The Behaviour of Reinforced Brickwork Beams & Panels

*R. HULSE BSc MSc MICE

*R.J. AMBROSE BSc MICE

+P.R. LUMBARD MIStructE

*COVENTRY (LANCHESTER) POLYTECHNIC - ENGLAND

+IBSTOCK BUILDING PRODUCTS - ENGLAND

ABSTRACT

The paper describes work carried out to investigate the strength and behavioural characteristics of brickwork reinforced in the bed joints with flat section reinforcement, spanning otherwise unsupported over 1.8 m wide openings and subject to in plane loading.

Tests on beams and deep beam panels are described, simple design charts are proposed and a long term loading test, at present under investigation is also described.

NOTATION

A_s	Cross sectional area of steel
L	Span
W	Superimposed distributed live load
d	Beam depth
d_{ef}	Beam effective depth
f_y	Characteristic steel strength
f_k	" brickwork compressive strength
f_{vb}	characteristic brickwork shear strength
t	Beam width

γ_{FD}	Partial safety factor for dead load
γ_{FL}	" " " " live load
γ_{mm}	" " " " brickwork in compression
γ_{ms}	" " " " steel strength
γ_{mv}	" " " " brickwork in shear
α	Unit weight of brickwork

1. INTRODUCTION

Bed joint reinforcement provides a simple means of reinforcing brickwork in flexure, yet is not a means which has been widely researched. Research has tended to be concentrated on heavy section reinforced masonry beams with large areas of reinforcement placed in cavities formed by special bricks or with difficult bonding patterns.

In some situations loads to be carried do not warrant difficult or expensive beam forms and simple bed joint reinforcement may be adequate.

A typical example is that of an opening in a wall panel which has sufficient depth of brickwork above it to ensure load dispersion by deep beam or arching action. Another may be where a depth of brickwork separating the top of one opening and the bottom of another is required only to carry its own weight and/or a small superimposed load.

Bed joint reinforcement provides an aesthetically pleasing alternative to conventional lintel support in these circumstances and an easier alternative to reinforced masonry beams of complex construction.

This paper describes a programme of tests carried out by the authors to investigate the behaviour of bed joint reinforced beams and deep beams spanning wall panel openings.

2. TESTS ON DEEP BEAM WALL PANELS

Figure 1 shows the form of the panels tested. All panels were built in single skin, stretcher bond brickwork with a 1.8 m wide opening. Table 1 gives details of the brick and mortar strengths used and the extent of reinforcement. Galvanized 'ladder type' reinforcement was used in all cases, each ladder providing 20.1 mm^2 of high yield reinforcement in each bed joint above the soffit of the opening.

All the reinforcement was strain gauged at midspan and endspan and midspan deflections were monitored.

Loading was applied at six equally spaced points using a hydraulic jack and spreader beam loading system.

The results of the tests all summarised more fully elsewhere[1] but the most important results, the failure loads, are given in Table 1. In all cases failure was due to diagonal tension cracks propogating from the corner of the opening and only in the case of the unreinforced panels did total coll-

apse occur.

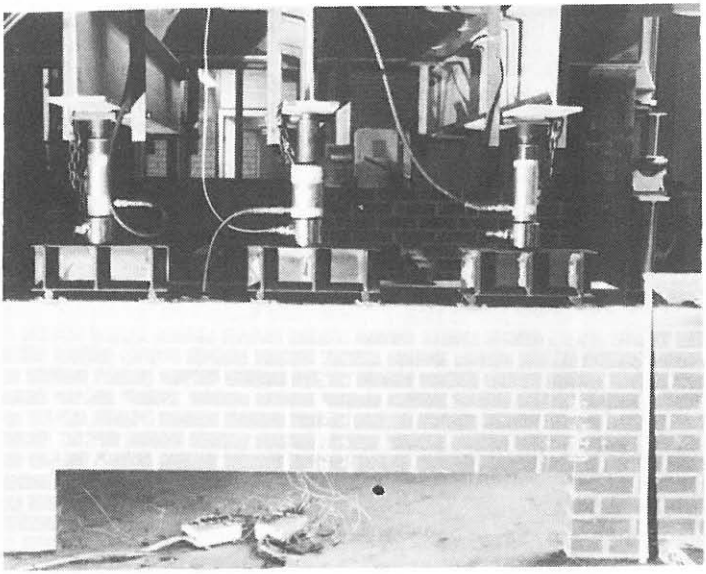


Figure 1. Typical deep beam panel.

The following general conclusions were drawn from these tests:-

(1) The load carrying capacity of openings in wall panels spanned by brickwork reinforced in the bed joints is appreciable. If the 45^{o} triangle of brickwork above an opening is the only load to be carried then one or more levels of reinforcement in the bed joints is an adequate means of construction.

(2) Openings in wall panels built with structural grade mortars have higher strength than those built in the more common 1:1:6 mortar. It is suggested that this form of construction should only be used with structural grade mortar.

(3) When superimposed loading is applied above the 45^{o} triangle above the opening deflections are small and structurally not significant in the working load range.

(4) The strength of the deep beam panels described is derived from arching action and depends on the shear strength of the brick-mortar interface. The strength is not enhanced by the presence of reinforcement but the reinforcement controls crack formation and prevents sudden and total collapse.

(5) Appreciable superimposed loading can be carried even when applied within the 45^{o} triangle above the opening. As the load is applied nearer to the soffit of the opening the load bearing brickwork behaves more as a beam and the reinforcement contributes more directly to the structural strength.

Panel	Mortar	Brick Strength	Depth of brick-work above Soffit	No. of Joints Reinforced	Failure Load
	(Volume)	N/mm^2	mm		kN
1	1:1:6	47	900	3	540
2	1:1:6	47	900	1	240
3	1:1:6	47	900	0	230
4	1:1:6	33	900	3	220
5	1:1:6	33	900	1	150
6	1:1:6	33	900	0	230
7	1:1:6	61.8	900	3	560
8	1:½:4½	61.8	900	3	>690
9	1:¼:3	61.8	900	3	690
10	1:½:4½	61.8	600	3	390
11	1:½:4½	61.8	300	3	114

TABLE 1 Tests on Deep Beam Panels

Beam	End Conditions	Mortar (Volume)	Failure Load (kN)	Average Failure Load (kN)	Mode of Failure
A1S A2S A3S	Simply Supported	1:¼:3	24 24 24	24	(3) (2) (3)
A1F A2F A3F	Fixed Ended	1:¼:3	84 108 96	96	(2) (2) (1)
B1S B2S B3S	Simply Supported	1:½:4½	24 24 24	24	(3) (3) (3)
B1F B2F B3F	Fixed Ended	1:½:4½	96 66 78	80	(1) and (2) (1) (3)
C1S C2S C3S	Simply Supported	1:1:6	21 24 21	22	(1) and (3) (1) (1)
C1F C2F C3F	Fixed Ended	1:1:6	72 54 60	62	(1) (1) (1)

TABLE 2 Tests on beams

3. TESTS ON REINFORCED BEAMS

A series of 300 mm deep, single skin bed reinforced beams were constructed and tested to failure.

Three different mortar mixes were used in construction. Half of the beams were tested simply supported over a span of 1.8 m, the remainder were rotationally restrained at the ends and tested identically. Rotational restraint was provided by heavy steel I beam sections placed over the ends of the beams and hand jacked against the steel of the test rig.

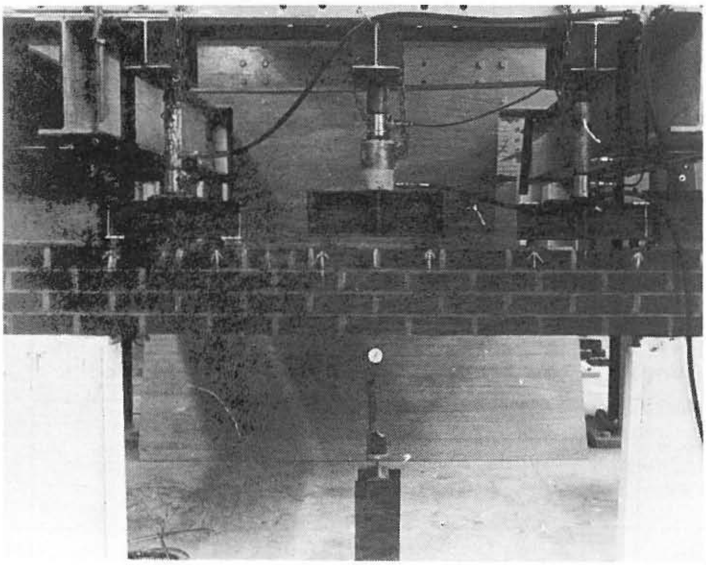


Figure 2. Typical beam test.

Figure 2 above shows a typical test arrangement. The results of the tests are more fully described in reference 2 and the failure loads are reproduced in Table 2.

Three modes of failure were identified:- (1) shear failure, (2) bending-compression failure, (3) bending with fracture of the bottom steel.

Failure loads, measured steel strains and midspan deflections were compared with theory[3] and the following conclusions were drawn:-

(1) Brickwork beams reinforced in the bed joints with flat steel reinforcement exhibit behavioural characteristics typical of composite reinforced beam construction.

(2) The failure loads of such beams are considerably enhanced by end fixity. Under such conditions of end fixity failure loads are appreciable and exceed theoretically predicted values.

(3) The strength of fixed-ended brickwork beams, but not, apparently, of simply-supported beams, increases with increasing mortar strength. With low-strength mortar failure is invariably in a shear mode but with high-strength mortar failure in bending with possibly compression failure of the brickwork is more likely.

(4) Deflexions can be safely but not excessively overestimated using a cracked section elastic analysis and material properties extracted from SP 91[3].

(5) Steel and brickwork strains in fixed-ended beams are greatly over-estimated using standard cracked section elastic methods because of the initial phase of pre-cracking elastic behaviour.

(6) Tensile cracking takes place when a limiting tensile strain of about 0.02-0.04% is developed in the brickwork. In the case of the fixed-ended beams investigated this cracking took place at approximately 25-40% of the ultimate strength of the beams, giving a significant and safe reserve of strength beyond the cracking load.

4. DESIGN OF BED-JOINT REINFORCED BRICKWORK

(a) Beams of depth less than half the span

As the foregoing experimentation has shown, bed joint reinforced beams exhibit behavioural characteristics typical of composite reinforced construction. It seems reasonable therefore that limit state design procedures[3] can be used but unless it is certain that the ends of the beams are firmly restrained it would seem prudent to assume that the beams are simply supported.

Hence the design bending moment can be expressed as:-

$$\{\gamma_{FL} W + \gamma_{FD} \alpha t d\} \frac{L^2}{8} \qquad \text{———— (1)}$$

The resistance moment of the beam is given by

$$\frac{A_s f_y z}{\gamma_{ms}} \qquad \text{———— (2)}$$

$$\text{where} \quad z = d_{ef} \left[1 - \frac{0.53 A_s}{t d_{ef}} \cdot \frac{f_y}{\gamma_{ms}} \frac{\gamma_{mm}}{1.5 f_k} \right]$$

Equating (1) and (2) the allowable superimposed uniformly distributed load is given by the expression

$$W + \frac{\gamma_{FD}}{\gamma_{FL}} \alpha t d = \frac{8 d_{ef}}{L^2 \gamma_{FL}} \left[1 - \frac{0.53 As fy}{t d_{eF} \gamma_{ms}} \frac{\gamma_{mm}}{1.5 f_k} \right] \qquad \text{———— (3)}$$

The design shear force can be expressed as:-

$$\left[\gamma_{FL} W + \gamma_{FD} \alpha t d\right] \frac{L}{2} \qquad \text{———— (4)}$$

The shear resistance of the beam is given by

$$V = \frac{f_{vb}}{\gamma_{mv}} \; t \, d_{ef}$$

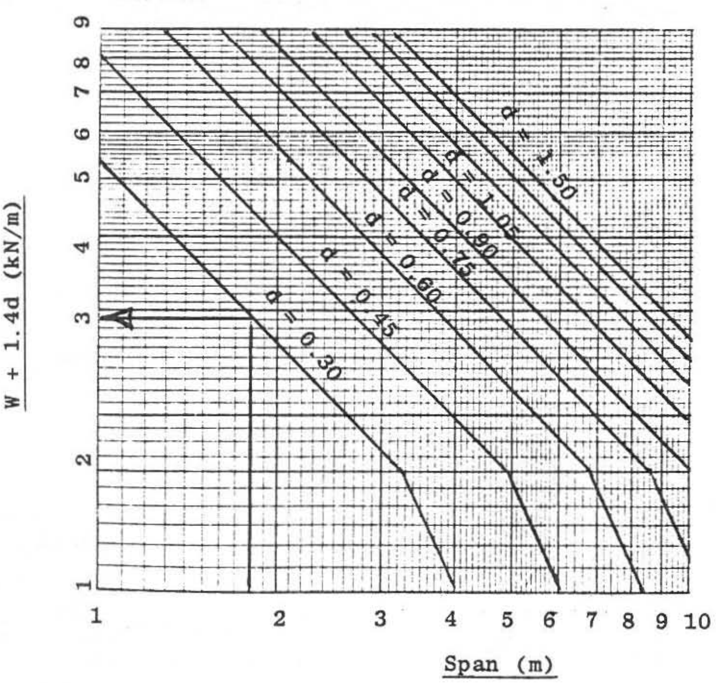
In the case of bed joint reinforced beams it would not be unreasonable to take the effective depth in the shear calculation as the actual depth. This assumption is supported by the results of the simply supported beam tests where better agreement between theory and experiment is obtained if the full beam depth is assumed to resist shear. Hence

$$V = \frac{f_{vb}}{\gamma_{mv}} \; t \, d \qquad (5)$$

Equating (4) and (5) the allowable uniformly distributed live load is given by:-

$$W + \frac{\gamma_{FD}}{\gamma_{FL}} \, \alpha \, t \, d = \frac{2}{L} \, \frac{f_{vb}}{\gamma_{mv}} \, \frac{td}{\gamma_{FL}} \qquad (6)$$

Equations (3) and (6) can be conveniently plotted on a log/log scale for any given set of parameters as shown in Figure 3. A set of lines is shown for differing values of beam depth 'd'.



Design graph for 100 mm thick brickwork in 1:½:4½ mortar

γ_{FD} = 1.4
γ_{FL} = 1.6
γ_{mv} = 2.5
γ_{mm} = 3.5
γ_{ms} = 1.15
f_{vb} = 0.35 N/mm^2
f_y = 485 "
f_k = 12.2 "

All bed joints are assumed to be reinforced

Figure 3

For a 1.8 m span, 0.3 m deep beam the design graph suggests a safe live load of 2.5 kN/m or 4.5 kN over the total span. (compare with the experimental results).

If it is certain that the ends of the beam are rotationally restrained with adequate steel anchorage beyond the supports then this load could be reasonably and safely increased by a factor of about 2.

Similar graphs can be constructed for a range of different brick and mortar strengths.

(b) Beams of depth equal to half the span

No logical design procedure exists for this case but an analogy can be drawn with proposed design methods for masonry walls on supporting beams described in ref. 4.

In this case the supporting beam can conservatively be thought of as that part of the brickwork which is bed joint reinforced. Sufficient depth of reinforcement can be provided to ensure sufficient bending resistance to the self weight of the 45° brickwork wedge above the opening and the bending action of the concentration of vertical superimposed loading near the supports.

A Finite Element analysis of a typical panel gave the shear stress and vertical stress contours seen in Figures 4 and 5. The concentration of stresses around the supports indicates that this analogy would not be unreasonable.

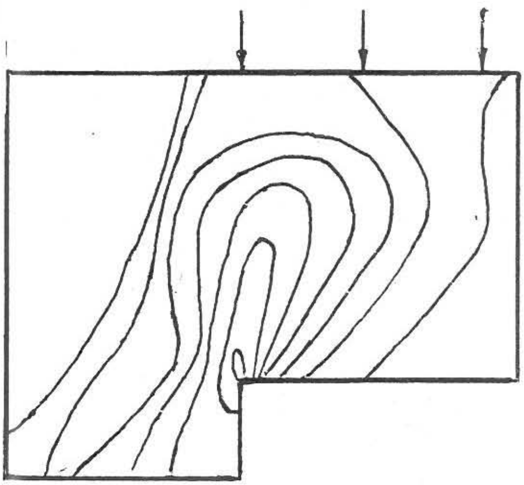


Figure 4. Shear stress contours

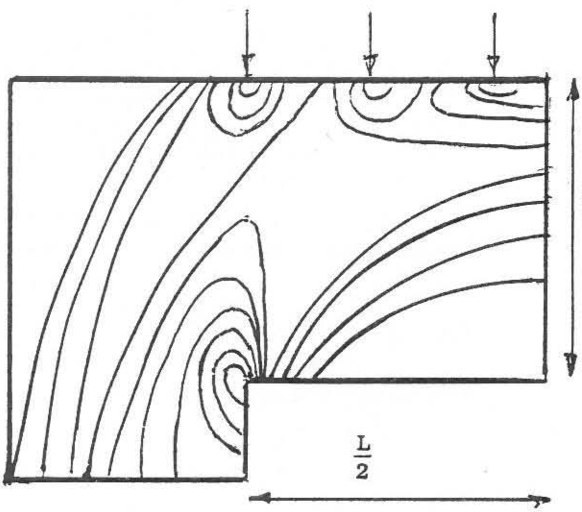


Figure 5. Vertical stress contours

Conservatively assuming simply supported beam behaviour the loading shown in Fig. 6 can be assumed.

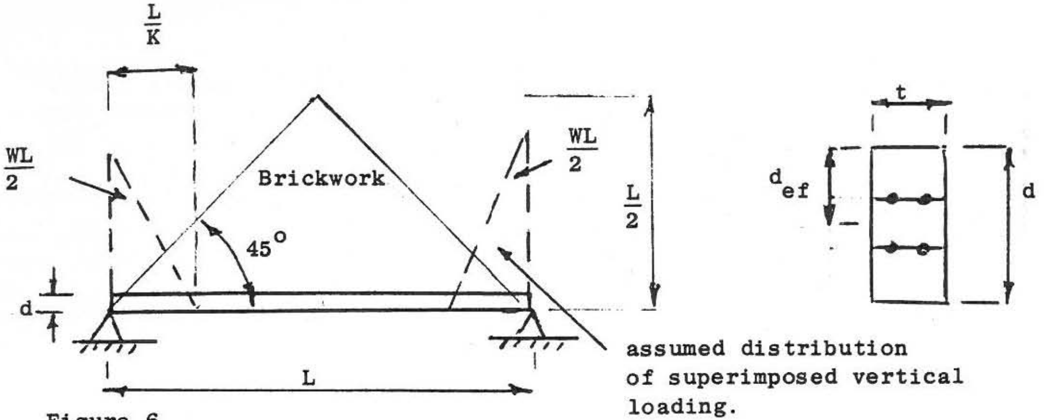


Figure 6

The design bending moment is given:-

$$\frac{\gamma_{FL}\, W\, L^2}{6\, K} + \gamma_{FD}\frac{L^3}{24}\, t\, \alpha \qquad (7)$$

where $K = 4\sqrt{\dfrac{E_w\, t\, L^3}{EI}}$ and

E = Young's modulus of supporting beam

I = Second moment of area of " "

E_w = Young's modulus of supported wall

$= 1.86 \left[\dfrac{L}{d}\right]^{0.75}$ for $E = Ew$

and $I = \dfrac{1}{12}\, t\, d^3$

The resistance moment of the beam is given by equation (2) and equating (2) and (7) the allowable superimposed live load is given by:-

$$W = \left(\frac{6K}{\gamma_{FL} L^2}\,\frac{A_s f_y d_{ef}}{\gamma_{ms}}\right)\left[1 - \frac{0.53 A_s}{t\, d_{ef}}\,\frac{f_y}{\gamma_{ms}}\,\frac{\gamma_{mm}}{1.5 f_k}\right] - \frac{\gamma_{FD}}{\gamma_{FL}}\,\frac{L\; t\; \alpha\; K}{4} \qquad (8)$$

All the experimentation to date has indicated that diagonal shear failure is the likely mode of failure. Average shear stresses, based on the total section depth, varied between 0.83 to 3.89 N/mm^2, the lower figure being for brickwork in 1:1:6 mortar. These values are consistent with tests on brickwork beams with low shear span to effective depth ratio.[5]

A design ultimate strength of 0.8 N/mm^2 based on the full section depth would seem reasonable. The design shear force can be expressed as:-

$$\gamma_{FL}\frac{WL}{2} + \gamma_{FD}\,\alpha\, t\,\frac{L^2}{8} \qquad (9)$$

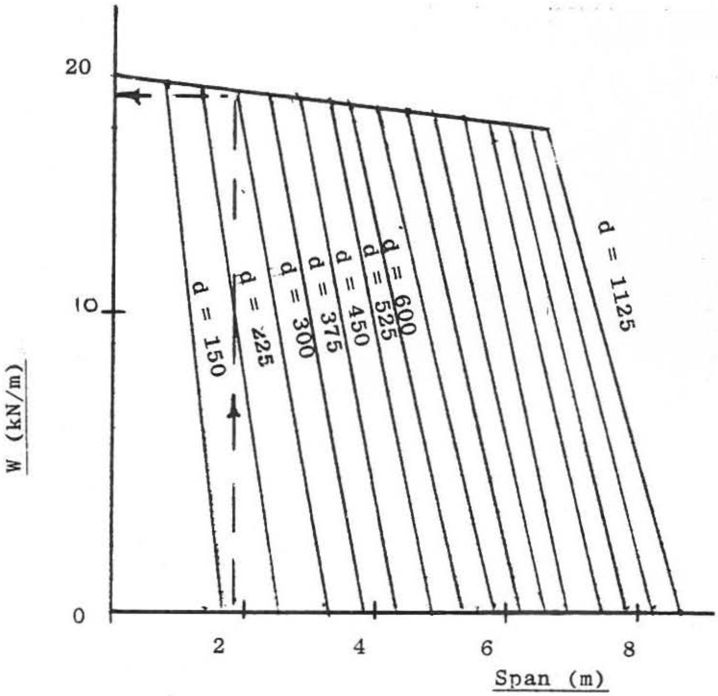
The shear resistance is given by:

$$V = \frac{f_{vb}}{\gamma_{mv}}\, t\,\frac{L}{2} \qquad (10)$$

From which it follows that

$$W = \frac{f_{vb}\; t}{\gamma_{mv}\,\gamma_{FL}} - \frac{\gamma_{FD}\,\alpha\, t\, L}{\gamma_{FL} 4} \qquad (11)$$

Equations (8) and (11) can be plotted as shown in Figure 6 below where f_{vb} has been taken as 0.8 N/mm^2 and all other parameters as in Figure 5. A set of lines is shown for differing values of reinforced depth 'd'.



e.g. For a span of 1.8m W = 19.25 kN/m Panel reinforced to a depth of 300 mm above the soffit

Figure 6

For a given span a vertical line drawn to the top of the diagram would indicate the safe superimposed load and the required number of reinforced bed joints above the opening.

The figures indicated are extremely conservative in the light of the reported experimental results. Further experimentation on openings of greater span would indicate whether these values could be safely increased

LONG TERM LOADING TEST

No information exists on the long term behavioural characteristics of bed joint reinforced brickwork acting as beams or deep beams.

The authors are at present testing the wall panel shown in Figure 7 which spans 1.8 m, has a depth of 600 mm and is reinforced in the bottom three bed joints. A 1:½:4½ mortar has been used in construction.

The original intention was to construct the panel in the outside environment to subject it to the effects of rain and temperature. For practical reasons it was eventually built in the laboratory, under near constant temperature conditions but the effect of rain was simulated by spraying the front face of the wall, twice a week, for four hour periods. The brick trough at the front of the wall holds the water which is circulated by pump

through a perforated hose along the top of the wall.

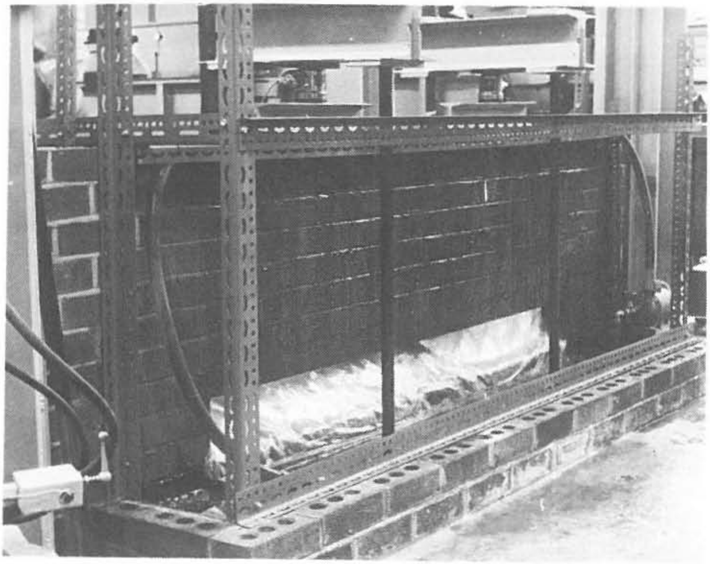


Figure 7. Long term wall test

The panel is loaded through a spreader beam system which is anchored down to the strong floor on which the panel is built. The anchorage bolts were tightened by hand to give a total load of 100 kN on the span; being approximately 1/3 of the anticipated failure load based on previous tests. Spring loaded washes are incorporated to minimise the loss of load due to creep or other effects.

Load cells incorporated in the system have indicated that there was a minimal amount of load shedding in the first few weeks of loading and after readjustment the loading has remained constant.

Strain gauges have been attached to the reinforcement at midspan and endspan and these have been monitored daily throughout the test. The data collected has been fed into a desk top microcomputer with a flat bed plotter which has enabled a continuous record to be kept of the steel strain profile with time. Midspan deflections have also been monitored.

Figure 8 shows the average recorded steel strains at midspan and endspan. It is evident that there is a considerable and very significant time dependent strain behavioural pattern. The strains induced by loading are small in comparison with those induced by creep and possibly moisture movement effects.

The graph shows an increasing strain profile for the first sixty days of loading followed by a sharp drop of strain and a subsequent levelling out. The average peak strain at midspan was approximately 0.1% and it is thought that at this point microcracking has taken place in the brickwork, relieving the strains locally at the point of measurement.

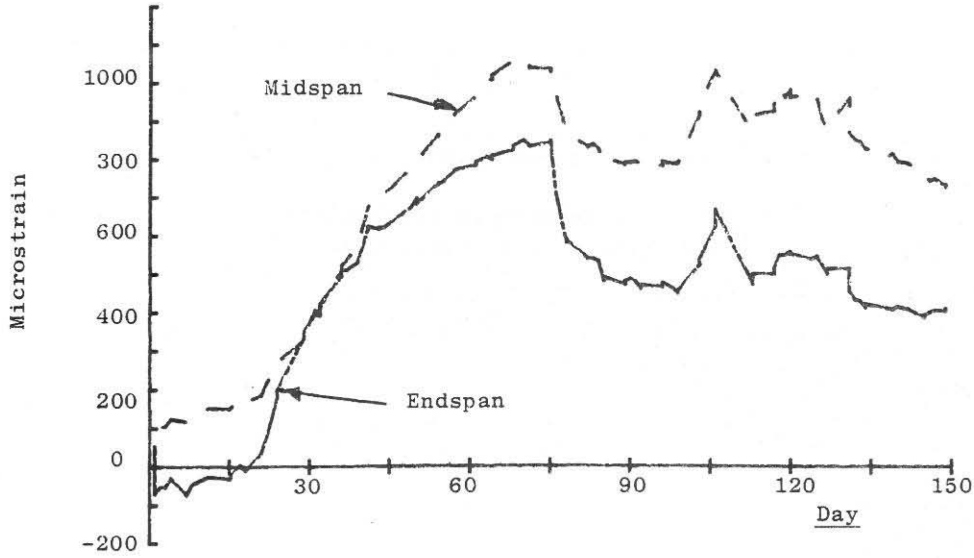


Figure 8. Average steel strains

It was found that wetting the panel resulted in small but noticeable changes in recorded strain values before and after wetting.

The maximum recorded midspan deflection is 0.5 mm with little fluctuation (±0.2%).

Variations on the test programme are planned including long term saturation of the panel, increasing the superimposed loading and finally loading to failure for comparison with the previous tests.

CONCLUSIONS

1. Reinforcement in the bed joint is a suitable means of reinforcing brickwork beams and lintels subjected to modest design loads. Where end fixity is assured significant loads can be sustained.

2. Deep beams spanning wall openings can sustain significant superimposed loads due to the arching action of the masonry above the opening. A simple design method is proposed which whilst giving conservatively low design strengths could be adjusted in the light of further experimentation to give more realistic values.

3. There is an appreciable time dependent strain variation in reinforced brickwork of this type, the effects of which warrant further investigation.

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