The Flexural Stiffness of Brickwork Panels subjected to Vertical and Lateral Loads

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Summary - Wall panels of brickwork supported on three or more sides may be subjected to two way bending under the effects of non-central vertical loads or under lateral loads such as wind. The behaviour of such panels is influenced by variations in flexural stiffness that may occur as the brickwork becomes partly cracked under load. This paper presents the results of both theoretical and experimental studies of the flexural stiffness of brickwork under horizontal bending about axes parallel to the perpend joints.

1. INTRODUCTION

Rectangular wall panels of brick masonry supported on three or four sides are frequently subjected to two-way bending by the effects of lateral loads such as wind or by non-central vertical loads acting in the plane of the wall. Some walls may be required to carry these two load types in combination. In two way bending, cracking occurs in both the horizontal bed joints and also the vertical perpend joints if the tension stresses in the joints exceed the tension strength of the mortar or the bond strength of the brick-mortar interface. The presence of cracking in a wall reduces its effective flexural stiffness so that the load-deformation behaviour and the ultimate strength for a cracked wall are significantly different from those for an uncracked wall.

The analysis of cracked walls supported only at the top and bottom acting in one-way vertical bending has been considered by a number of authors(1) and a method(2) proposed for allowing for the discrete cracks that may occur on the bed joints. Lawrence and Morgan(3) conducted a series of experimental investigations on the behaviour of brickwork in horizontal bending and found that the change in stiffness was a well defined proportion of the original stiffness. This change was attributed to partial cracking of the perpend joints. Base and Baker(4) studied the flexural behaviour of brickwork panels in horizontal bending and also noted from their experimental results that a distinct change in stiffness occurred during the application of the load. No analytic methods were found to describe the observed behaviour. In this investigation, a numerical model has been developed to predict the behaviour of brickwork in horizontal bending. The method allows for the formation of discrete flexural cracks at the joints and the theoretical results have been checked against experimental observations made on a series of test walls.

2. THEORETICAL ANALYSIS

The arrangement of bricks and mortar in conventional stretcher bond is shown in figure 1(a). If the panel is subjected to uniform bending, a small volume of the panel, defined by planes A_{12} A_{34}, B_{12} B_{34}, C_{12} C_{34} and D_{12} D_{34} and referred to as a panel module, may be used to analyse the behaviour of the whole panel (figure 1(b)). The dimensions of the panel module given in figure 1(b) refer to the particular bricks used in the experiments described later in the paper. It may be assumed that shear bond on the brick-mortar interfaces transfers shear forces across the bedjoint and perpend mortars. For walls carrying vertical compression the tensile bond between the brick and mortar components is taken as zero to represent the wall behaviour after the formation of cracks.

The extent of cracking on the bedjoints depends on the eccentricity of the vertical force resultant[2]. Brickwork panels may be partially cracked on the bedjoints and may also be cracked on the perpends because of tensile bond failure due to horizontal bending. The stiffness of such brickwork has been investigated by the finite element method in which the panel module is subdivided into twenty-node isoparametric three-dimensional elements.

Initially, the finite element method was used to calculate the flexural stiffness of uncracked brickwork subjected to horizontal bending. It was assumed that the plane boundaries A_{12} A_{34}, B_{12} B_{34}, C_{12} C_{34} and D_{12} D_{34} of the panel module remained plane during bending. Planes C_{12} C_{34} and D_{12} D_{34} were rotated about vertical axes through the centre plane of the wall by prescribing the displacements of all finite element nodes on those planes. Planes A_{12} A_{34} and B_{12} B_{34} were restrained against out-of-plane translation (figure 2). The bending moment required to achieve the prescribed end rotations was calculated from the reactions at the finite element nodes on planes C_{12} C_{34} and D_{12} D_{34}. Because there are no resultant forces parallel to the bedjoint on the planes C_{12} C_{34} and D_{12} D_{34}, an effective flexural stiffness per unit height for the panel module is given by $(EI)_p$ where

(1) $$(EI)_p = \left(\frac{M_p}{\theta_p}\right) . \left(\frac{L + p}{b + H}\right)$$

in which M_p is the resultant moment of the end forces on planes C_{12} C_{34} and D_{12} D_{34} about the middle surface of the panel

θ_p is the relative rotation of planes C_{12} C_{34} and D_{12} D_{34}

L is the brick length

H is the brick height

b is the mortar bedjoint thickness

p is the mortar perpend thickness

A summary of calculated relative stiffnesses for selected brick:mortar modular ratios is given in Table 1 and figure 3.

Modular Ratio ($\frac{\text{Brick Modulus}}{\text{Mortar Modulus}}$)	Relative Stiffness (a)	
	Base and Baker(4)	Finite Element Method
1.0	1.00	1.00
2.0	0.92	0.94
4.0	0.83	0.85
5.0	0.80	0.83
10.0	0.67	0.73
20.0	0.51	0.62

(a) Bending Stiffness relative to brickwork with modular ratio 1·0

TABLE 1 : Flexural Stiffness of Brickwork Subject to Horizontal Bending

The differences between the finite element results and those obtained by Base and Baker may be attributed essentially to the assumption in the latter work that plane sections remain plane and hence that brickwork subject to horizontal bending deforms into a cylindrical circular surface. The finite element analysis showed, however, that brickwork does not deflect into such a cylindrical shape and that significant twisting moments and shear stresses may exist on the bedjoints, particularly for modular ratios greater than 5·0.

Tensile bond failure on the perpends was simulated by uncoupling element modes on the brick mortar interfaces wherever normal tensile stresses could occur. As in the previous analyses, planes A_{12} A_{34}, B_{12} B_{34}, C_{12} C_{34} and D_{12} D_{34} were assumed to remain plane during bending. An approximate profile of the cracking in the perpends is shown in Figure 4. Relative stiffnesses of brickwork with cracked perpends, calculated using the finite element method and equation (1) are summarized in Table 2.

Modular Ratio ($\frac{\text{Brick Modulus}}{\text{Mortar Modulus}}$)	Relative Stiffness[(a)] (Finite Element Method)
1.0	0.768
2.5	0.766
10.0	0.765

(a) Bending stiffness of cracked brickwork relative to uncracked brickwork with same modular ratio

TABLE 2 : Flexural Stiffness of Brickwork Cracked on Perpends Only

The brickwork module was also analysed with simultaneous cracking on the perpends and cracking on the bedjoints caused by an eccentric vertical load (figure 4). For simplicity, the cracking on the bedjoints was assumed to occur on the same panel face as the cracking on the perpends. The finite element program was used to analyse brickwork with simulated cracked perpends and bedjoint cracking up to one-half the panel thickness. The relative flexural stiffnesses for horizontal bending of cracked brickwork, calculated for selected brick : mortar modular ratios, are shown in Table 3.

Relative Stiffness(a) - Finite Element Method			
Modular Ratio	Depth of Bedjoint Crack(b)		
$\left(\frac{\text{Brick Modulus}}{\text{Mortar Modulus}}\right)$	$d/6$	$d/3$	$d/2$
1.0	0.751	0.724	0.699
2.5	0.745	0.718	0.691
10.0	0.733	0.705	0.676

(a) Bending stiffness of cracked brickwork relative to uncracked brickwork with the same modular ratio

(b) Perpend and bedjoint cracks on same panel face

TABLE 3 : Flexural Stiffness of Brickwork Cracked on Perpends and Bedjoints

3. EXPERIMENTAL RESULTS

Six brickwork panels, each six bricks long by five courses high, were constructed to check the results summarized in Tables 1 and 2. All bricks were solid, nominally 230 mm × 110 mm × 65 mm, and laid on-edge to give the panels a height-to-thickness ratio of 9·1. The mortar was 1 cement : 1 lime : 6 sand by volume with a water-to-cement ratio of 1·41 by weight. All panels were cured in polythene sheeting for 21 days and subsequently were cured in ambient conditions.

The mean brick elastic modulus was measured to be $21{\cdot}1 \times 10^3$ MPa with a coefficient of variation of 4·9 percent and the mean mortar modulus at low stress was $12{\cdot}3 \times 10^3$ MPa with a coefficient of variation of 5·4 percent. The mean brickwork compressive strength normal to the bedjoints was 50·0 MPa (coefficient of variation 3·0 percent).

Each panel was set up in the test apparatus shown in figure 5 so that a vertical axial load could be applied simultaneously with a uniform horizontal bending moment. The out-of-plane displacements of the panel were measured using displacement transducers connected to a multi-channel computer-based logger which enabled the automatic calculation of the curvatures in horizontal planes at the top, centre and base of the panel.

Initially, with no vertical load on the panel, horizontal bending was applied incrementally without cracking the perpends. The three

calculated curvatures at each moment increment were found to be within 5 percent of one another, with the moment-curvature relationship being linear as shown in figure 6(a). The panel was then subjected to horizontal bending together with average vertical axial stresses of either 1·3 MPa (figure 6(b)) and 2·6 MPa (figure 6(c)). The results showed that the moment-curvature relationships were independent of the applied vertical stress and that the mean effective stiffness of the brickwork was 295×10^9 Nmm^2, with a coefficient of variation of 4·7 percent. The stiffness calculated by the finite element method (Equation (1) and Table 1) was approximately 280×10^9 Nmm^2, only 5 percent less than the experimental value.

Each panel was then loaded so that horizontal bending caused cracking to occur in the perpends. The moment-curvature relationships, shown typically in figure 7, are summarized for the six panels in Table 4, in which the slope of each graph has been taken as a measure of the flexural stiffness.

Panel No.	Ratios of Slopes from Moment-Curvature Graphs [a]		
	Slope 2 : Slope 1	Slope 3 : Slope 1	Slope 4 : Slope 1
1	0.65	0.86	0.81
2	0.70	0.79	0.78
3	0.67	0.89	0.84
4	0.85	0.76	0.78
5	0.68	0.78	0.77
6	0.66	0.90	0.88
Mean	0.70	0.82	
c.v. (%)	10	21	

(a) Definition of Slopes 1 to 4 is shown in figure 7

TABLE 4 : Relative Horizontal Stiffnesses of Brickwork Panels

A one-way analysis of variance shows that the stiffness ratios Slope 3 : Slope 1 and Slope 4 : Slope 1 are statistically from the same population, but are different from the ratios Slope 2 : Slope 1. The difference may be explained by an observed non-elastic behaviour in which the perpend cracks appear not to close completely on unloading (figure 7). It is also significant that for the first loading, the panels were loaded from the uncracked to the cracked condition whereas for the subsequent tests, the panels were cracked throughout the entire loading range. The computed stiffness ratio of 0·77 (Table 2) compares favourably with results given in Table 4, especially with the entries in the last two columns. This close correlation may be attributed to the fact that the assumption of zero tensile bond made in the calculations corresponds more closely with the behaviour of a panel with pre-existent perpend cracks than with that for a panel which is initially uncracked. It should be noted also that the experimentally-derived ratio of approximately 0·57 proposed by Lawrence and Morgan[3] differs from the results summarized in Tables 2 and 4, but their tests were conducted on panels of brick laid on flat with a geometry markedly different

from that of the panels in the present investigation.

4. CONCLUSIONS

For brickwork panels carrying two way bending, the flexural stiffnesses for horizontal and vertical bending depend upon the extent to which the mortar in the bedjoints and the perpend joints is cracked under load. Numerical modelling of the particular combination of bricks and mortar investigated in this study indicated that for walls carrying axial precompression in the vertical direction, the flexural stiffness in horizontal bending was only 77 per cent of the uncracked stiffness. This value has been confirmed by a series of tests on experimental walls. The reduced stiffness is relatively insensitive to the effects of moderate vertical axial precompression, but further reductions in stiffness may occur if the precompression is eccentric with respect to the wall centreplane. Reductions in stiffness are also dependent upon the geometrical configuration of the bricks and the mortar as well as the material properties. Research is now in hand to assess the significance of stiffness reductions in relation to the load capacity of complete wall panels carrying both vertical and lateral loads.

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[4] G.D. BASE, L.R. BAKER: "Fundamental Properties of Structural Brickwork". Journal of the Australian Ceramic Society, Vol. 9, No. 1, May 1973.

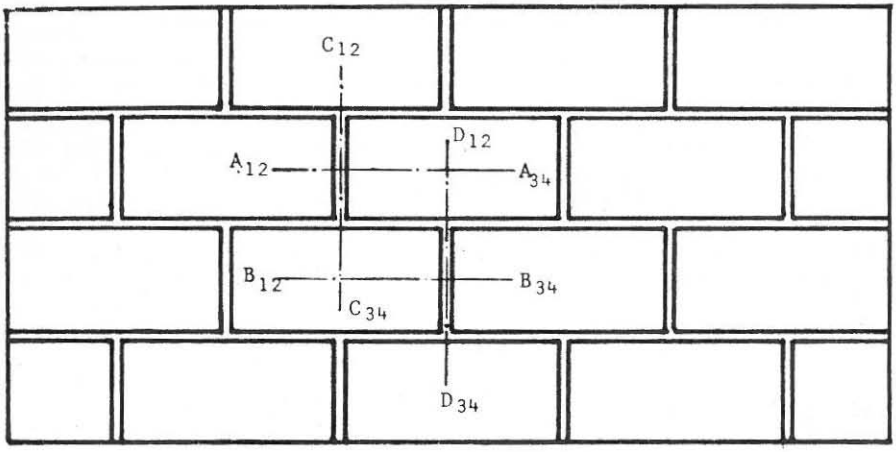


Figure 1(a). Elevation of Panel

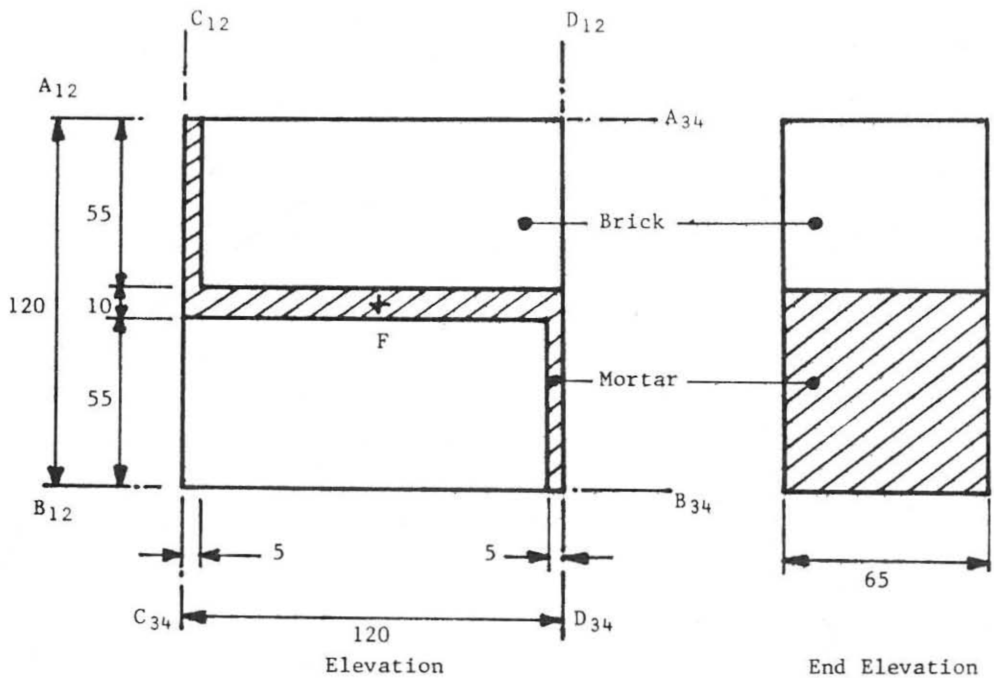


Figure 1(b). Details of Panel Module

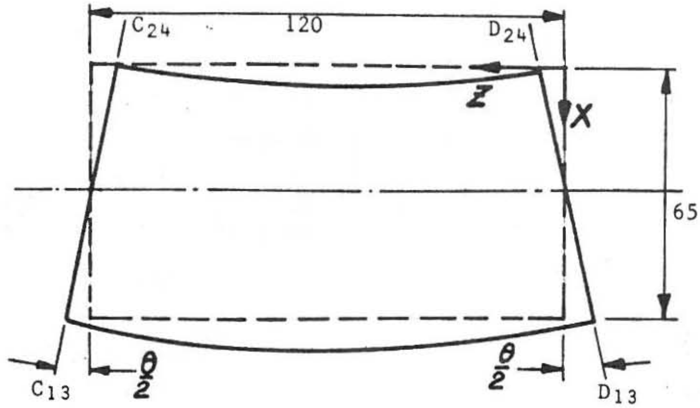


Figure 2. Plan View of Panel Module Showing Horizontal Bending

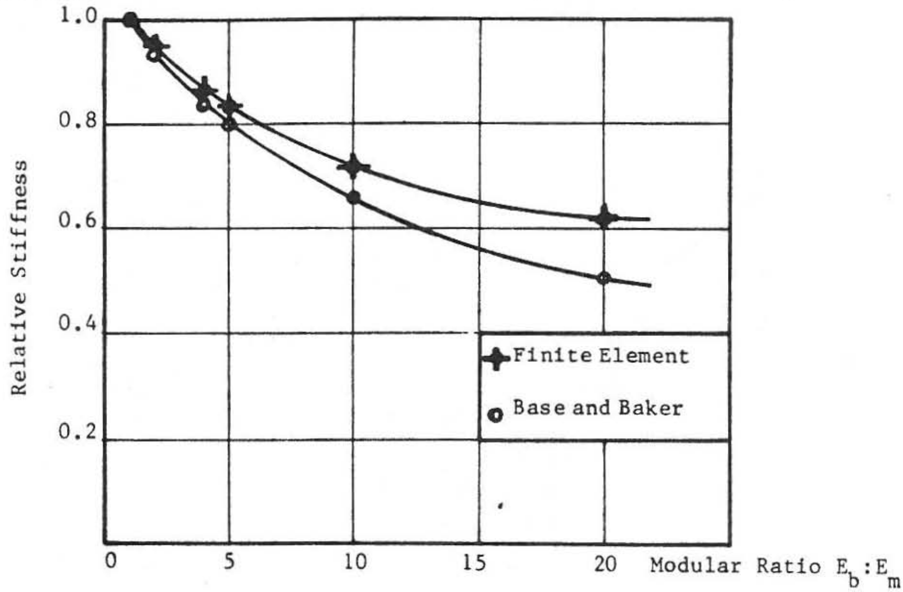


Figure 3. Flexural Stiffness Relative to Stiffness of Brickwork with Modular Ratio 1·0

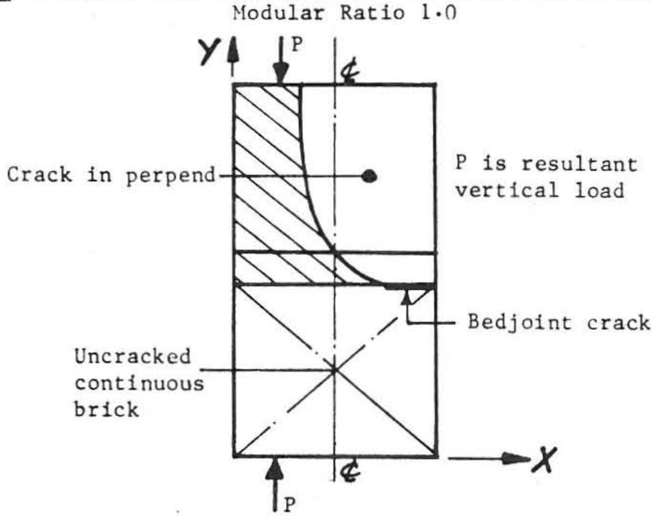


Figure 4. Crack Profile in Perpend

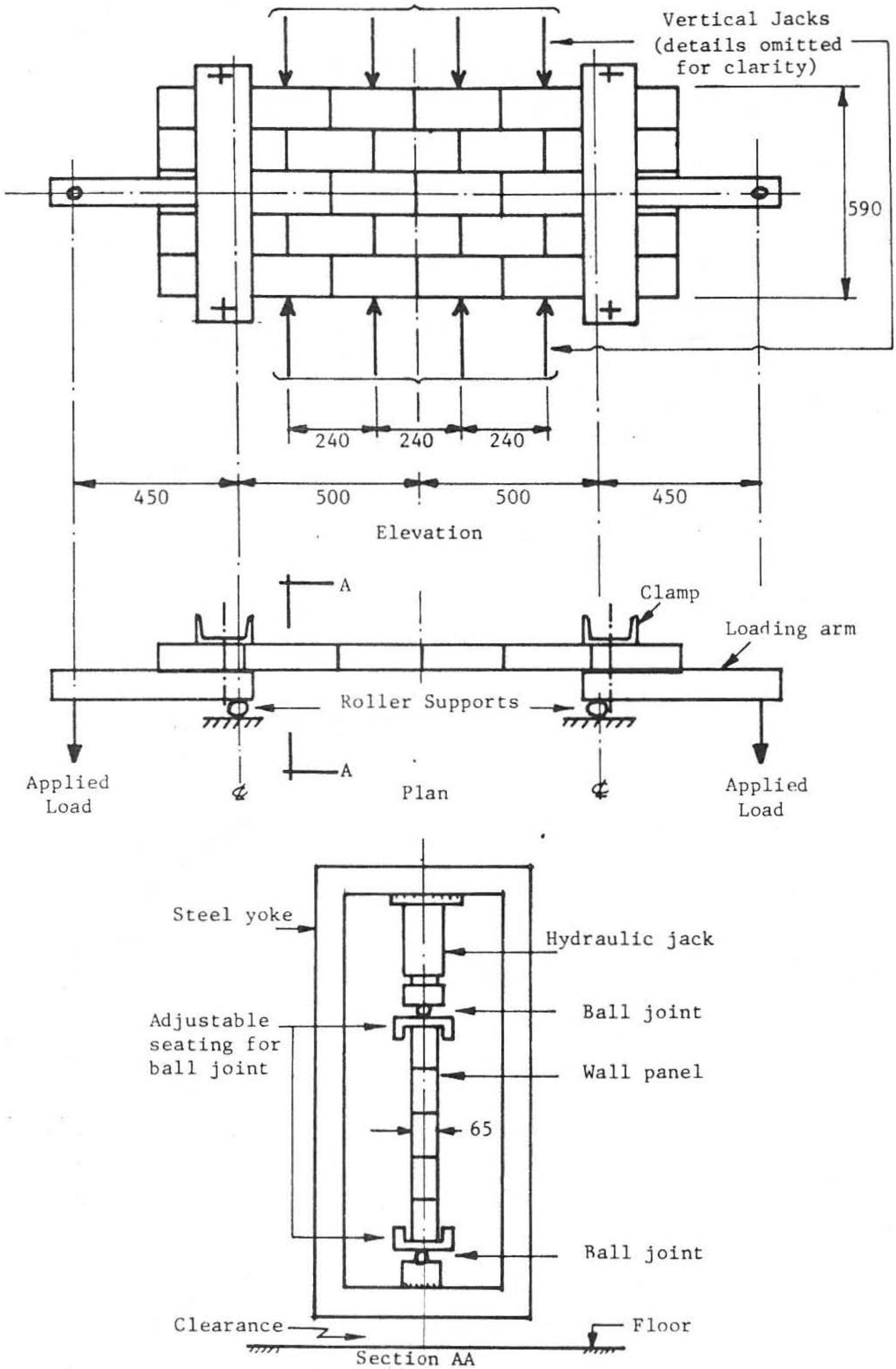


Figure 5 : Test Apparatus for Wall Panels

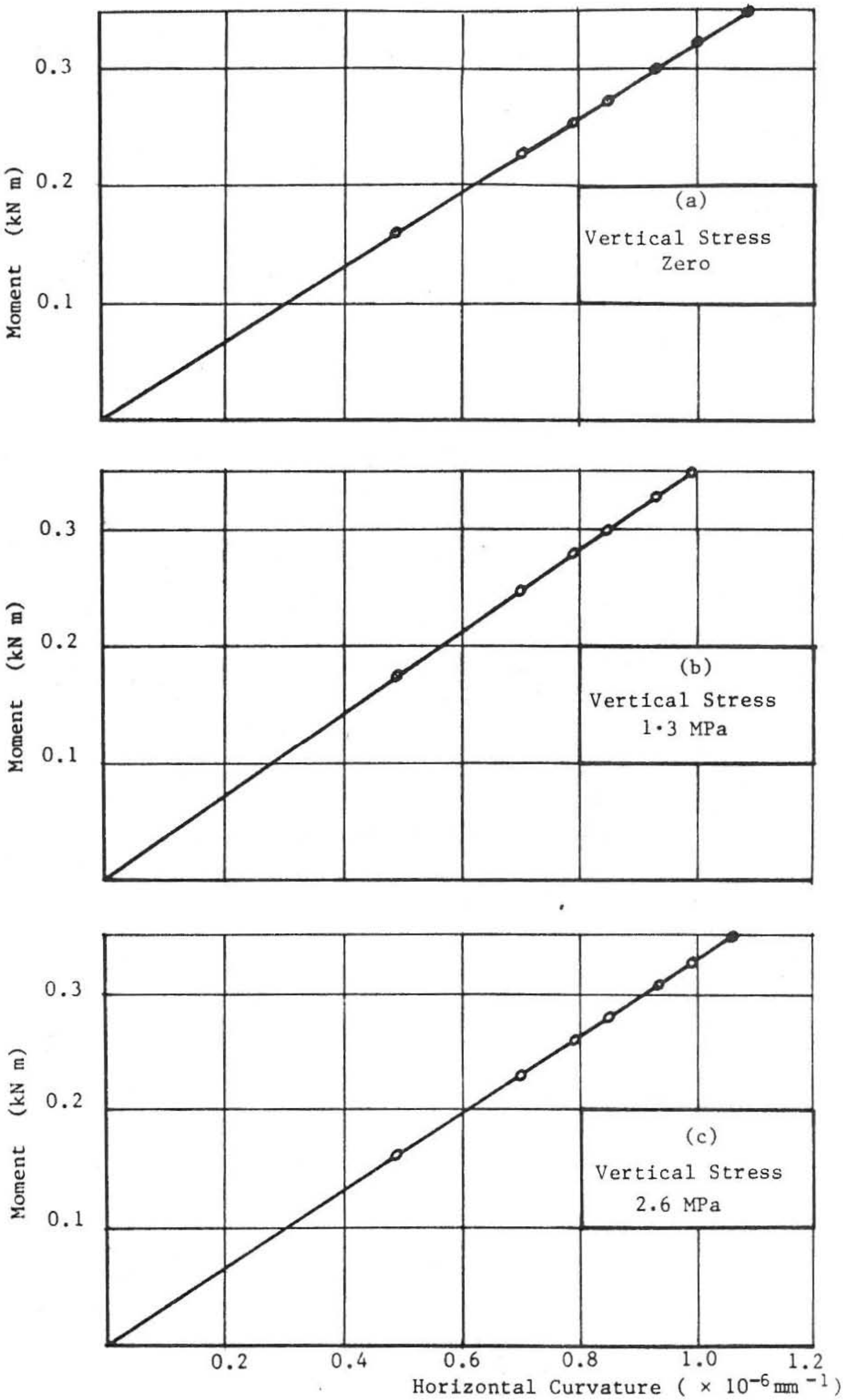
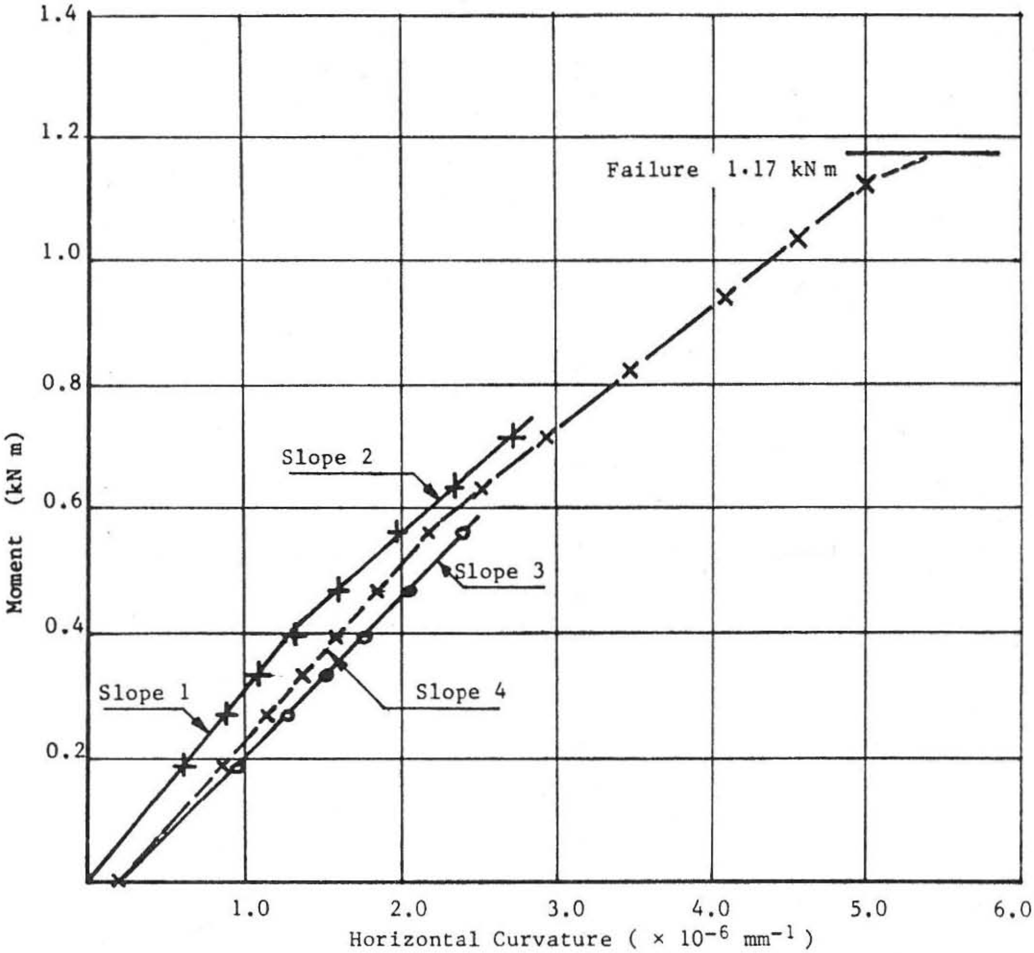


Figure 6 Moment Curvature Relationships for Uncracked Brickwork



First Loading
- + Slope 1 - Uncracked; Vertical stress 2·6 MPa
- + Slope 2 - Cracked perpends; Vertical stress 2·6 MPa

Second Loading
- o Slope 3 - Cracked perpends; Vertical stress zero

Third Loading
- × Slope 4 - Cracked perpends; Vertical stress 2·6 MPa; Load to failure

Figure 7 Moment Curvature Relationships for Cracked Perpends