An Experimental Investigation of the Biaxial Strength of Brick Masonry

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SUMMARY

Masonry is a material which exhibits distinct directional properties because the mortar joints act as planes of weakness. To define failure under biaxial stress, a three-dimensional surface in terms of the two principal stresses and their orientation to the bed joints is required. This paper describes an experimental investigation which determines this failure surface. Biaxial tests were performed on half-scale brickwork panels with the principal stresses oriented at various angles to the bed joints. Failure surfaces were obtained for biaxial compression and biaxial tension - compression. These surfaces are described and discussed.

1. INTRODUCTION

Almost all masonry walls subjected to in-plane loads are in a state of biaxial stress; for example, shear walls, infill walls, walls supported on elastic foundations and beams etc. In recent years there has been considerable research on the in-plane behaviour of masonry. The principal aim of this research has been to produce suitable design information for codes of practice. The resulting rules tend to be based on empirical relationships established from tests on structural elements. Very little emphasis has been placed on the development of a fundamental theory of failure which could be applied to any case of in-plane loading. The advent of computer based numerical techniques has made the need for this information more pressing, since the definition of local failure is of prime importance in realistically modelling masonry behaviour.

Masonry exhibits distinct directional properties due to the influence of the mortar joints acting as planes of weakness. Its failure cannot therefore be defined simply in terms of a criterion based on the principal stresses at any point. The influence of a third variable, the bed joint orientation relative to the principal stresses, must also be considered. Depending upon the orientation of the joints to the applied stresses, failure can occur in joints alone, or in some form of combined mechanism involving the mortar and the masonry unit.

Thus, to completely define masonry failure, a three-dimensional failure surface in terms of the principal stresses σ_1 and σ_2, and their respective orientations to the bed joint, θ and $90° + \theta$, is required. To derive this surface, tests must be performed to cover the compression - compression, compression - tension and tension - tension principal stress domains. In practice, the most critical regions are those of tension - compression and compression - compression.

This paper describes an investigation into the biaxial strength of half-scale brick masonry aimed at developing a (σ_1, σ_2, θ) failure surface for all principal stress combinations. This involved biaxial tests on square panels of brickwork with varying principal stress ratios and bed joint orientations. Previously reported results for the compression - compression principal stress region are summarized, and preliminary results for the tension - compression region presented.

2. PREVIOUS RESEARCH

Researchers have long been aware of the significance of joint orientation to the applied stress. Johnson and Thompson [1] carried out diametral tests on brick masonry discs to produce indirect tensile stress on joints inclined at various angles to the vertical compressive load. Similar tests on grouted and ungrouted concrete masonry have been reported by Drysdale et al [2]. The influence of bed joint orientation has also been shown in many investigations carried out into shear wall behaviour [3].

There have been few attempts to obtain a general failure criterion for masonry because of the difficulty in developing a representative biaxial test as well as the large number of tests involved. The problem has been qualitatively discussed by Yokel and Fattal [4] and Hendry [5]. Samarasinghe and Hendry [6] obtained a (σ_1, σ_2, θ) failure surface for the tension - compression principal stress range from a limited number of tests on one-sixth scale brickwork. A failure surface for brickwork in the tension - tension principal stress region has been derived analytically by Page [7]. The shape of both these failure surfaces was found to be critically dependent on the bed joint orientation and the relationship between the shear and tensile bond strengths of the joints.

The influence of joint orientation has been found to be less significant for grouted concrete masonry. From a series of biaxial tests on full-scale grouted concrete masonry (both reinforced and unreinforced), Hegemier et al [8] found the influence of the bed joint angle to be minimal and the behaviour essentially isotropic. However, this isotropy could be destroyed by non-judicious selection of block and grout strengths.

No previous studies of the compression - compression principal stress regions have been reported. This is despite the fact that biaxial compression failure can have important practical significance, particularly in predicting crushing failure near the toe of shear walls.

3. BIAXIAL TESTING PROGRAMME

The following is a brief description of the experimental procedures used in the biaxial tests. The experimental apparatus is described in greater detail elsewhere [9].

3.1 Brickwork

All biaxial tests were carried out on 360 mm square, half-scale brickwork panels constructed in stretcher bond. The brickwork was manufactured from half-scale bricks sawn from the cross section of pressed paving bricks, and 1:1:6 mortar (cement:lime:sand, by volume). The properties of the brick, mortar and resulting brickwork, as determined from the standard tests defined in AS 1640, SAA Brickwork Code [10] are summarized in the Appendix. Previous work has shown that scale effects are negligible [11].

To minimise the effects of workmanship, all panels were constructed horizontally on a rigid form with the bricks being glued to a perspex backing sheet to ensure a constant joint thickness. Panels were manufactured with varying bed joint angles by cutting individual bricks to the shape required. Due to their high suction value, the bricks were soaked and drained before pouring the mortar joints. The mortar was then poured into joints and thoroughly compacted. The hardened panels were stripped, cured for twenty-seven (27) days and left to air dry for twenty-four (24) hours before testing.

A preliminary study was carried out on the bond characteristics of the brickwork, as previous research has shown that these can critically influence the shape of the failure surface [6,7]. The seven day shear and tensile bond strengths were determined from triplet and couplet tests respectively. The mean shear and tensile bond strengths from six tests of each type were 0.30 MPa and 0.13 MPa respectively. The ratio of shear to tensile bond strength was thus 2.31 - a value typical for brickwork.

3.2 Testing Rig

The testing rig is shown in Fig. 1. A biaxial stress state was induced in the panel by loading with hydraulic jacks in orthogonal directions. A constant load ratio was maintained during each test by means of the spreader beam. The load in each direction was monitored by load cells immediately adjacent to the specimen.

To minimize the effects of platen restraint and thus ensure a more uniform state of stress in the panel, steel brush platens were used on the four bearing surfaces of the specimen. With brush platens, the load is applied through a series of slender filaments which individually possess a very low resistance to lateral movement while still being able to transmit their proportion of axial load without buckling. Restraint against lateral expansion of the panel is thus kept to a minimum. In this case the filaments were 4 mm square, 140 mm long, with a 2 mm clear spacing in each direction. A study of the effectiveness of the brushes has been previously described [9].

In all tests, strains were measured in three directions on each side of the panel using displacement transducers mounted on a gauge length of 270 mm.

4. BIAXIAL COMPRESSION TESTS

A total of 102 panels was tested. Ratios of vertical compressive stress σ_1 to horizontal compressive stress σ_2 of infinity (i.e. uniaxial σ_1), 10, 4, 2 and 1 were used in conjunction with a bed joint angle θ with respect to the σ_1 direction of 0°, 22.5°, 45°, 67.5° and 90°. Principal stress ratios of 0.5, 0.25, 0.1 and 0 (i.e. uniaxial σ_2) were obtained from the results using the symmetry of the panels and the loading. A minimum of four tests were performed for each combination of σ_1, σ_2 and θ.

4.1 Failure Mode

Two distinct failure modes were observed depending on the principal stress ratio. Typical examples are shown in Fig. 2.

For uniaxial compression, failure occurred in a plane normal to the plane of the panel. Depending upon the orientation of the bed joint to the applied load, failure occurred by cracking and sliding in the bed and/or header joints, or in a combined mechanism involving cracking in both brick and joint. In the case of

uniaxial compression parallel to the bed joint (i.e. $\sigma_2 = 0$, $\theta = 0°$), failure initially occurred by splitting in the vertical bed joints due to lateral spreading of the panel. The resulting columns of brickwork were capable of sustaining further load, and final collapse of the panel occurred at a higher load level. In the results, initial splitting of the bed joints was taken as failure, as this was consistent with the modes of failure for other bed joint angles.

For biaxial compression, the above failure mode was prevented by the presence of the second principal compressive stress, and failure occurred by splitting in in a plane parallel to the free surfaces of the specimen at mid-thickness, regardless of bed joint angle. The splitting failure occurred suddenly in a brittle manner and often commenced at one of the loaded edges and propagated into the panel.

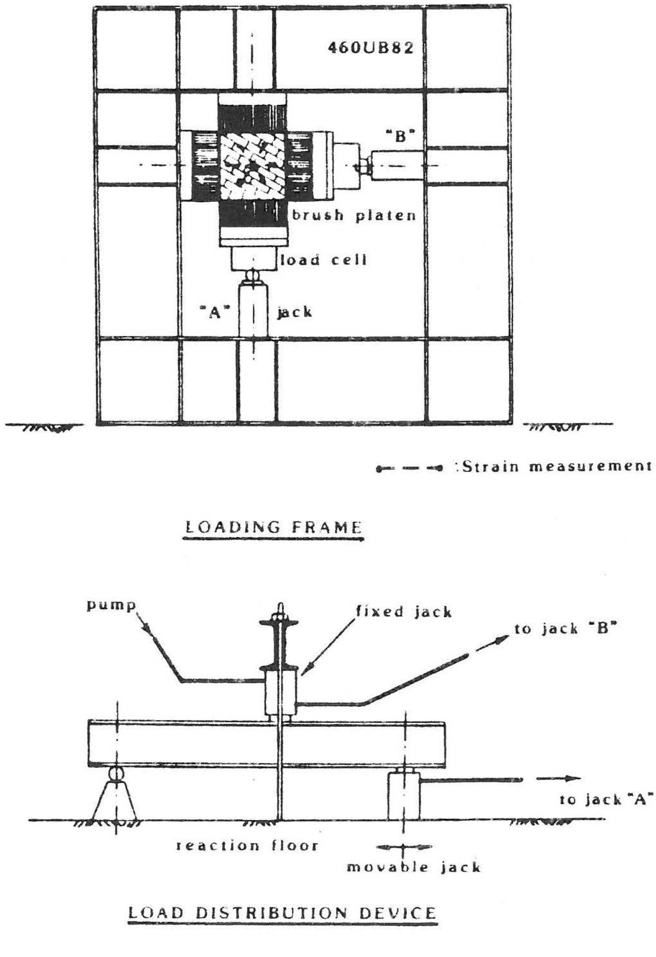

Fig. 1. - General Arrangement of Biaxial Tests

The transition between the failure modes shown in Figure 2 occurred at high σ_1/σ_2 ratios, with the bed joint orientation playing a significant role. For most angles, the transition occurred with the principal stress ratio in the order of 10:1, in a combined mechanism involving joint failure and lateral splitting.

4.2 Failure Surface

The failure surface obtained by plotting the mean curve for each bed joint angle is shown in Figure 3. These curves have been non-dimensionalised using the value of F'_m, the minimum ultimate compressive strength of six, four-high stack bonded piers as defined by AS 1640, SAA Brickwork Code [10]. This value was determined at half scale using the same construction and curing techniques as for the panels (see Appendix).

The deviation of results above and below these mean curves was not excessive. This was indicated by the ratio of the maximum to minimum failure stress determined for each principal stress ratio for all bed joint angles. The mean of these ratios was 1.21, with a coefficient of variation of 11%.

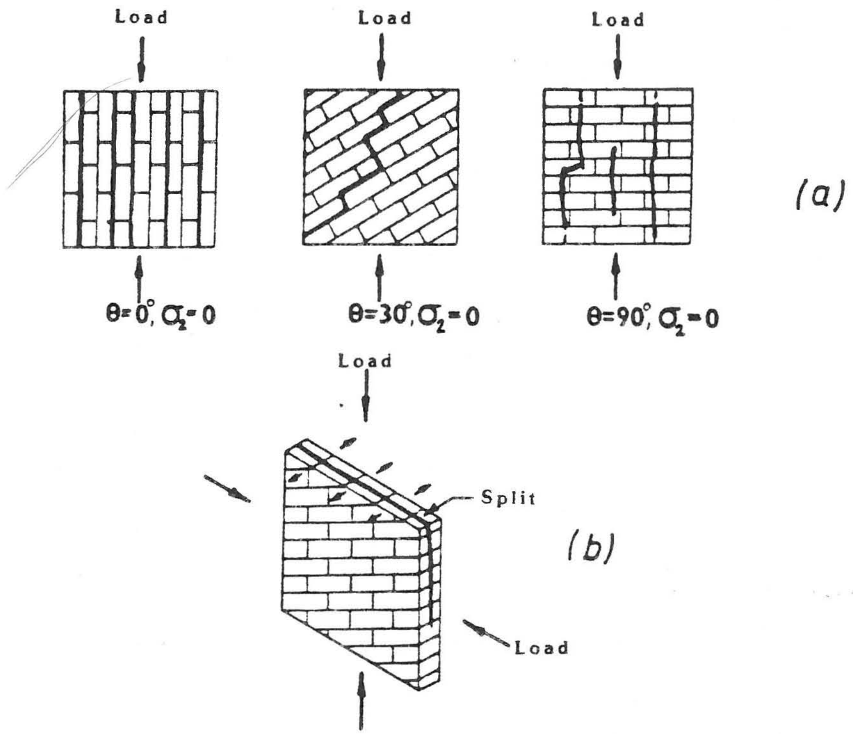

Fig. 2. - Failure Modes for Biaxial Compression Tests on Brickwork: a) Uniaxial Compression; b) Biaxial Compression

The surface projected onto the σ_1-σ_2 plane is shown in Fig. 4. For most values of σ_1 and σ_2 the bed joint angle exerted little influence on the strength. This was reflected in the failure mode discussed above, which was typified by splitting in a plane parallel to the free edges of the specimen. As this type of failure was not significantly influenced by the joints, it is reasonable to assume that the mortar type and joint bond strength should not exert a significant influence.

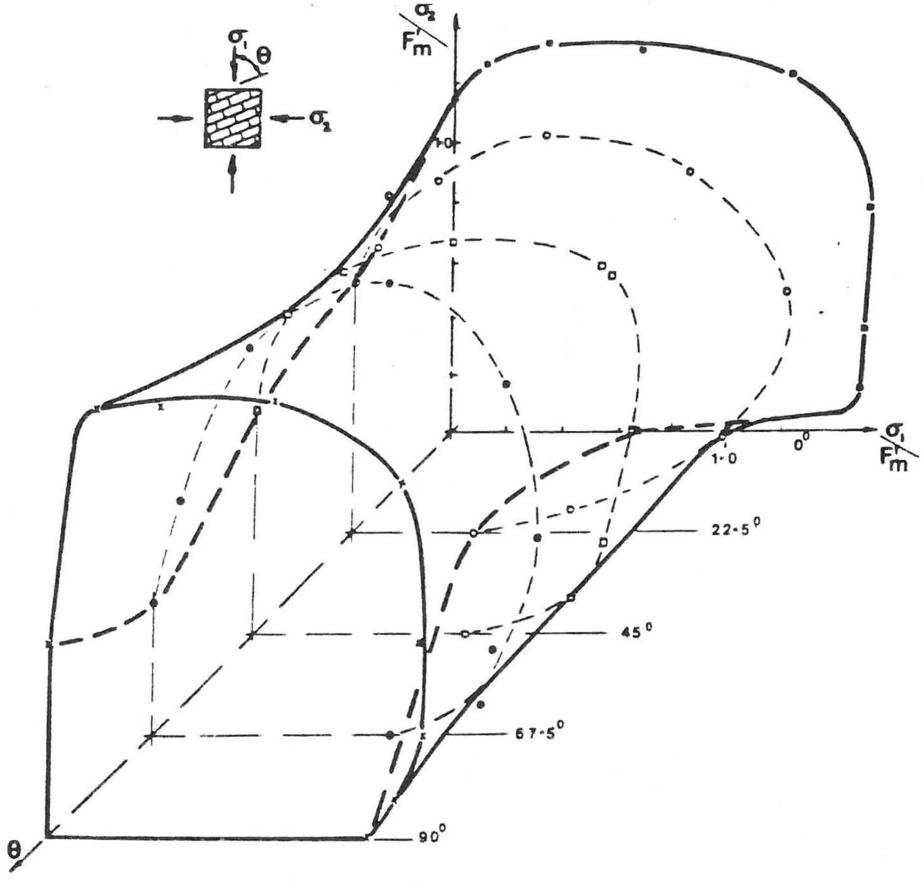

Fig. 3. - Failure Surface for Half-Scale Brickwork Under Biaxial Compressive Stress

When one principal stress dominated, however, the bed joint orientation markedly influenced the strength, with failure occurring in a plane (or planes) normal to the plane of the specimen. When failure occurred by sliding down a bed joint (e.g. $\sigma_2 = 0$, $\theta = 22.5°$), the strength of the panel was greatly reduced. With these failures; the mortar type and bond characteristics will play a significant role.

It can also be seen from Fig. 4 that the uniaxial panel strength with $\theta = 90°$ underestimates biaxial failure for most principle stress ratios, regardless of bed joint orientation. The minimum ultimate compressive strength F'_m gives an even more conservative estimate of biaxial compressive strength for most σ_1/σ_2 ratios.

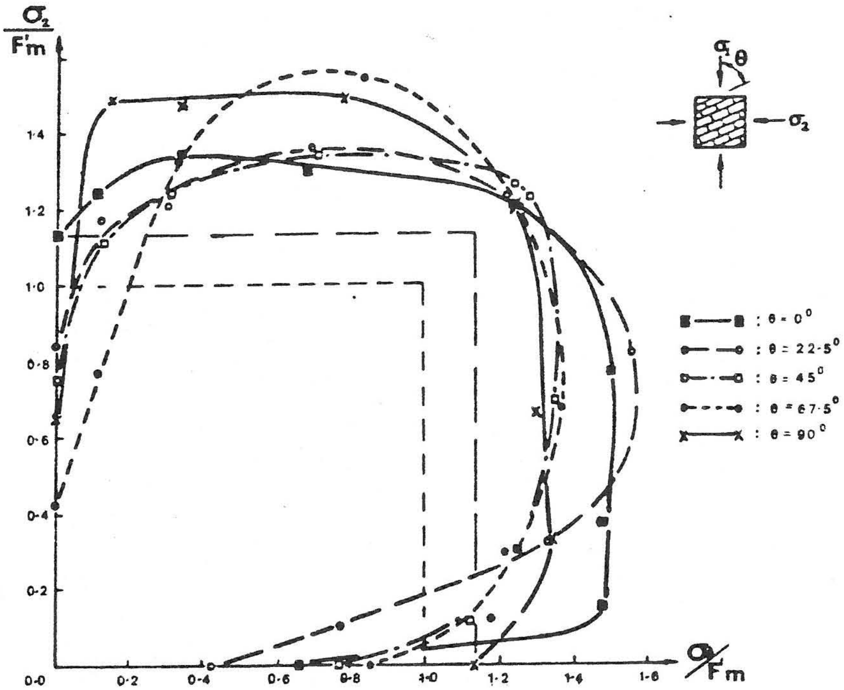

Fig. 4. - Failure Surface for Brickwork Under Biaxial Compression Projected onto σ_1 -σ_2 Plane

5. BIAXIAL TENSION-COMPRESSION TESTS

The tests in the tension-compression principal stress region are still in progress. However, sufficient data is available to allow preliminary results to be presented. More detailed results will be published in the near future.

A total of 89 panels have been tested. Ratios of horizontal compressive stress σ_2 to vertical tensile stress σ_1 of 5, 10 and 30 as well as uniaxial tension and compression, have been used, in conjunction with a bed joint angle θ (with respect to the tensile loading (σ_1) direction) of 0°, 22.5°, 45°, 67.5° and 90°.

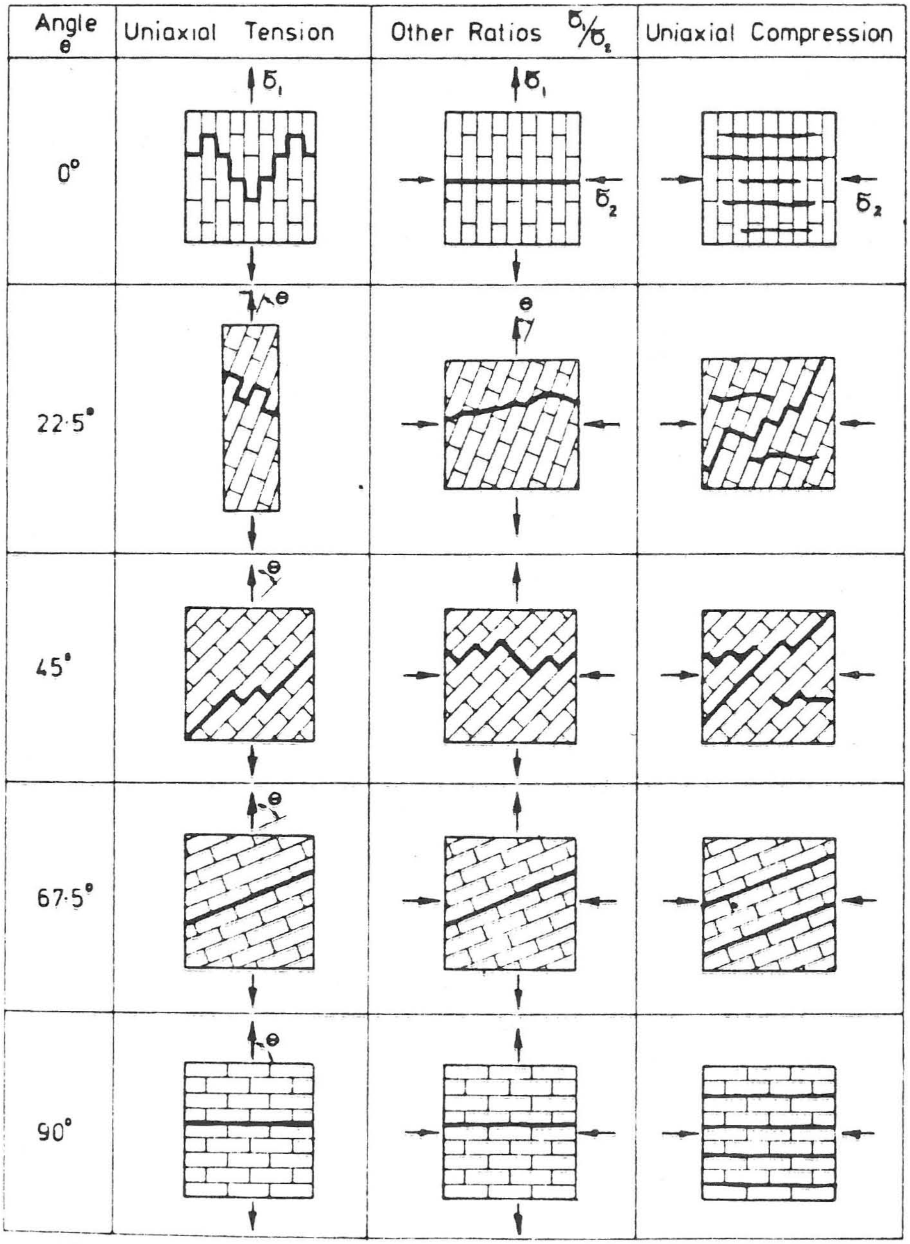

Fig. 5. - Failure Modes for Biaxial Tension-Compression Tests on Brickwork

The procedure for manufacturing and testing the brickwork panels was the same as that for the biaxial compression tests. The same biaxial testing arrangement was used, with minor modifications to the hydraulic jack arrangement to apply the tensile load. For uniaxial tests on specimens with a steep bed joint (i.e. θ = 22.5°), a longer specimen was used to ensure that several full bed joints intersected the free edges of the specimen. All tensile loads were applied by gluing the brush platens to the ends of the specimen with an epoxy cement. Thin walled hollow plastic tubing was inserted between the brush filaments before gluing to prevent the epoxy penetrating the brushes, and consequently allowing lateral movement of individual filaments during the test.

A minimum of three tests were performed for each combination of σ_1, σ_2 and θ. Strains were measured on each side of the specimen as for the biaxial compression tests.

5.1 Failure Mode

In contrast to the biaxial compression tests, failure occurred in a plane (or planes) normal to the plane of the panel in all cases. The typical failure modes for the various bed joint angles and principal stress ratios are summarized in Fig. 5. It can be seen that both bed joint angle and principal stress ratio considerably influenced the mode of failure. Failure occurred by cracking either in the joints alone, or in a combined mechanism involving both brick and joint. Failure occurred suddenly in a brittle manner in all cases.

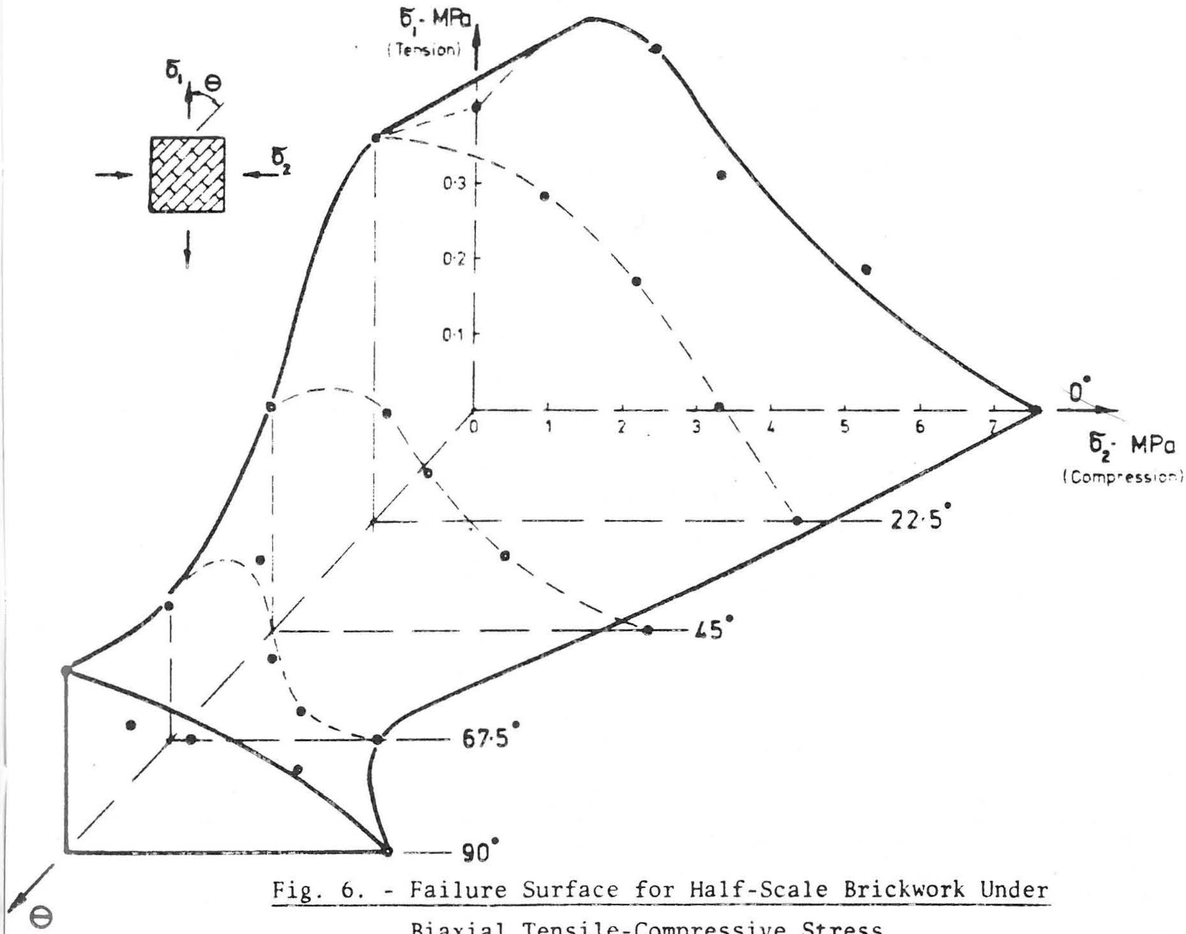

Fig. 6. - Failure Surface for Half-Scale Brickwork Under Biaxial Tensile-Compressive Stress

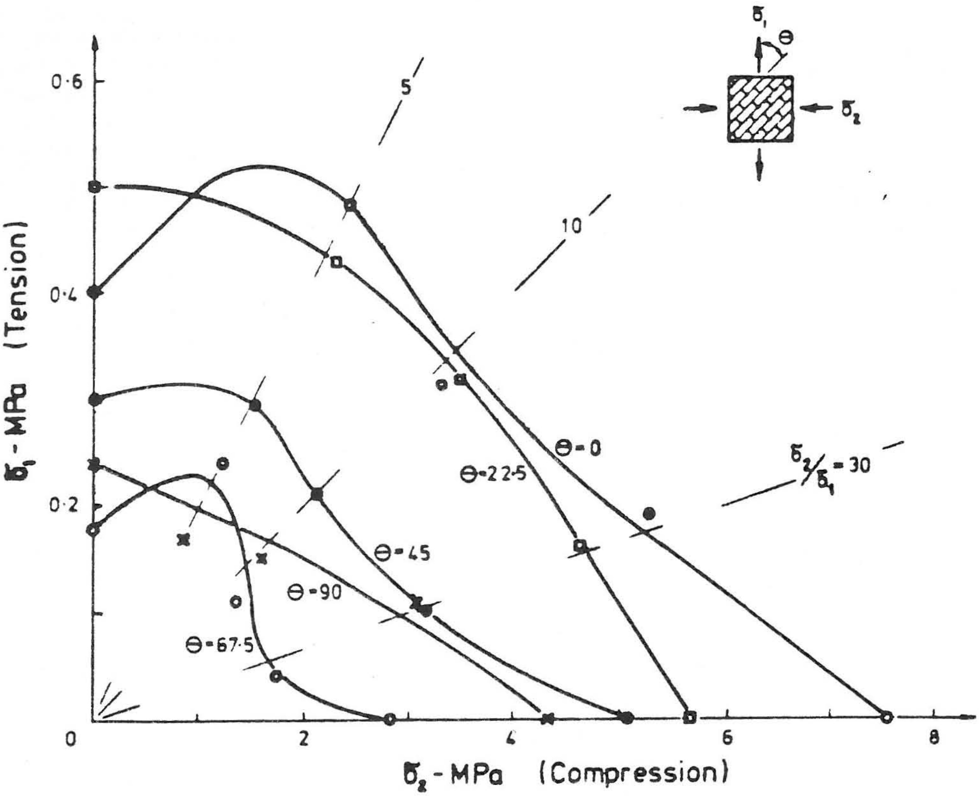

Fig. 7. - Failure Surface for Brickwork Under Biaxial Tension-Compression Projected onto $\sigma_1 - \sigma_2$ Plane

5.2 Failure Surface

The failure surface obtained by plotting the mean curve for each bed joint angle is shown in Fig. 6. The decrease in biaxial strength with increasing bed joint angle is evident. The increase in uniaxial compressive strength for $\theta = 90°$ compared to $\theta = 67.5°$ is caused by differing failure modes (for $\theta = 90°$, failure occurred by splitting parallel to the bed joints; for $\theta = 67.5°$, failure occurred by premature sliding down the steeply inclined bed joints). The scatter of results was greater than that for the biaxial compression tests, but still not excessive.

The increased scatter of results for the tension-compression tests is consistent with the different mode of failure. In contrast to biaxial compression, (where failure occurred by lateral splitting for most principal stress ratios), joint failures predominated in all cases. Random variations in joint strength will therefore play a more significant role particulary when tensile stresses are present on the joints.

The failure surface projected onto the $\sigma_1 - \sigma_2$ plane is shown in Fig. 7. Additional tests are being carried out to more fully define the shape of the curves particularly in the region $\sigma_1/\sigma_2 < 5$.

6. FAILURE DEFINED IN TERMS OF BED JOINT STRESSES

An alternative means of defining failure under biaxial stress is a criterion in terms of the stresses normal and parallel to the bed joints. This is part-

icularly relevant for brickwork, since most of the inelastic behaviour, (and often failure), occurs in the mortar joints. Also, the strength of panels under combined shear and compression is usually expressed in this form.

The stresses normal and parallel to the bed joints (σ_n and σ_p respectively), and the shear stress (τ) have been derived from the relevant values of σ_1, σ_2 and θ for both the biaxial compression and biaxial compression - tension tests. The resulting (σ_n, σ_p, τ) failure surface projected onto the σ_n - σ_p plane is shown in Figure 8.

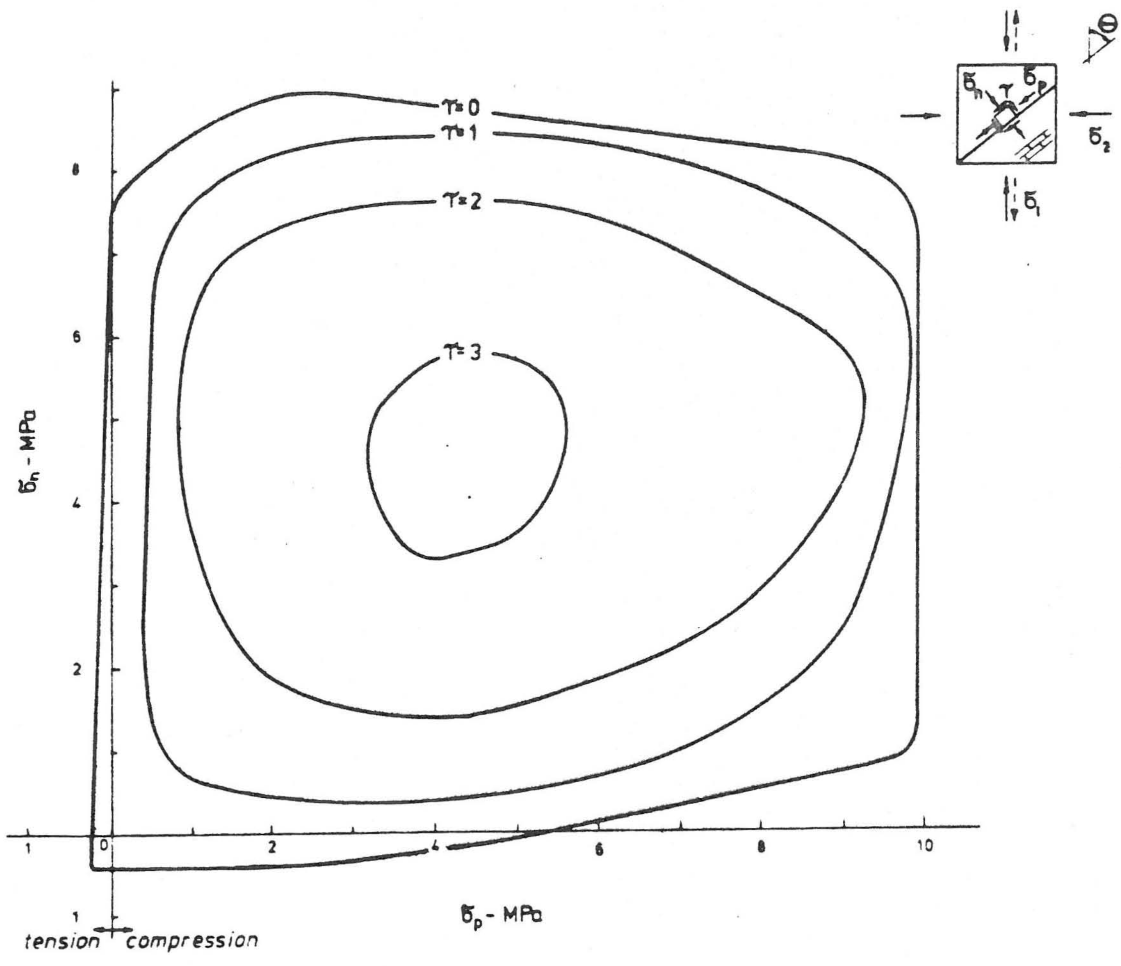

Fig. 8. - (σ_n - σ_p - τ) Failure Surface for Brickwork Projected onto σ_n - σ_p Plane

7. CONCLUSION

Masonry is a material which exhibits distinct directional properties due to the influence of the mortar joints acting as planes of weakness. To completely define failure, a three dimensional surface in terms of the principal stresses and bed joint orientation is required. Local failure in shear walls or panels subjected to uniaxial loads would represent particular points on this (σ_1, σ_2, θ) surface.

This paper has described a series of tests on half-scale brickwork aimed at developing a failure criterion for brickwork subjected to biaxial stress. Tests were performed on square brickwork panels with the principal stresses oriented at various angles to the bed joints. Brush platens were used to minimize the effect of platen restraint and to produce a more uniform biaxial stress field in the specimen.

Failure surfaces in terms of the two principal stresses and the bed joint orientation have been presented for biaxial compression and biaxial tension-compression.

For biaxial compression, the bed joint orientation did not play a significant role for most principal stress ratios, since a splitting failure occured in a plane parallel to the free surface of the specimen. However, when one principal stress dominated, failure occurred by cracking and sliding in the joints and/or bricks. For most principal compressive stress ratios, the uniaxial panel strength with the load normal to the bed joint underestimated the biaxial compressive strength, regardless of bed joint orientation.

For biaxial tension-compression, the bed joint orientation was critical for all principal stress ratios, since failure always occurred in planes normal to the free surface of the specimen. Depending on the joint orientation and principal stress ratio, failure occurred either in the joints alone or in a combined mechanism involving both brick and joint.

From the two distinct failure modes observed, it follows that variations in joint strength should not greatly influence the biaxial compressive strength, except when one principal stress predominates. However, joint strength will be an important parameter in the biaxial tension-compression stress region, since all failures are influenced by the joint properties and orientation.

8. ACKNOWLEDGMENTS

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10. APPENDIX

Properties of Brickwork, Bricks and Mortar

(Determined in accordance with the Australian Brickwork Code [10])

(a) Brick: Mean compressive strength of half scale bricks (12 tests) = 15.41 MPa
Coefficient of variation = 18%
Minimum ultimate compressive strength C = 11.82 MPa
Initial rate of absorption = 130 gm/25 000 mm^2/min

(b) Mortar: Mean compressive strength of 70 mm cubes (265 tests) = 5.08 MPa
Coefficient of variation = 11%

(c) Brickwork: Mean compressive strength $\bar{x}$ of four-high stack bonded piers = 9.85 MPa
Coefficient of variation = 9%
Range R = 2.48 MPa
Minimum ultimate compressive strength $F'_m = 0.75^* (\bar{x} - 0.38R)$
$= 6.68$ MPa

* The factor of 0.75 is applied to relate pier strength to wall strength.