Forces Acting within a Reinforced Brickwork Beam in determining the Serviceability Limit

C. APPLETON B.Sc (Hons) RESEARCH ASSISTANT
C. SOUTHCOMBE B.Sc (Eng), MSc, CEng MICE PRINCIPAL LECTURER

Department of Civil Engineering, Plymouth Polytechnic, ENGLAND

SUMMARY

This paper reports on research work, conducted at Plymouth Polytechnic, on reinforced brickwork beams, using cross bonding, with grouted pocket cavities containing the reinforcement. It describes the beam format and materials. Experimental results are presented and compared with the requirements of the draft code, British Standard 5628, Part 2 (1). The draft code's design predictions and the observed behaviour are discussed.

1. INTRODUCTION

Reinforced brickwork beams, with grouted cavities, were proposed for experimental study, as part of a research programme into the behaviour of reinforced brickwork members, sponsored by Structural Clay Products of Hertford.

Various designs were already being tested. Two of these used a central reinforced cavity while a third used a soldier bond incorporating cross bonding (2,3,4.). The former designs used no ceramic interlock across the width of the beam and the latter design involved a construction which was apparently awkward for bricklayer and steelfixer.

An alternative construction, increasing the ceramic interlock, reducing the volume of grout and maintaining a flexibility for shear reinforcement was evolved. This consists of two courses in stretcher bond forming the cavity for the tensile reinforcement, with the minimum depth of two further courses in quetta bond. The pocket cavities were infilled with grout. Initial design was based upon CP111 and SP 91 (5,6).

2. MATERIALS

2.1 Bricks

Three types of brick have been included in the tests, two were of medium compressive strength and the third was of high strength. The brick types complied with B.S.3921 (7). Their properties are shown in table 1. Type 1 was a perforated ten hole brick, type 2 was a perforated three hole brick, and type 3 was a fourteen hole perforated brick. The volume of holes was less than 25% of the total volume for each type and the bricks were classed as solid (7).

BRICK TYPE	M.C.S. (N/mm^2)	W.A. (%)	I.S.R. ($kg/m^2/min$)
1	38.2	16.7	1.032
2	32.0	13.5	0.758
3	107.9	5.2	0.249

Table 1: Brick Properties

M.C.S = Mean compressive strength (7) W.A = Water absorption by 5hr boil
I.S.R = Initial suction rate to S.P.56 (8).

2.2 Grout

This was a 1:3:2 (cement:sand:stone) mix by volume. The water cement ratio was specified as 0.75. To increase workability a superplasticizer, 1% by weight of the cement content added was included. The average 28 day strength was 28.3 N/mm^2 using 100 mm cubes, cured in water.

2.2.1 Cement: Ordinary Portland cement to B.S.12 "Portland cement (ordinary and rapid hardening)."

2.2.2 Fine aggregate (sand): The fine aggregate used was a crushed limestone satisfying the zone 2 grading of B.S.812 and was obtained locally.

2.2.3 Coarse aggregate (stone): This was a 14 mm to 5 mm crushed limestone from the same quarry as the sand.

2.3 Mortar

The mortar was a 1:3 (cement:sand) mix by volume using the same materials as the grout. A water/cement ratio was not specified, the bricklayer being left to produce a workable mix. The average 28 day strength was 31.8 N/mm^2 using 100 mm cubes, cured in water.

2.4 Reinforcement

The tension steel was hot rolled, deformed hybar of 16 mm diameter, from which samples were tested in tension, Table 2. The shear reinforcement was 8 mm diameter mild steel for the designed links and 6 mm diameter mild steel for the nominal links.

SAMPLE	YIELD STRESS (N/mm^2)	ULTIMATE STRESS (N/mm^2)	YOUNG'S MODULUS (kN/mm^2)
1	471.5	586.0	195.5
2	473.5	580.4	190.5
3	477.0	579.4	192.1
MEAN=	474.0	582.0	192.7

Table 2: Steel characteristics

3. BEAM DETAILS

3.1 Construction

The beams were 4265 mm long, 290 mm high and 327 mm wide, Figure 1. The beams were constructed on a soffit of timber formwork similar to that used in reinforced concrete construction.

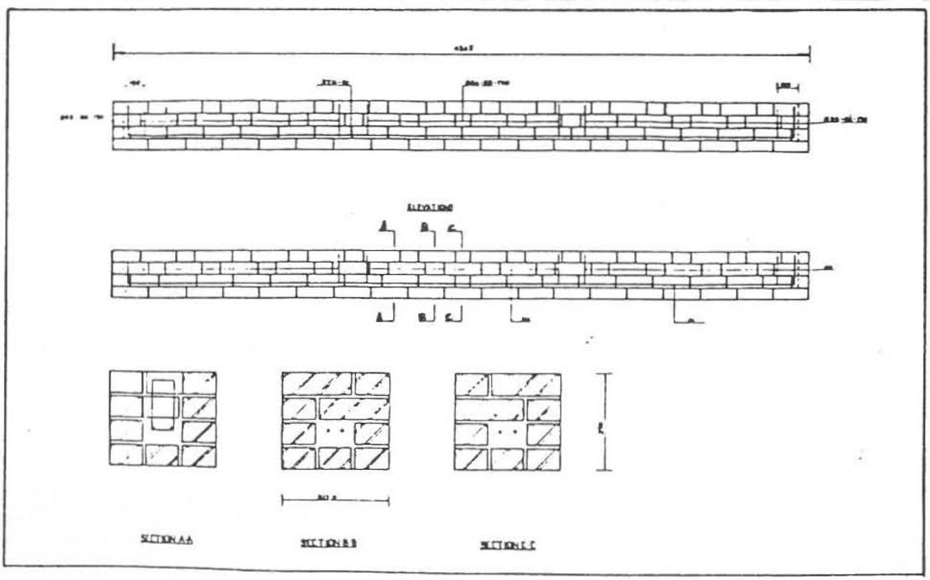


Figure 1: Details of test beams

The beams consist of a base course, one and a half bricks (327 mm) wide with a second course in stretcher bond forming the cavity for the tension reinforcement (figure 2). The third and fourth courses were in quetta bond. This provides the pockets for the shear reinforcement and the ceramic interlock by cross bonding (figure 3). Prefabricated reinforcement is positioned after the second course has been laid. Two beams of each brick type were built, one of each pair having the design shear links omitted from one end. (This was part of further research into the behaviour of this type of beam not covered in this paper).

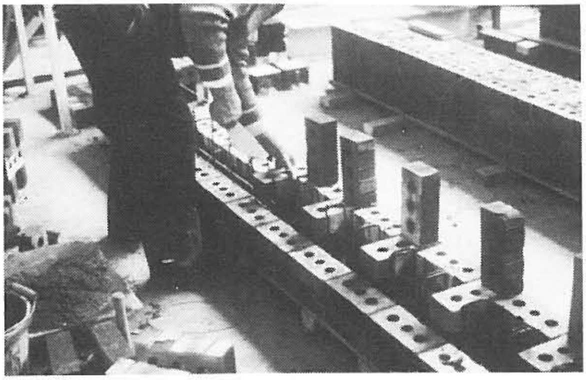


figure 2: Building the beam.

The beams were given a three figure number for identification. The first digit represents the brick type, i.e. 1 = brick type 1 etc. The second digit (the number 4) represents the test span, in metres. The third digit indicates whether or not the design shear links were omitted; 0 represents that shear steel was omitted and 1 that it was present.

3.1.1 Construction times: Each beam contains 184 bricks. The construction time, for a bricklayer plus labourer, inclusive of batching the mortar, was one and one half hours. The beams were left overnight before grouting took place, which inclusive of batching required two man hours.

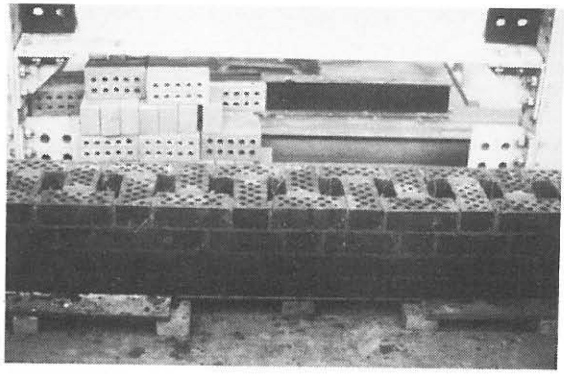


figure 3: The completed beam.

4. TEST DETAILS

4.1 Apparatus

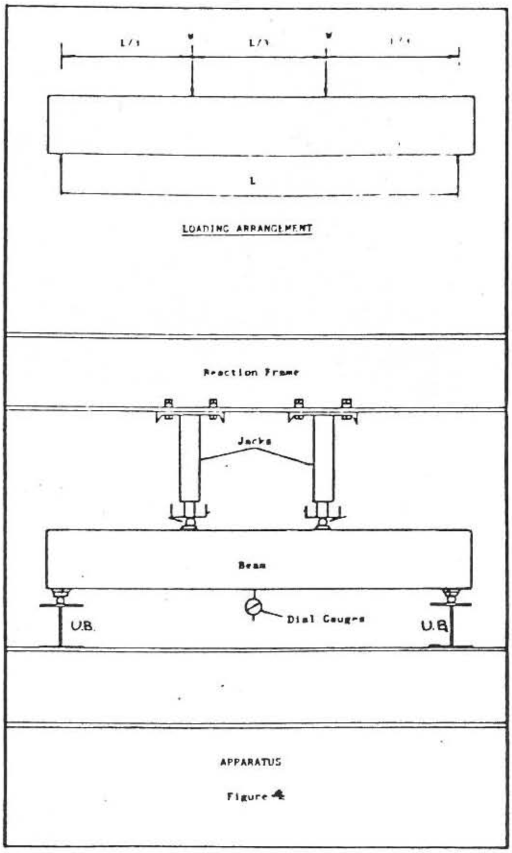
The loading arrangement and test apparatus are shown on figure 4. Loading was applied by 230 kN capacity, hydraulic jacks and transmitted, via a channel section and circular bar to the beam. Loading was applied in equal increments of 2.3 kN, with an equal time interval between successive load increments.

4.2 Strain Gauges

Strains in the tensile steel were measured using, paper backed, electrical resistance gauges, positioned: at the centre of the beam; under the jack load point and midway between these points (a distance of $L/_{12}$ from the beam centre).

Calibration of the gauges was carried out by testing strain gauged specimens in axial tension. The idealised, mean, stress-strain curve is shown in figure 5.

For measuring the surface strains on one face of the beam, a demec gauge of 203 mm (8 inches) gauge length was used. The studs were only used between the jacks, in the central third and were positioned about the beam centre. The locations are shown in figure 6.



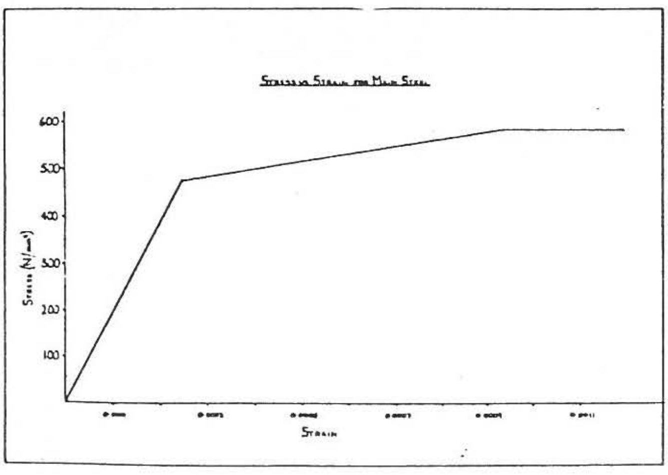


figure 5: Stress-Strain curve for tensile reinforcement

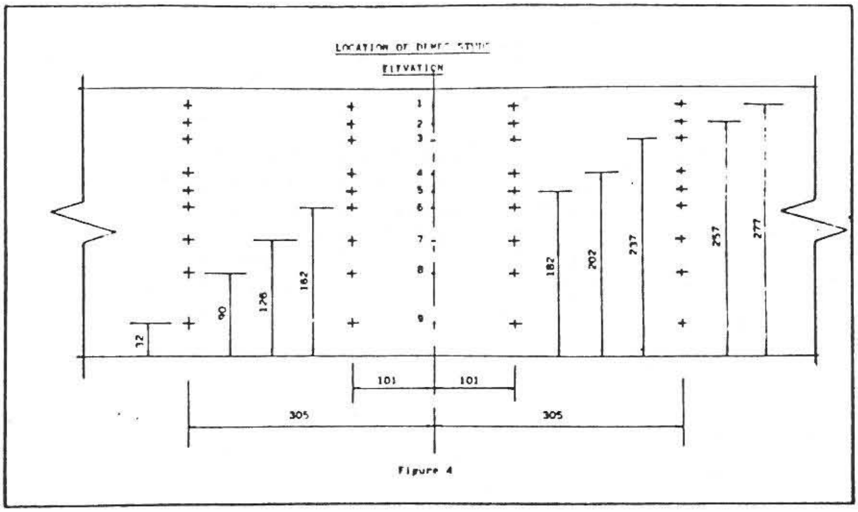


Figure 4

5. RESULTS

5.1 Design Moments

The design ultimate moments for the beams were: brick type 1 = 9.62 kNm, brick type 2 = 8.23 kNm, brick type 3 = 18.63 kNm. The design service moments were: brick type 1 = 6.49 kNm, brick type 2 = 5.61 kNm and brick type 3 = 12.12 kNm.

5.2 Deflections

All of the beams exceeded the design ultimate moment, as derived from B.S.5628 part 2(1). The beams all failed in flexure with the minimum factor of safety, F = 2.10 (9). F was determined from the experimental failure moment divided by the design ultimate moment. Shown in table 3 are the observed deflections at the draft code's design service and design ultimate, moments. Also shown are the corresponding deflection/span ratio's.

BEAM	$\Delta_{service}$ (mm)	$\frac{\Delta_s}{span}$	$\Delta_{ultimate}$ (mm)	$\frac{\Delta_u}{span}$
140	2.40	1/1667	3.96	1/1010
141	2.40	1/1667	3.90	1/1026
240	3.06	1/1307	4.98	1/803
241	2.04	1/1961	3.30	1/1212
340	6.00	1/667	11.25	1/355
341	5.88	1/690	10.84	1/369

Table 3: Deflections

5.3 Crack widths

Table 4 shows the measured crack widths at the draft code's design service and design ultimate, moments. The nominal crack widths referred to are indicating the average crack width. These are shown to give a comparison with the maximum measured crack width.

BEAM	Max. $\ni_s$ (mm)	Nominal $\ni_s$ (mm)	Max. $\ni_u$ (mm)	Nominal $\ni_u$ (mm)
140	0.117	0.077	0.146	0.065
141	NCV	NCV	0.176	0.113
240	0.079	0.052	0.159	0.103
241	NCV	NCV	0.085	0.072
340	0.180	0.128	0.267	0.178
341	0.175	0.088	0.249	0.124

Table 4: Crack widths

where: $\ni_s$ = crack width at service moment

$\ni_u$ = crack width at ultimate moment, NCV = No cracks visible.

6. DISCUSSION

6.1 Two differing theories for the selection of an acceptable service moment were studied:

(a) The bending moments which satisfied the draft code's serviceability requirements were selected from the experimental results (6.2).

(b) Simple bending theory was used to obtain the apparent forces in the beams during the tests. This showed that under certain circumstances the draft code theory oversimplifies the situation. An amended theory was used to represent the forces (6.3).

6.2 Deflection theory

From the design using the draft code the beams tested were calculated as being over reinforced (1). The experimental results showed this was not the case; the beams behaved as under reinforced sections. Steel yield occured first followed by some crushing of the bricks in the compressive zone. Having also found that the draft's deflection requirements were easily met an increase in the design service moment was proposed. This was determined as follows. The deflection at the limiting deflection/span ratio of 1/250 was calculated. From the results ultimate moments corresponding to this deflection are obtained. By designing in reverse, using the draft code's load factors, the proposed service moments were found. These values and the respective deflections and crack widths are shown in table 5.

BRICK TYPE	CODE SERVICE MOMENT (kNm)	Proposed service moment (kNm)	measured values		
			Δ_s (mm)	Max $\ni_s$ (mm)	Nominal $\ni_s$ (mm)
1	6.49	12.22	8.13	0.373	0.201
2	5.61	10.98	9.54	0.265	0.169
3	12.12	14.10	7.80	0.218	0.124

Table 5

The draft code gives three equations used to design the beam in bending. These cover the moment in the compressive zone of brickwork (i), the moment in the steel (ii), and an expression for the lever arm used in the previous equation (iii).

These equations are:

$$M = \frac{0.375.b.d^2.f_f}{\gamma_{mm}} \quad \ldots\ldots\ldots\ldots \quad \text{(i)}$$

$$M = \frac{As.fy.Z}{\gamma_{ms}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(ii)}$$

$$Z = d \quad 1 - \frac{0.5.As.fy.\ mm}{b.d.\ \gamma ms.f_f} \quad \ldots. \quad \text{(iii)}$$

where M = moment
b = breadth of beam
d = effective depth
γ_{mm} = brickwork partial safety factor
f_f = characteristic strength in bending
As = Area of tensile steel
fy = Steel yield stress
z = lever arm
γ_{ms} = steel partial safety factor

In the analysis carried out on the test results it was assumed that the following items were acceptable: As, fy, γms, b, d. One or more of the remaining terms were varied to achieve the proposed ultimate moment. This proved to be unsuccessful. Further inspection revealed that the expression for determining Z was not producing comparable values to those obtained experimentally. Because of this discrepancy in the lever arm value a study was made of the apparent forces in the beam.

6.3 Tensile Force Theory

In the draft code it has been assumed there is a single compressive force and a single tensile force within the beam. This is based on the assumptions that brickwork has no tensile resistance and that plane sections remain plane after bending. Thus the tensile force is that in the reinforcement.

The compressive stress block is assumed to be a rectangle.

By taking moments about C (figure 7) the expression $M = S_t.Z$ is obtained. But S_t = As.fy and hence M = As.fy.Z is derived; which is equation (ii) without the γ_{ms} term.

where:
C = compressive force in brickwork
S_t = tensile force in steel
d = effective depth
Z = lever arm

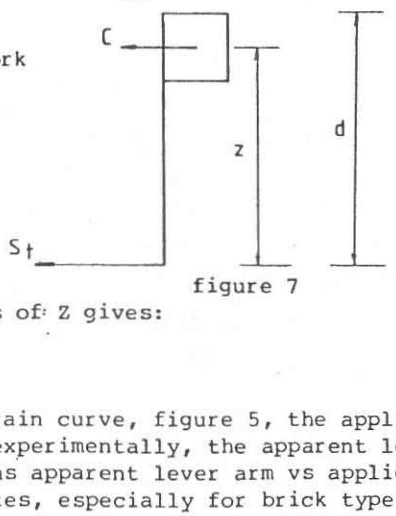


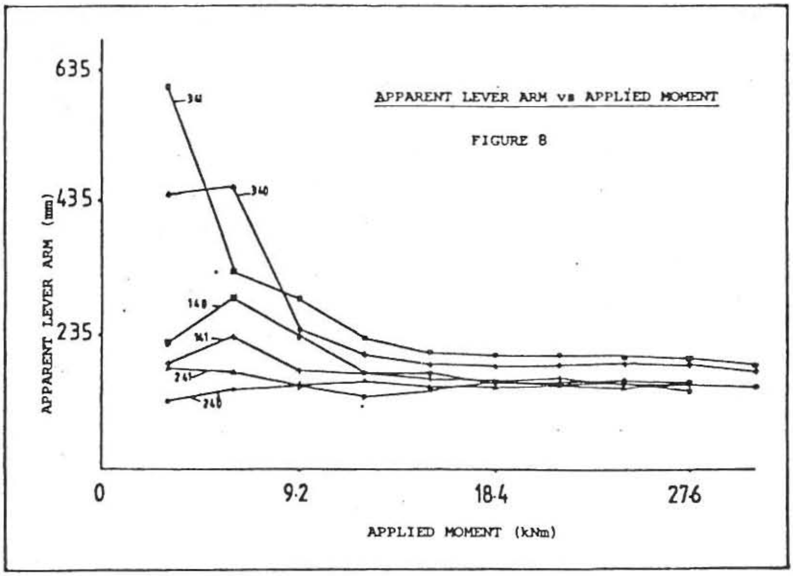
figure 7

Rearranging this expression in terms of Z gives:

$$Z = \frac{M}{As.fy} \quad .\ .\ .\ . \quad \text{(iv)}$$

By using the actual steel stress-strain curve, figure 5, the applied moments and steel strains obtained experimentally, the apparent lever arm was obtained. These are shown as apparent lever arm vs applied moment in figure 8, which demonstrates, especially for brick type 3, that this does not provide a consistent estimate.

From the surface strain readings, taken with the demec gauge, an estimate of the neutral axis depth was made. A typical example of these readings is shown in figure 9. Using these results and substituting them into equation (iv) the values for the predicted applied moment and the actual applied moment were found to be unequal, with the predicted values being lower. Because of this the



above theory was amended. The shape of the compressive strain block showed that the assumption of only one compressive force appears to be valid. Hence an additional force was likely to come from any

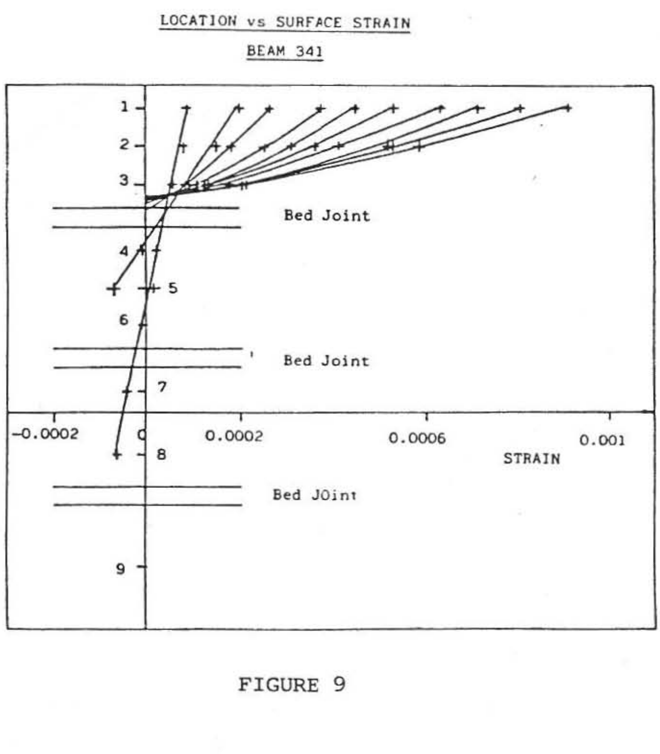
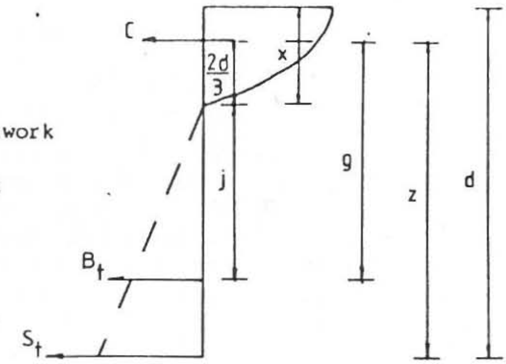


FIGURE 9

tensile resistance within the brickwork. The amended theory becomes:

x = depth of compression zone
Z = lever arm from C to S_t
g = lever arm from C to B_t
j = depth from N.A to B_t
C = compressive force in brickwork
B_t = tensile force in steel
B_t = tensile force in brickwork



It was observed that during testing the brickwork below the steel cracked quite quickly. Cracking above the steel was more limited and occured more slowly. From this it is assumed that the brickwork tensile resistance will only act between the neutral axis and the reinforcement. It was also assumed that the brickwork tensile stress distribution was triangular.

From this $Z = d - {}^{1}/_{3}x$ . . . . (v)

The depth from the neutral axis to B_t , $j = {}^{2}/_{3}(d - x)$

from which $g = {}^{2}/_{3}(d - x) + {}^{2}/_{3}x = {}^{2}/_{3}d$ . . . . (vi)

Taking moments about C to obtain the moment due to the tensile forces: $M = ZS_t + gB_t$ . . . . (vii)

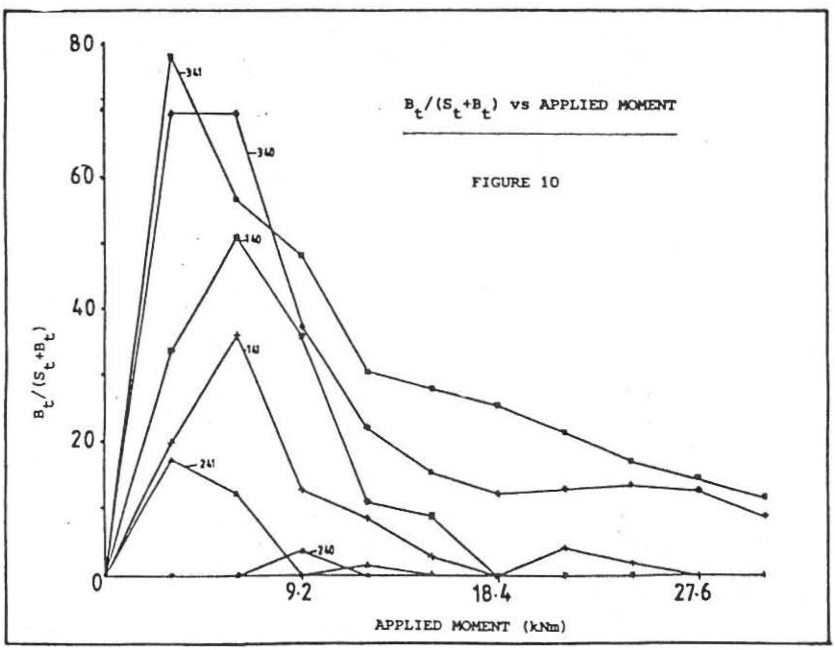
rearranging in terms of B_t and substituting for g from (vi) gives:

$$B_t = {}^{3}/_{2}\left[\frac{M - Z.S_t}{d}\right] \; . . . . \text{(viii)}$$

but

$$S_t = A_s fy$$

$$\therefore \; B_t = \frac{3}{2d}(M - A_s.fy.Z) \; . . . . \text{(ix)}$$



$B_t/(S_t+B_t)$ vs APPLIED MOMENT

FIGURE 10

By substituting the observed data into equation (ix) the brickwork tensile resistance, B_t, was obtained at each increment of applied moment. The results are shown in figure 10, in the form of B_t as a percentage of $S_t + B_t$, against the applied moment.

Figure 10 shows that the greater the compressive strength of the brick, for the beam design used, then there is a greater tensile force in the brickwork. These values peak after one or two increments of applied moment after which they decrease with increasing moment.

At the service moments proposed in 6.2 the percentage of $B_t/(S_t + B_t)$, from figure 10, was greater than 50% for brick type 3, greater than 30% for brick type 2 and greater than 10% for beam 241. Thus showing a possible cause for the difference between theoretical and experimental lever arm values.

7. CONCLUSIONS

7.1 The construction method adopted produced a beam:

(a) Whose service and ultimate moments exceeded the requirements of the Draft Reinforced and Prestressed Masonry Code (1).

(b) Which was under reinforced, contrary to the draft codes predictions.

(c) With a lever arm which did not confirm the value obtained using equation (iii) page (7).

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