theory to the problem of covering large openings and spaces. Their use for this purpose has been largely superseded in the last century by the development of structural materials having, unlike masonry, appreciable flexural strength e.g. steel and reinforced concrete. However, the aesthetic appeal of brickwork has meant the continued use of brick segmental arches and flat arches with specially shaped voussoir bricks for spanning relatively small openings such as over doors and windows.

In recent years, because of the skilled labour required and the expense of special bricks, various types of purpose made concrete and steel lintels have been developed for use with standard bricks to form false arches. In Scandinavia the use of flat brick arches without additional support is common and there is no apparent reason why they should not be used similarly in the U.K., given adequate design guidance.

4.2 Behaviour of flat unreinforced arches

Nilsson(1) suggests that the behaviour of these arches is the same for point loads and uniformly distributed loads (except where the load is only just above the arch). He assumes that after the formation of a horizontal crack at load level the arch behaves as a restrained (continuous) beam, until the flexural strength of the brickwork at the abutments and at the centre of the span is exceeded; cracks form at these positions and the behaviour becomes that of a three pin arch. Failure may then occur in a number of modes which depend upon the strength of the abutment.

These are :

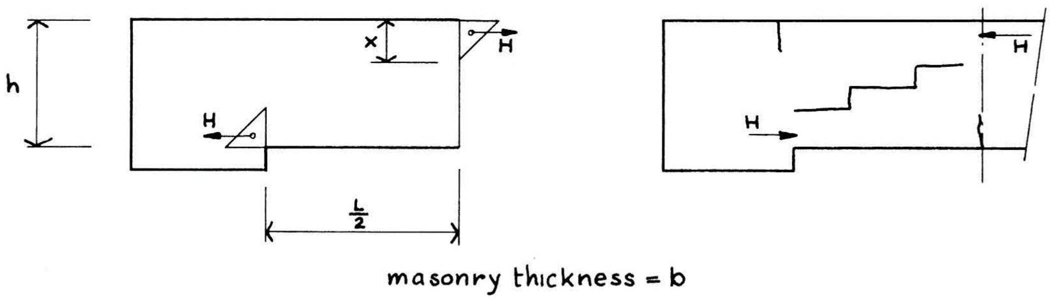
1) Where the arch thrust cannot be resisted, the abutment shears or overturns.

2) Where the abutment can resist the arch thrust, the arch fails by :

a) crushing of the brickwork in the compression zones at the abutments and at the centre of the arch, or

b) by the shearing of one half of the arch along its middle joints.

These modes of failure are illustrated below.



crushing at hinges shearing along middle joints

Fig. 2 Failure Modes After Nilsson[1]

Nilsson suggests that failure type 2(b) does not occur in arches with bricks laid on end (soldier courses) and that short spans (not defined) may fail in punching shear. He proposed the following formulae for modes of failure 2 a) and b) based upon elastic behaviour of the brickwork and the development of triangular compressive stress distribution in the compression zones of the arch hinges.

2 a)
$$H = \frac{\sigma\, b\, x}{2}$$
$$M = \frac{\sigma\, b\, x}{2} (h - 0.67\, x)$$

2 b)
$$H = \frac{\tau\, b\, L}{2}$$
$$M = \frac{\tau\, b\, L}{2} (h - 0.67\, x)$$

Where σ is the ultimate compressive strength of the brickwork in bending

and τ is the average ultimate shear strength of the brickwork.

Hulse and Ambrose[2] recorded similar push through punching shear failures in tests on two unreinforced stretcher bond arches but they made no attempt to explain the mode of failure, being more concerned with bed joint reinforced brickwork arches. Little other recent research appears to have been carried out into this type of arch according to the review of literature on brickwork arches by Tellett[3].

4.3 Behaviour of flat reinforced arches

In the U.K. it is common practice to provide bed joint reinforcement in brickwork spanning across small openings. The work of both Nilsson and Hulse and Ambrose indicates that the provision of such reinforcement does not generally enhance the ultimate strength of the arch, indeed the former suggests that unreinforced arches behave rather better. Hulse and Ambrose, however, found that the reinforcement controlled crack formation and prevented sudden collapse. Where the load was applied near to the arch level they found that the reinforcement did contribute more directly to the strength of the arch.

A traditional method of construction of flat arches in the U.K. was to incorporate a steel strap or bar in the bed joint beneath the arch soffit. In addition to preventing the collapse of the brickwork the strap may also provide the tensile element in a tied arch structure.

4.4 Test behaviour

The most significant aspect of the results of the flat arch tests carried out todate, as given in Table 2, is that the ultimate loads on the five restrained arches were within ten per cent of each other. Thus, neither the incorporation of a layer of bed joint reinforcement nor of a bar beneath the arch, or indeed the use of lower strength bricks made any significant difference to the ultimate strength of the arches. Similarly there was little difference in the pattern of deflections during the tests, (see Table 3). The onset of cracking, however, was influenced by the reinforcement; in all but arch test 2 it appears from sudden movements of the strain curves that initial cracking occurred in the soldier course at relatively low loading. This results from the low bond strength of the vertical joints in the soldier course; the tensile stress in test 2 was either suppressed by, or more evenly distributed because of, the presence of the tie bar. The bed joint reinforcement in arch 3 may have acted as a crack inducer (see Plate 2), although the soldier course may also have contributed to this effect. Indeed the presence of the soldier course, whilst aesthetically desirable, may be of limited structural value. Future arch tests, built completely in stretcher bond, are expected to have a greater initial crack strength and probably greater ultimate load capacity.

The estimate of the stress at which the soldier course cracked in five of the tests, when analysed as unreinforced beams (see Table 2 for estimated uniformly distributed crack load), results in a calculated stress of $0.58N/mm^2$. This compares with a characteristic flexural strength of $0.3N/mm^2$ for the relevant brick/mortar combination as obtained from BS5628 Part 1 for failure parallel to the bed joint. Based upon the elastic modulus, E, measured from couplet tests of $6800N/mm^2$ ($900\ f_k = 7020N/mm^2$), the strain at the above stress is 0.85×10^{-6} compared with 0.5×10^{-6} and 0.8×10^{-6} for tests 1 and 3 respectively.

After cracking of the soldier course at mid span, and at the top of the brickwork at the supports, arching action takes over. With the exception of test No. 8 all the flat arch strain readings (see Table 4), indicated a

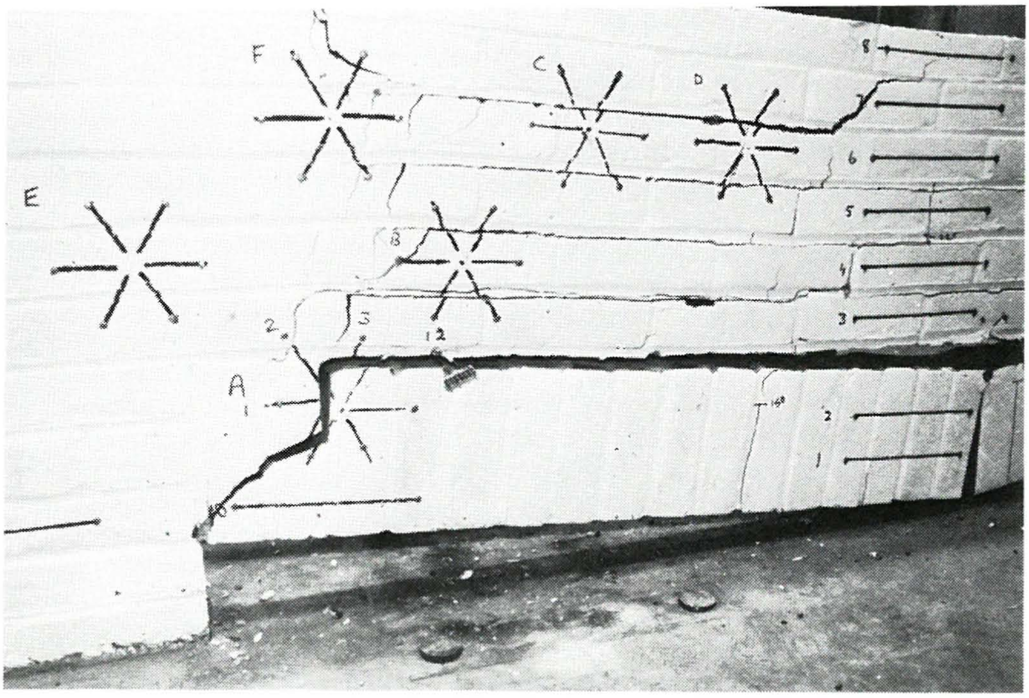


PLATE 2 Arch No.2 After Failure

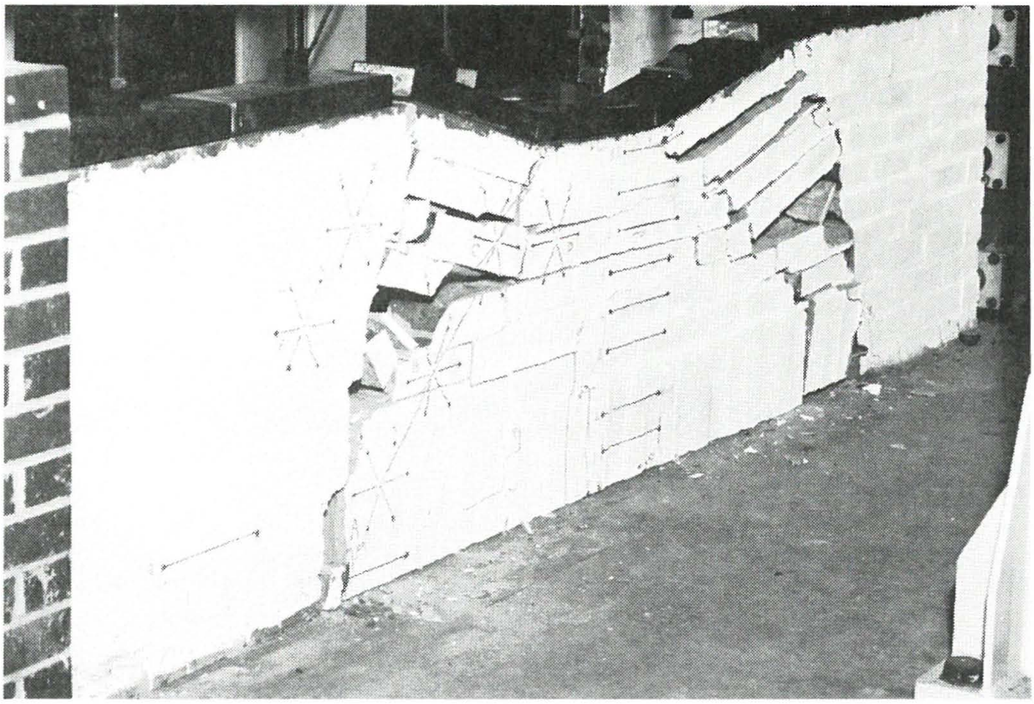


PLATE 3 Failure Crack Pattern - Arch No.8

compression zone depth at mid span, at ultimate load, of 200 to 225mm; the readings also suggest a linear strain distribution in the compression zone. Using the formulae proposed by Nilsson, (para.4.2) a crushing failure load of 134 kN/m and a half arch shearing failure load of 86.6 kN/m are obtained. Whilst the latter load would correspond well with the actual failure loads for arches 1, 2, 3, 7 and 8, the actual crack patterns did not quite correspond to that assumed by Nilsson. The assymetry of the crack pattern and relatively intact central area of the arch suggest that the crack patterns may have been influenced by the loading arrangement, constraining the arch to fail typically in the manner shown in Plate 3.

The ultimate calculated failure loads for the two modes of failure are given in Table 5.

Table 5 : Calculated failure loads according to Nilsson.

Brick Strength	Failure Load (kN/m)	
	Mode of Failure	
(N/mm^2)	crushing	shearing
31.7	134.0	86.6
19.6	97.4	86.6

It can be seen that for both brick types shear failure is the critical mode.

Inspection of the failure crack pattern suggests that horizontal half arch shearing did occur and it can be seen from Table 5 that Nilsson's equations give good correlation with the experimental results. It is proposed to modify the loading system to investigate its influence upon the failure pattern in a future test.

The strain rosette readings generally confirm the development of the arch thrusts in the principal compressive strain directions anticipated. The rosettes are of limited value however, once they are intersected by cracks. The maximum uncracked compressive strain readings recorded are of the order of 1.0×10^{-6} which corresponds to a stress of about $7N/mm^2$.

The bar reinforcement in wall 2 was strain gauged. It was noteworthy that the strain in the steel bar was not symmetrical, being higher at the end of the arch opposite to that where the bed joints sheared but where some crushing of the soldier course brickwork occurred. The maximum strain recorded corresponds to a steel stress of about $50N/mm^2$ in the steel.

Similarly, the Murfor reinforcement in Arch No.3 was strain gauged. Again the strains were not symmetrical; they did confirm the presence of the abutment arch compression zones in that the end of the Murfor was in compression for most of the test with the central section in tension. Only at a load of about 60kN/m did the 'shear' end of the Murfor go into tension

and the other end at about 75kN/m. Interestingly the maximum tensile force carried by the Murfor was only of the order of 5kN representing a stress of about 215N/mm^2 in the reinforcement (yield strength 500N/mm^2).

Load cells were initially positoned top and bottom at one abutment to record the residual horizontal thrust over and above that resisted by the abutment in shear. The forces recorded were surprisingly small considering that the abutments were built on a separating layer. For this reason in the last two tests a third load cell was introduced at mid height and all three cells were interposed between the actual arch abutment and the brickwork infill. Although the forces recorded by the load cells increased considerably, the results were still inconclusive.

Arch No.5 had no thrust restraint other than that provided by the frictional resistance of the base of the abutment. It initially behaved as the other flat arches with a crack occurring in the soldier course at a load of 14.8kN/m. Unlike the restrained arches, after the initial crack arching action could not develop beyond the shear capacity of the abutment and the arch punched through at a verticl shear stress of 0.8N/mm^2. The ultimate load on this arch was about 60% of that on the other flat arches.

The segmental arch, test No.4, had a span to rise ratio of approximately 7, and as can be seen from Table 2, it had an ultimate load of the order of 66% greater than the flat arches.

In service conditions cracking of the soldier course would constitute serviceability failure. A crack load of 14.8kN/m, even with the application of a materials partial safety factor, should ensure the satisfactory behaviour of an unreinforced soldier course provided that:

a) The brickwork continues above the soldier course by at least 450mm, and

b) No additional loads other than self weight of the brickwork are applied to the arch.

It is probable that additional loads could be applied above the 60^o triangle over the arch without causing cracking, but this has not yet been investigated.

From the tests it can be seen that neither the ultimate limit state nor the serviceability limit state of deflection are likely to be critical provided that the abutments of the arch are adequately restrained against shear or overturning failure.

5. CONCLUSIONS.

The programme of tests is not complete, but for the arches tested it can be considered that:

5.1 The incorporation of light prefabricated reinforcement in a single bed joint does not significantly influence the behaviour of the arch in terms of cracking, deflection or ultimate strength.

5.2 The incorporation of a mild steel bar beneath the soldier course does not significantly influence the deflection or ultimate strength of the arch but controls cracking and prevents ultimate collapse.

5.3 Nilsson's explanation of the behaviour of flat arches appears to largely mirror the behaviour of the arches described here, and his proposed equations can be used to predict the ultimate strength of the arches to a reasonable degree of accuracy.

5.4 The use of a relatively weak brick does not adversely affect the ultimate strength of the arch provided it fails in the same shear mode.

5.5 Unreinforced soldier course flat arches should perform satisfactorily in service provided that their abutments are adequately restrained, there is at least 450mm of brickwork above the soldier course and only self weight of brickwork is carried.

6. ACKNOWLEDGEMENTS.

The authors acknowledge the assistance of staff at the British Ceramic Research Association in carrying out the practical work, and also the assistance of Mr.J.N.Tutt of Jenkins and Potter in analysis of the test results.

7. REFERENCES

(1) NILSSON, S. "Flat Brick Arches". Chalmers University of Technology, Gothenburg, Sweden, 1964.

(2) HULSE, R and AMBROSE, R.J. "The Strength of Reinforced Brickwork Spanning Openings in Wall Panels". Proceedings of The British Ceramic Society, Seventh International Symposium on Loadbearing Brickwork, London 1980.

(3) TELLET, J. "A Review of the Literature on Brickwork Arches". Technical Note No. 338, British Ceramic Research Association,Stoke on Trent, England, August 1982.