BEHAVIOUR OF PARTIALLY PRESTRESSED BRICKWORK BEAMS

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ABSTRACT The paper summarises the result of an investigation on the behaviour of full-scale partially prestressed brickwork beams. 10 full-scale beams of span 6.2 m were tested to study the ultimate moment, the moment-deformation relationship, and mode of failure. The variables considered were the percentage of steel and brick strength.

The experimental ultimate moment and moment-deformation relationship are compared with theoretical analysis using the material properties obtained from the brickwork prism tests.

INTRODUCTION

The technique of prestressing is generally associated with concrete. Prestressed concrete has established itself as a major structural material, which is used widely in the construction industry. The principle of prestressing which is so widely used for concrete can also be applied to brickwork. Recently, a comprehensive research program (1) has been carried out to study the behaviour of fully prestressed brickwork beams. From this investigation it is very clear that the brickwork can be fully prestressed, but the transfer stress has to be kept low to prevent splitting in the anchorage zone. In addition, the prestressing steel has to be kept at 'kern' limit to avoid the development of tensile stresses due to prestressing. As a result of this constraint, the width of the crack may be much larger than allowed for a class 3 prestressed concrete member [2] at service load. The width of the crack can be controlled by 'partial prestressing'. Partial prestressing of a section is achieved in two ways: i) either by reducing the level of initial prestress applied to the entire tensile reinforcement required for ultimate load, or ii) by prestressing part of the tensile reinforcement to a maximum allowable stress level and leaving the rest non-stressed [3]. As no work has been done so far in this field, a comprehensive investigation of the behaviour of partially prestressed brickwork beam was undertaken to study the effects of the following variables:

i) percentage of steel
ii) ratio of prestressing steel to ordinary reinforcement
iii) mortar strength or grade $1:\frac{1}{4}:3$ and $1:\frac{1}{2}:4\frac{1}{2}$ (Cement: Lime:Sand).
iv) brick strength

on ultimate moment, deflection and cracking.

This paper only summarises the result of the preliminary investigation on 10-full-scale partially prestressed brickwork beams.

MATERIALS

Mortar: A $1:\frac{1}{4}:3$ (Cement:Lime:Sand) mix by volume was used throughout the construction of the beams. The average compressive strength of the mortar for each individual beam is given in Table 2.

Concrete: A $1:2\frac{1}{2}:2$ (Cement:Sand:Pea gravel) mix was used for all the beams except 5 and 6. The mix used for the beams 5 and 6 was 1:2 (Cement:Sand).

In both mixes a plasticiser (Conbex) was used to reduce the effects of shrinkage and to shorten the setting time. Three 100 mm cubes were cast during each concreting operation and tested at 7 days. The average compressive strength of the concrete is given in Table 2 for each of the test specimens.

<u>Bricks</u>: 3-hole perforated bricks were used throughout the test programme. The average compressive strength of high and medium strength bricks was 82.0 N/mm^2 and 58.9 N/mm^2 respectively.

<u>Prestressing Reinforcement</u>: 10.9 mm diameter, stabilised steel strand was used for prestressing. The average ultimate stress was 1708 N/mm^2, with 0.2% proof stress of 1640 N/mm^2. The modulus of elasticity was 214 kN/mm^2.

<u>Non-stressed Reinforcement</u>: 12 mm diameter, high strength deformed bars were used throughout, with an ultimate stress of 670 N/mm^2, a yield stress of 535 N/mm^2 and Young's Modulus 200 kN/mm^2.

The stress-strain relationship of prestressing steel and reinforcement was idealised in tri-linear form as shown in Fig. 1 and 2 for theoretical analysis.

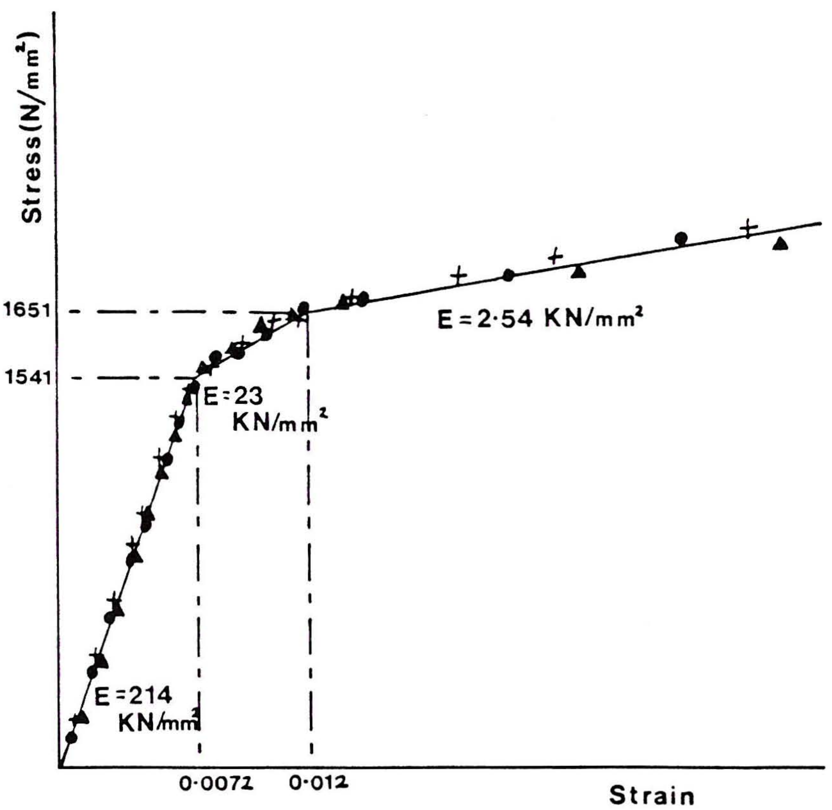


Fig. 1 Idealised tri-linear stress/strain relationship for prestressing steel

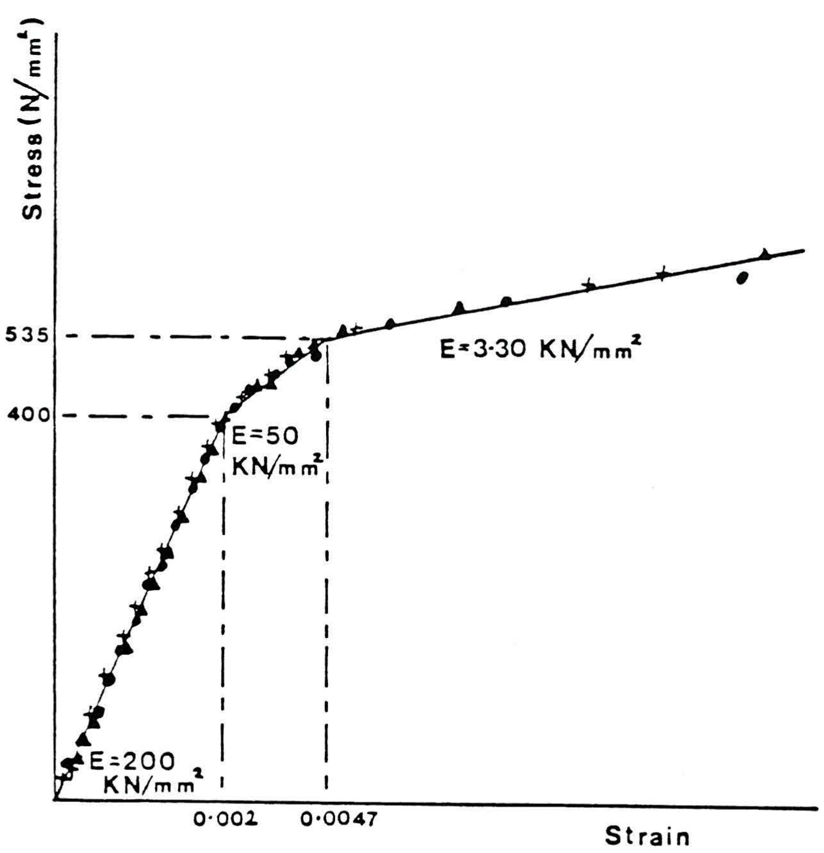
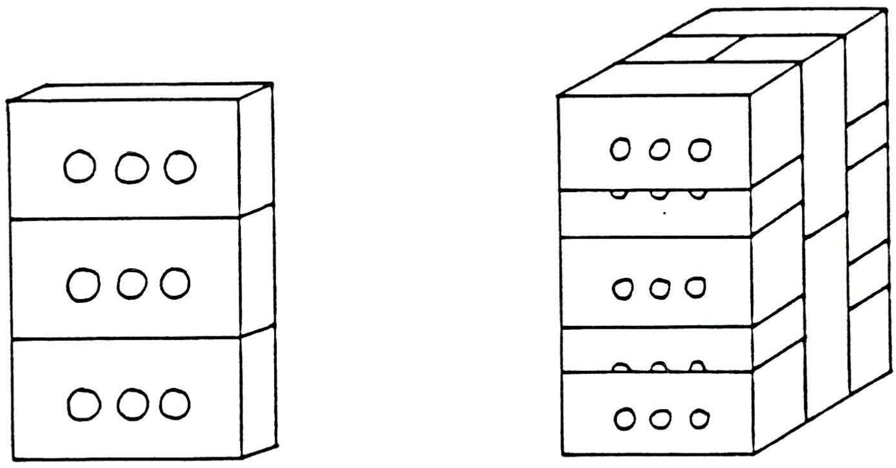


Fig. 2 Idealised tri-linear stress/strain relationship for reinforcement

PROPERTIES OF BRICKWORK

<u>Brickwork prism specimen</u>: The strength and stress-strain relationship, are both required for theoretical analysis. Two types of prisms as shown in Fig. 3 were selected to obtain the strength and material properties of the brickwork. Prism B represents the top three courses of the brickwork resisting the compressive force developed in the beam during early stages of loading. During the testing of the beam, it was observed that the cracks developed after the neutralisation of the prestress and penetrated deeper than the level of prestressing steel. As a result, only the topmost course of brickwork resisted the compressive force, hence single course prism was also tested to obtain the strength and material properties. The test results are given in Table 1.



Single Course
Prism Type A

Three Course
Prism Type B

Fig. 3 Brickwork Prisms

Brick Strength N/mm^2	Mortar grade	Prism type	Test No.	Ultimate Compressive Strength N/mm^2 Test Results	Average	Ultimate Compressive Strain x 10^{-5} Test Results	Average
			1	28.9		305	
			2	24.2		261	
82.0	1:¼:3	Single	3	29.9	28.8	313	292
		Course	4	30.0		281	
			5	31.8		337	
			6	28.0		255	
			1	16.6		189	
			2	19.2		196	
82.0	1:¼:3	Three	3	21.5	19.4	211	213
		Course	4	23.6		257	
			5	17.5		224	
			6	18.0		201	
			1	10.8		253	
58.9	1:¼:3	Three	2	13.9	11.8	294	270
		Course	3	10.8		264	

Table 1 Properties of Brickwork Prisms

Stress-strain relationship: Both types of brickwork prisms were tested under uni-axial compression and the resulting strain was measured with a 'demec' gauge. The experimental stress-strain relationship was mathematically idealised and the relationship was obtained by a third-degree polynomial (Fig. 4) of the form:

$$f/f_m = 1.95(\varepsilon/\varepsilon_m) - 1.24(\varepsilon/\varepsilon_m)^2 + 0.29(\varepsilon/\varepsilon_m)^3$$

The equation was very similar to the one proposed earlier [4] . From the stress-strain relationship, the stress block factors $\lambda_1 = 0.63$ and $\lambda_2 = 0.37$ were obtained.

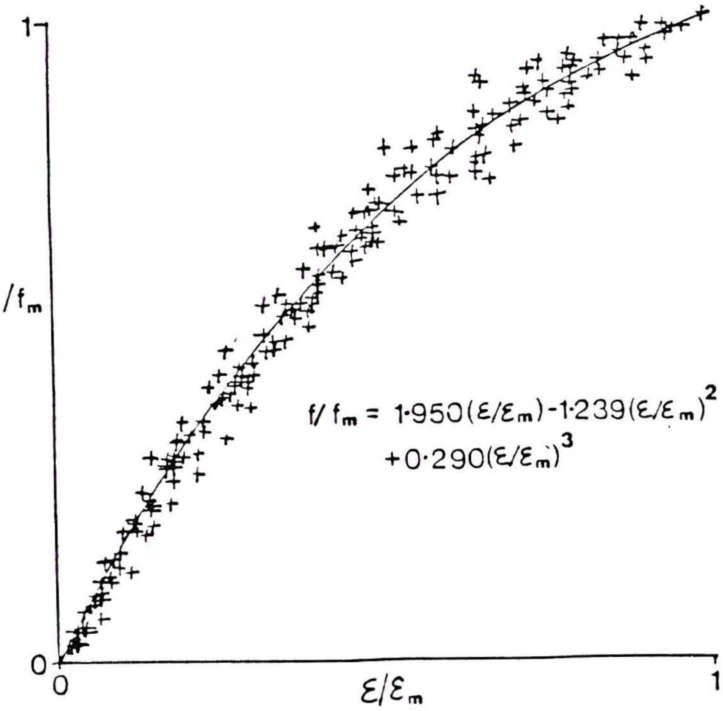


Fig. 4 Non-dimensional stress/strain relationships for brickwork

CHOICE OF BRICKWORK SECTION FOR PARTIALLY PRESTRESSED BEAMS

Any development in brickwork to be of practical use, needs to take into account the available skill and the available shape of the unit. Ignoring these two major constraints may lead to constructional difficulties associated with useless costly development. In addition the section must offer certain other competitive advantages over other forms of construction such as:

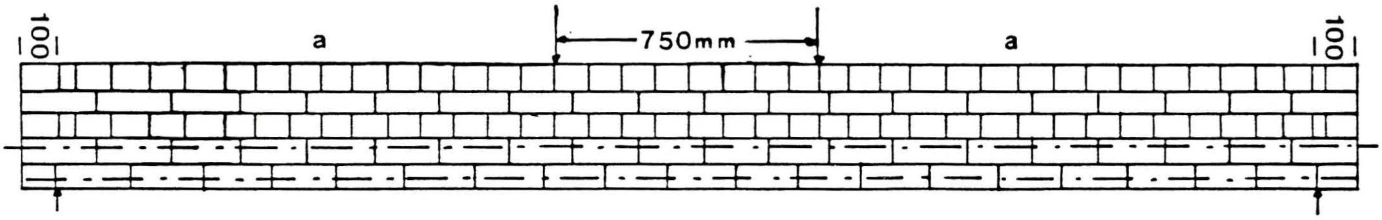
i) effective utilisation of as much ceramics as possible

ii) ease of grouting

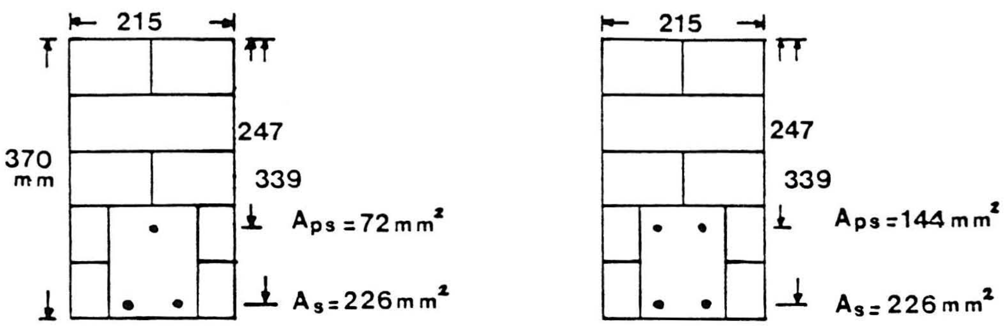
iii) provision of cavity for placement of the reinforcements at required depth

iv) elimination of formwork

Keeping these in mind, the section developed for the beam is shown in Fig.5 . The top three courses of the beam were built in normal English bond and the bottom two courses receiving the reinforcement was formed by splitting the bricks lengthwise and placing them flush with the face. The cavity allowed positioning of the prestressing steel at the 'kern' limit and the non-stressed reinforcement at any suitable depth. The area of the cavity to be filled with concrete was 18% approximately of the total cross-sectional area.



BEAM EVELATION



Section
Beams 1-8
p=0.47%

Section
Beams 9-10
p=0.61%

Fig. 5 Beam elevation, brick bonding arrangement and sections

CONSTRUCTION OF THE BEAMS

All test beams were built on the floor of the laboratory by an experienced bricklayer. To prevent horizontal splitting of the bedjoints the ends of the beams were reinforced with 6 mm mild steel rods to resist the anchorage forces which develop in the 'lead in length'.

The beams were cured for 21 days before post-tensioning. 25 mm thick mild steel anchorage plates were attached to the beams. The beams were prestressed to 70% of the tendon's ultimate strength. Immediately after prestressing, the non-stressed steel was put in position and then the concrete was poured to fill the cavity. The beams were tested after 7 days of concreting.

The amount of prestressing steel and non stressed-steel for various beams are shown in Fig. 5.

TEST ARRANGEMENTS AND INSTRUMENTATION

The test set-up is shown in Fig. 6. The test rig (Fig. 7) provided pin and roller support. Load was applied by jacks connected to a hydraulic pump. The loads at the jacking point were measured with load-cells connected to a pen-chart recorder. Strains up to failure were measured in the constant moment zone at various depths of the beams by a 'demec gauge'. Steel strains were measured by the electrical resistance gauges. Crack width and depth were also recorded at each load interval. Central deflection of each beam was measured with dial gauges reading to 0.02 mm.

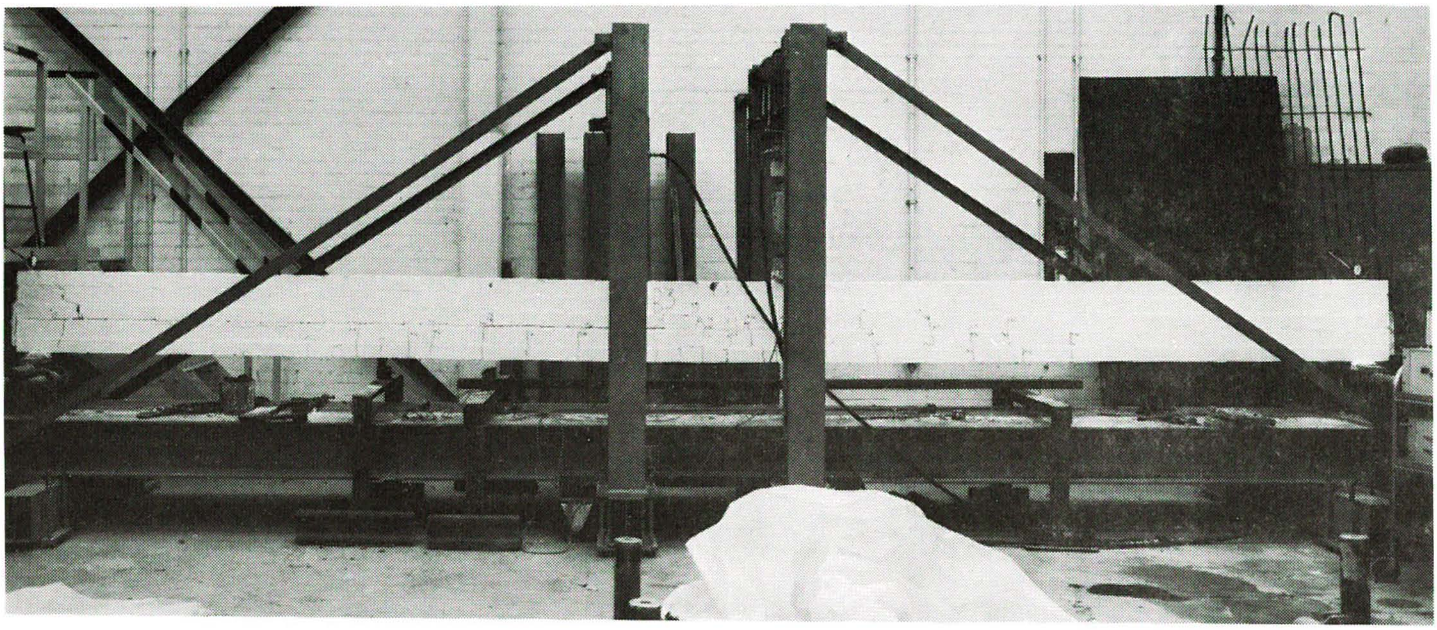


Fig. 6 Test set-up, showing the failure of a beam in shear

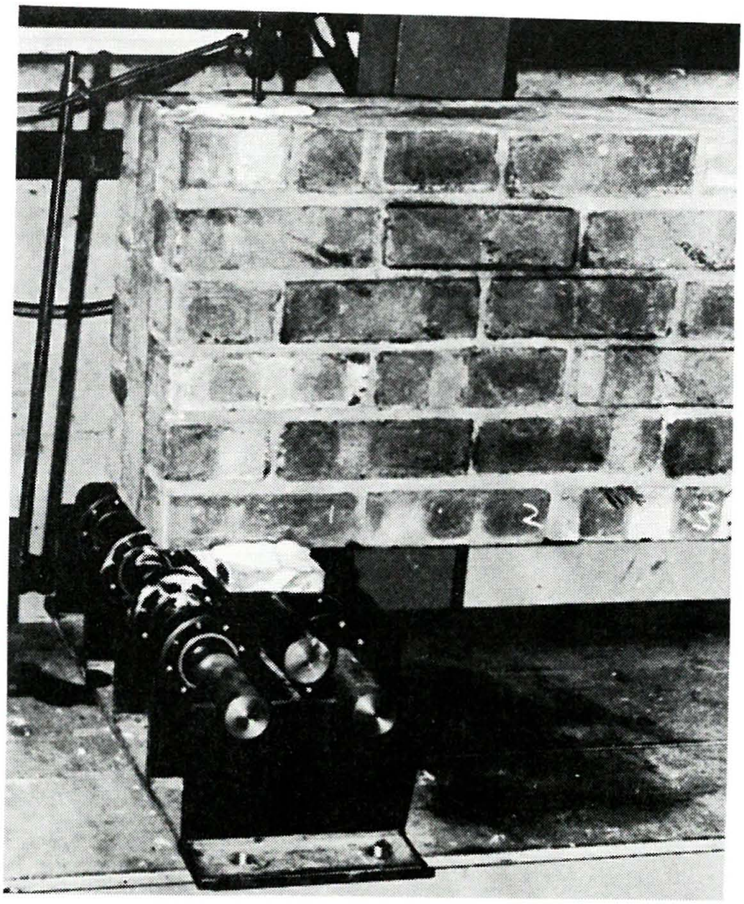


Fig. 7 Showing Roller Support

THEORETICAL ANALYSIS

Determination of moment-curvature relationship and deflection: This direct method uses the experimental idealised stress-strain curves of brickwork (Fig. 4) and both prestressing and reinforcing steel (Figs 1 & 2) to calculate the moment and curvature of the partially prestressed beams. The moment-curvature for the whole loading history is used to calculate the deflection. The applied loading is considered in three stages (1,5):

i) prestressing
ii) prestressing to cracking
iii) post cracking to ultimate load

Due to the large number of iterative operations involved in obtaining the moment-curvature relationship and deflection of the beam, a computer program was written to cope with these. The detailed derivation of this method is given elsewhere [1].

Calculation of ultimate-moment of resistance: The moment of resistance of the beam was also calculated from the stress block in addition to the direct method of calculation described above. At the time of failure, in any beam, the prestressing force is completely neutralised in maximum moment zone and the behaviour of partially prestressed beams then will be very akin to a reinforced brickwork beam.

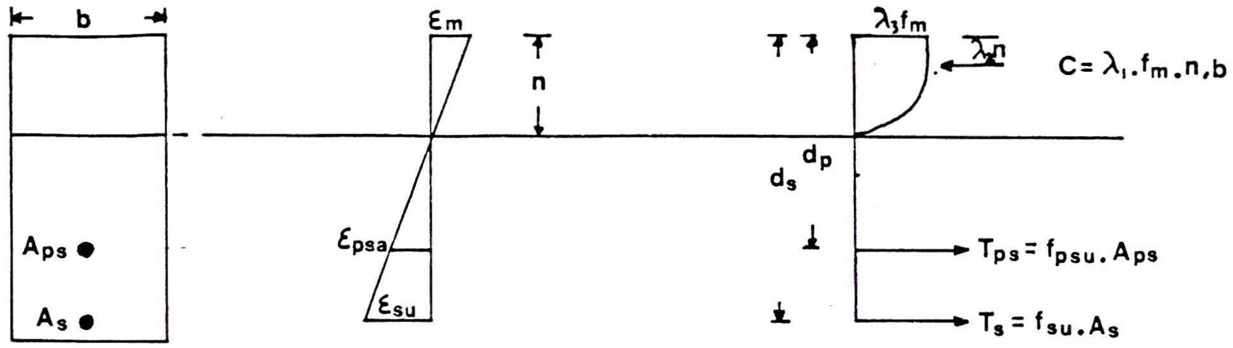


Fig. 8a Beam Section

Fig. 8b Strain Distribution at Failure

Fig. 8c Stress distribution at Failure

From Fig. 7 the total force of compression (6,7) and tension will be given by:

$$F_c = \lambda_1 . b . n . f_m \qquad -(i) \; ; \quad \text{since } \lambda_3 = 1 \ (7)$$

$$F_t = A_{ps} f_{psu} + f_{su} . A_s \qquad -(ii)$$

$$F_c = F_t \qquad -(iii)$$

$$n = \frac{A_{ps} . f_{psu} + A_s f_{su}}{\lambda_1 . b . f_m}$$

$$\varepsilon_{psu} = \varepsilon_{sp} + \varepsilon_{psa} \qquad -(iv)$$

where ε_{psa} = strain due to applied load

ε_{sp} = strain due to prestress

Assuming full bond between the steel and concrete at failure, the strains in the prestressing and non-stressed reinforcement respectively are given by:

$$\varepsilon_{psa} = \varepsilon_m . \frac{(d_p - n)}{n} \qquad -(v)$$

$$\varepsilon_{su} = \varepsilon_m \left(\frac{d_s - n}{n}\right) \qquad -(vi)$$

where ε_m is the ultimate strain derived from the brickwork prisms test.

Once ε_{psu} and ε_{su} are known, f_{psu} and f_{su} may be obtained from the respective stress-strain relationships for the steel. This method for the calculation of ultimate moment involves a process of trial and error to calculate n, such that $F_c = F_t$.

Once this is satisfied, moment is given by:

$$M_{su} = f_{psu} . A_{ps} [d_p - \lambda_2 . n] + f_{su} . A_s [d_s - \lambda_2 n] \qquad -(vi)$$

The theoretical moment thus calculated was compared with the experimental results in Table 3.

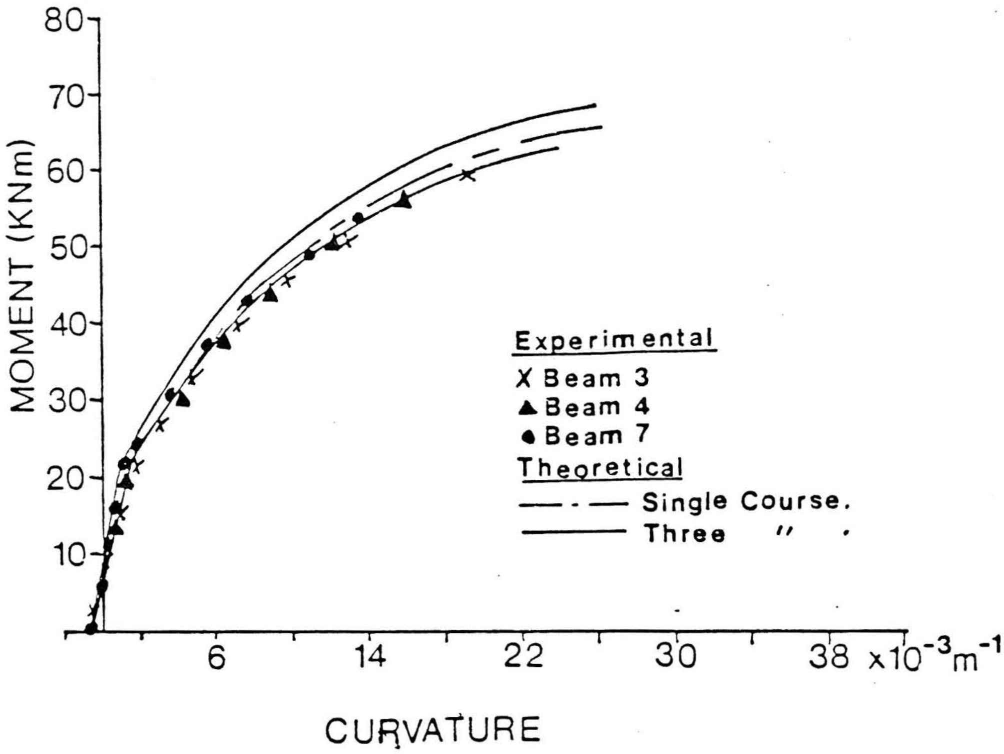


Fig. 10 Moment-curvature relationship for beams of 0.47% steel

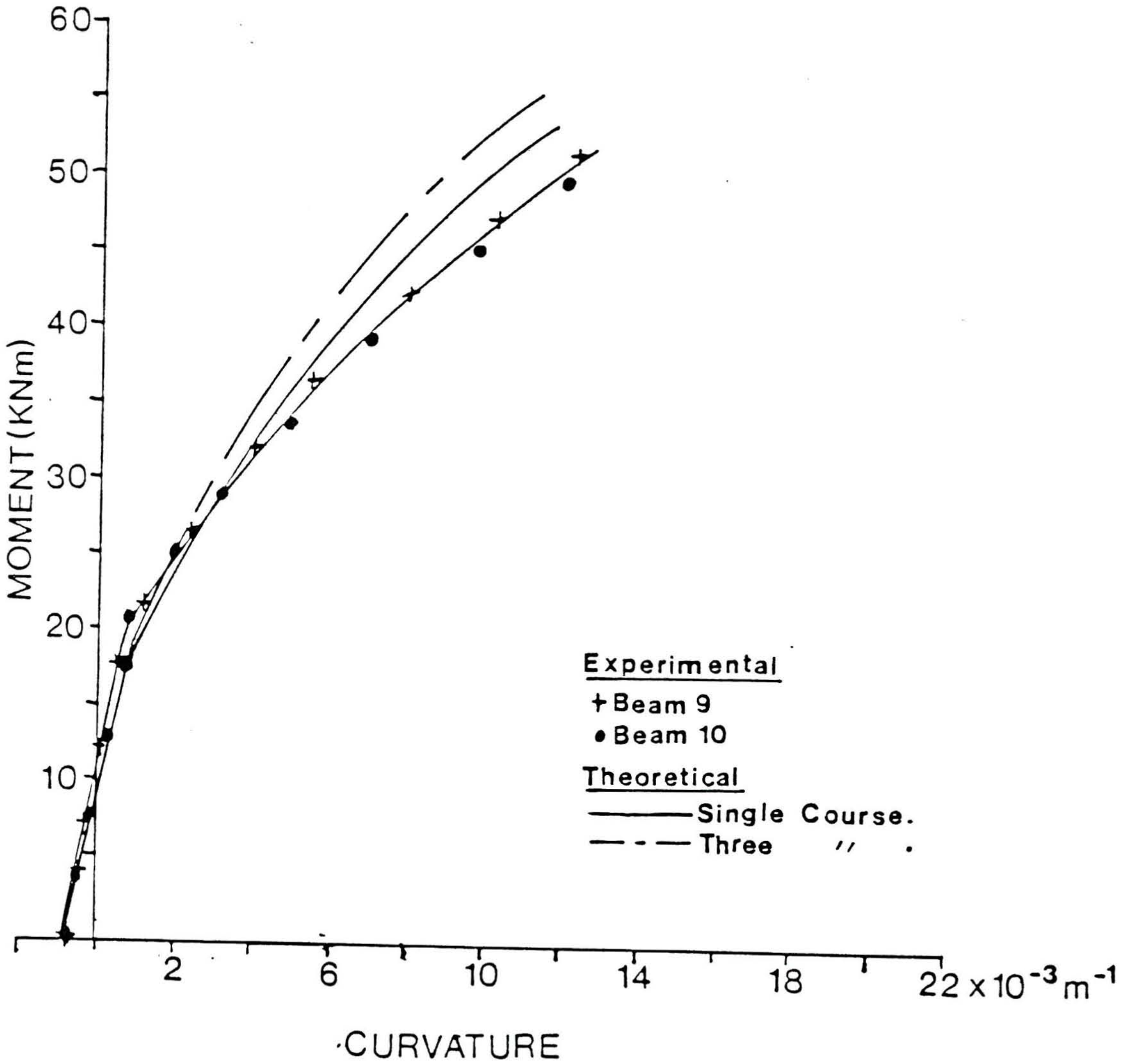


Fig. 11 Moment-curvature relationship for beams of 0.61% steel.

RESULTS AND DISCUSSION

The test results for all the beams and their mode of failure is given in Table 2.

Moment-Curvature Relationship: Typical moment-curvature relationship for the tested beams are shown in figures 9 to 11, the beams (figs. 9,10) with a 0.47% of steel which failed in flexure show three distinct phases: linear up to cracking, cracking up to yield stress of steel and post yield phase when it becomes parallel to x-axis. The beams with 0.47% and 0.61% steel area which failed prematurely due to shear, the third phase was completely absent (fig.11).

As expected, the curvature for the beams 9-10 with higher percentage of steel (0.61%) was lower than for beams 1-4 with percentage of steel equal to 0.47.

From figs 9-11, it can be seen that there is very good agreement between the experimental and theoretical values of m-ϕ derived by direct method from both types of brick prisms, but the single course prism results giving slightly better agreement.

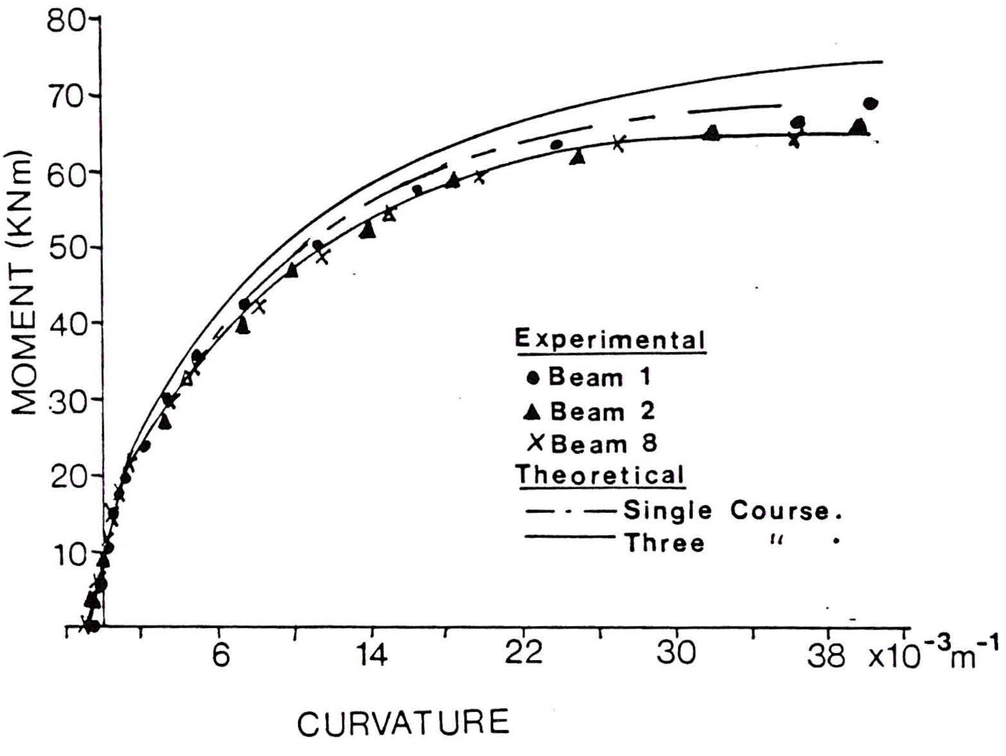


Fig. 9 Moment-curvature relationship for beams of 0.47% steel

Deflection: Figs 12, 13 and 14 show typical moment-deflection relationships for the tested beams, Fig. 11 indicating three distinct phases as with the moment-curvature relationship. Comparing the predicted deflections with those experimentally derived the agreement is good, especially for the deflections using the results of the single course prism tests.

The recovery of deflection after release of the load was between 23 and 46% for beams failing in shear.

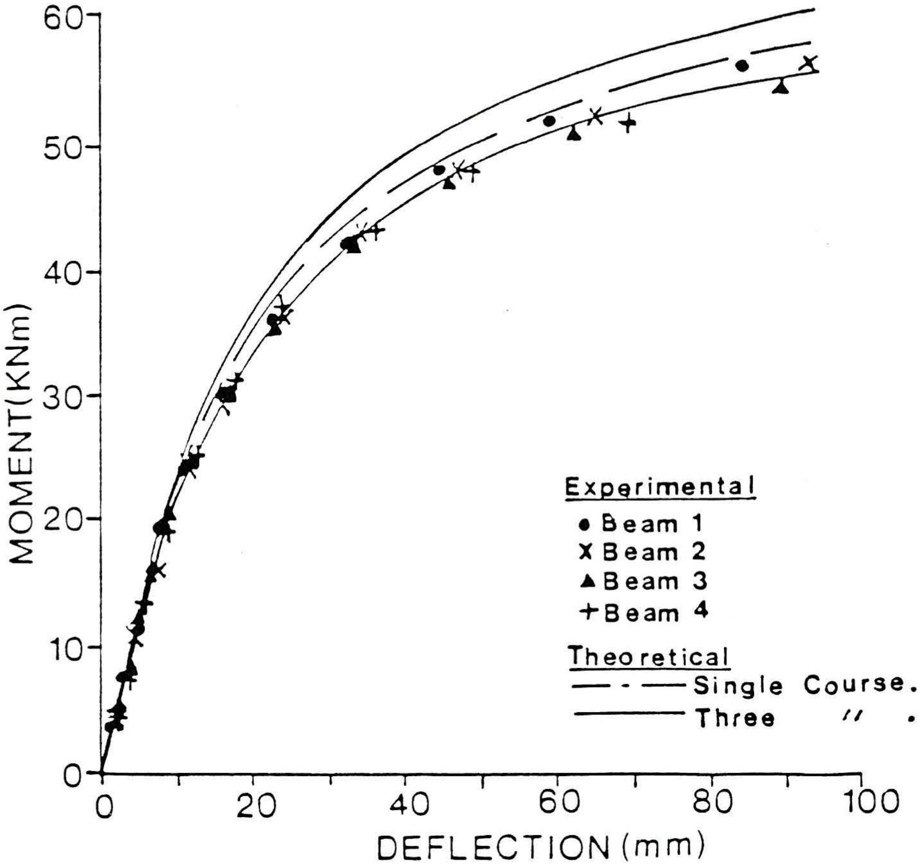


Fig. 12 Moment-deflection relationship for beams of 0.47% steel, span 6.2m.

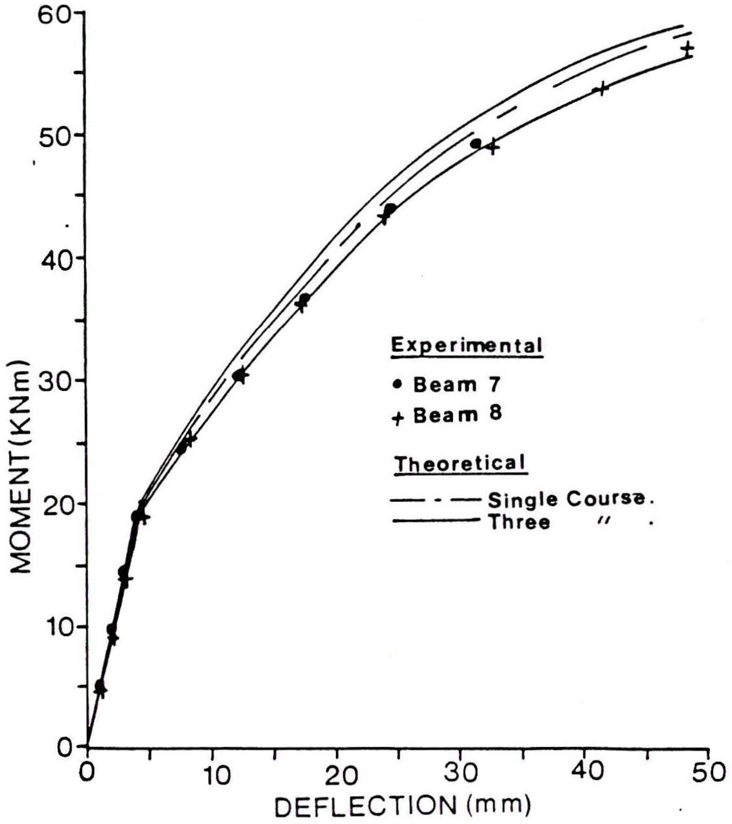


Fig. 13 Moment-deflection relationship for 0.47% steel, span 5.2 m

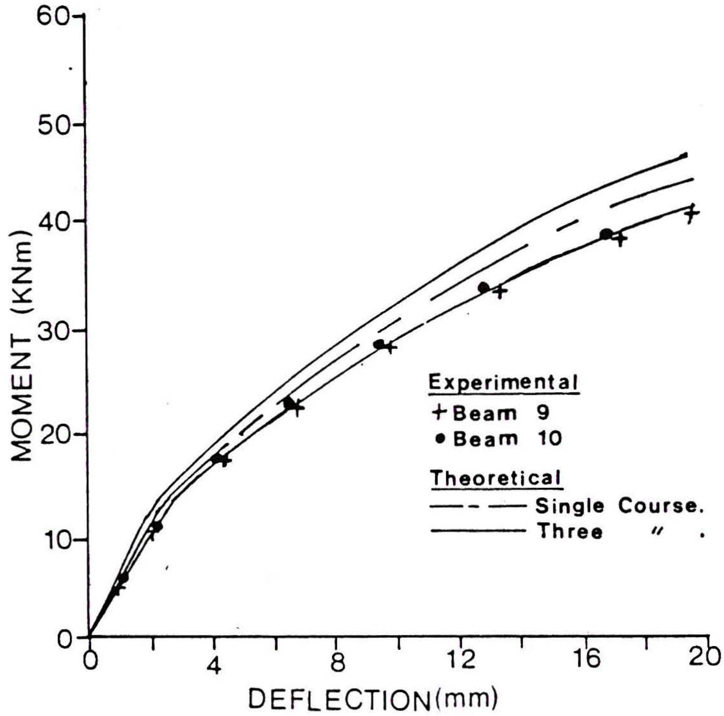


Fig. 14 Moment-deflection relationship for beams of 0.61% steel, span 5.2 m

Beam	Brick Strength N/mm^2	Mortar Strength N/mm^2	Grout Strength N/mm^2	Span m	Effective Prestress kN	Experimental Ultimate Moment kNm	Ultimate Shear Stress, V_u* N/mm^2	Failure Mode
1	82.0	25.8	25.8	6.2	70.4	67.60	0.39	Tension
2	82.0	23.2	24.7	6.2	68.2	66.70	0.39	Tension
3	82.0	16.9	19.8	6.2	68.5	61.33	0.36	Shear
4	82.0	19.8	21.7	6.2	67.8	58.13	0.34	Shear
5	58.9	24.9	25.3	6.2	66.8	59.43	0.35	Tension
6	58.9	29.9	36.5	6.2	66.8	59.43	0.35	Tension
7	82.0	17.0	21.4	5.2	66.9	52.30	0.31	Shear
8	82.0	30.7	21.2	5.2	69.3	73.09	0.42	Tension
9	82.0	26.9	-	5.2	69.9	59.25	0.36	Shear
10	82.0	35.1	21.4	5.2	67.7	44.42	0.31	Shear

$*V_u = \frac{V}{bd}$. Ultimate shear stress is calculated as the loading at failure, irrespective of the failure mode.

Table 2 Summary of Beam Test Results

Ultimate Moment and Mode of Failure: Beams 1, 2 and 8 (p = 0.47%) of the high strength brick all failed in tension, with yielding of the steel reinforcement leading to crushing of the brickwork (average ultimate moment = 69.1 kNm). Other beams 3, 4 and 7 in this series failed in shear, with a reduction in average ultimate moment of 17% (Table 2). The shear failures of these beams occurred with longitudinal splitting along the concrete/brickwork interface from the support to the loading point (Fig. 6).

The medium strength brick beams 5 and 6 both failed in tension (table 2) with a 14% reduction in ultimate moment compared with the average moment of the high strength brickwork beams failing in tension.

Shear failure occurred with shear cracks propagating from the support along the concrete/brickwork interface to the loading point (fig. 6) all the shear failures occurring suddenly with no warning. But unlike reinforced brickwork there was no 'total' collapse and the beams were still able to carry some load after failure.

Table 3 compares the experimentally and theoretically derived ultimate moment. The experimental results of beams which failed in flexure are only compared with the theory, since it assumes the crushing of the compression zone at ultimate failure. From table 3 it can be seen that the methods presented predict the moments to a very satisfactory degree of accuracy. Thus using either method presented the ultimate moment of a partially prestressed brickwork may be calculated.

Beam No.	Experimental Ultimate Moment, kNm	Moment predicted using stress block factors				Moment predicted by direct method			
		SINGLE COURSE		THREE COURSE		SINGLE COURSE		THREE COURSE	
		kNm	Exp./theo.	kNm	Exp./theo.	kNm	Exp./Theo.	kNm	Exp./Theo.
1	67.6	66.8	1.01	61.1	1.11	73.6	0.92	68.2	0.99
2	66.7	66.8	0.99	61.1	1.09	73.6	0.91	68.2	0.98
5	59.4	-	-	54.0	1.10	-	-	53.3	1.12
6	59.4	-	-	54.0	1.10	-	-	53.3	1.12
8	73.1	66.8	1.09	61.1	1.20	73.6	0.99	68.2	1.07

Table 3 Comparison of experimental and theoretical ultimate moments

SUMMARY AND CONCLUSIONS

i) The section used in this investigation proved satisfactory and no problems were encountered in prestressing, concreting and handling of the specimens.

ii) The ultimate moment of a partially prestressed brickwork beam can reliably be predicted by the methods proposed in this paper.

iii) The direct method proposed in this paper which takes the non-linear behaviour of materials into account predicts accurately the load deflection relationships of the partially prestressed brickwork beams up to failure.

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NOTATION

a	Shear span
b	Breadth of beam section
d_p	Depth of prestressing steel
d_s	Depth of non-stressed steel
f_m	Ultimate compressive strength of brickwork
f_{psu}	Stress in prestressing steel at failure
f_{su}	Stress in 'non-stressed' steel at failure
n	Neutral axis depth
A_{ps}	Area of prestressing steel
A_s	Area of non-stressed steel
E	Young's Modulus
F_c	Compressive force at failure
F_t	Tensile force at failure
M_u	Ultimate bending moment
ε_m	Ultimate compressive strain of masonry
ε_{psa}	Strain in prestressing due to prestress
ε_{pse}	Strain in prestressing steel at failure due to applied loading
ε_{psu}	Strain in prestress steel at failure
ε_{su}	Strain in 'non-stressed' steel at failure
λ, λ_2	Stress block factors

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