Anisotropic Tensile Strength Characteristics of Brick Masonry

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SUMMARY

The tensile strengths of brick masonry are investigated under tensile loads having different orientations from the bed joint direction. Two different testing techniques were used; splitting and axial tension. The degree of anisotropy of masonry in the two orthogonal directions was studied for different mortar types. Correlations between the tensile strength normal, parallel and diagonal to the bed joints and the compressive strength were investigated. The results show that brick masonry strength is highly sensitive to the state of stress normal and parallel to the bed joint direction. The bond characteristics of the mortar are not directly related to its strength properties. It is also concluded that the diagonal tensile strength of masonry is not directly related to its compressive strength. A better correlation exists between the diagonal tensile strength and the average tensile strengths in the two orthogonal directions, normal and parallel to the bed joints.

1. INTRODUCTION

In-plane horizontal forces in combination with gravity loads on shear walls will produce tensile stresses at different orientations from the bed joint depending on the relative magnitudes of the horizontal and vertical forces. Because brickwork is a composite of strong bricks and weak mortars, it cannot be considered as an isotropic material and the concept of invariant state of stress is not applicable (9,12). For such an anisotropic material, the orientation of the tensile stresses from the bed joint is a function of the stress field and hence it should be considered for the assessment of strength (11,18). It is also suggested that the failure mode will be highly sensitive to the relative magnitudes of stresses in the two orthogonal directions, normal and parallel to the bed joint. It has been shown (8,9) that the bed joint is the weakest plane where failure by debonding will be initiated.

Numerous studies (3,4,10,11,14) on the tensile strength of brickwork have been done. Different test techniques using various shapes of specimens such as the racking test, the wallette test, the cantilever test, and the splitting test all were intentionally designed to force diagonal tension failure to occur. Because each test technique has different boundary conditions and a different stress field, no correlation exists between the different studies (6). Some investigators considered the diagonal tension capacity to be a constant value directly proportional to the square root of the masonry compressive strength. Proportionality constants ranging from 2.5 to 4.5 have been reported (6). This wide range is not surprising because the previously mentioned anisotropy of masonry results in it being highly sensitive to the stress field which varies for different test techniques.

It is the objective of this paper to discuss the anisotropic nature of masonry under tension using two different types of tests. Both the splitting tension test and the axial tension test provide means of creating different stress fields and different combinations of stresses along the joints. The comparative study illustrates the effect of the stress field on masonry tensile strength.

2. EXPERIMENTAL PROGRAM

2.1 Materials

The geometric and physical properties of the bricks used in the tests are presented in Table 1. Compressive strength was determined by testing sulphur capped half-bricks flatwise and full bricks endwise. The flexural tensile strength was determined from testing two brick long beams under two point loading where the bricks were epoxy glued end to end and tested flatwise.

The three mortar types used conform with CSA Standard A179-M1976 and have the proportions listed in Table 2. The water contents were established by the mason's requirements for suitable workability which resulted in an initial flow of about 115%. Three air cured 2 inch (51 mm) mortar cubes were used as control specimens for each batch. The average compressive strengths are also listed in Table 2.

2.2 Test Techniques and Test Specimens

Both test techniques accommodated application of tensile forces with different orientations from the bed joint direction. This facilitated study of the degree of anisotropy of masonry as a composite material. The splitting test technique adopted by Johnson and Thompson (11) was used. However a square shaped specimen for tension normal and parallel to bed joints and a hexagonal shape for diagonal tension were adopted instead of the common circular disks. An elastic finite element analysis (9) showed that these shapes gave almost the same transverse tension over the central height of the specimen as is given by the standard equation (11).

$$f_t = \frac{2P}{\pi A} \quad (1)$$

in which f_t = tensile strength; P = the failure load; and A = the area along the splitting plane. Therefore, it was convenient to avoid having to cut the specimens to approximate the circular shape. Figure 1 shows the test set up where the line loads that caused the splitting tension were oriented at 45^o (diagonal) to bed joint direction. The loads were applied to the specimen through 12 mm thick steel plates resting on 12 mm thick plywood strips. This avoided local crushing failure and direct wedging action at the mortar joint.

The other test technique used in this program is the axial tension test. Figure 2 shows the test set-up (for tension oriented at 45^o from the bed joints). To provide the specimens for tension at 45^o to the bed joints, prisms were cut at 45^o from large panels using a diamond saw. To apply the axial load, loading mechanisms were attached to both ends of the prisms. Each steel loading mechanism consisted of a threaded bar which was attached to a reinforced channel. This rested on the ends and had angles bolted to it, extending along the faces of the prisms as shown in Figure 2. An epoxy cement was used to bond the angles and the reinforced channel to the faces and ends of the prism. The mechanical connection could be adjusted to assure proper alignment of the specimen in order to minimize the eccentricity of the applied load.

Half bricks cut horizontally were used to fabricate specimens for tension parallel to the bed joint. This was necessary to provide equal cross sectional areas of the head joints and bricks.

3. DISCUSSION OF TEST RESULTS

3.1 Failure Modes

For the splitting tests, the typical failure for tension normal to the bed joint is mortar debonding as shown in Figure 3(a). For splitting tension parallel to the bed joints, debonding of the mortar along the head joints at alternate courses was accompanied by tensile failure of the brick in the other courses as shown in Figure 3(b). The failure plane for principal tension at 45° from the bed joints passed through the bricks and mortar joints in a nearly direct path between the loading plates. A typical pattern of failure is shown in Figure 3(c).

For the axial tension tests, the failure modes for tension normal and parallel to the bed joints were similar to those observed for the splitting tests. Figures 4(a) and 4(b) are photographs of typical failures. However for tension oriented between 15° and 75° from the bed joints, the failure under axial tension was always by debonding along combinations of the bed and head joints, a typical example of which is shown in Figure 4(c) for tension at 30° from the bed joints. Thus, there were no signs of the failure in the bricks as had been the case for splitting tension at 45° from the bed joints. This change in the failure mode is attributed to the different stress fields associated with the two test techniques. For the splitting test, when tension is oriented at 45° from the bed joints, the bed joint is under shear along the joint combined with compression normal to it (11) which increases the shear strength due to friction (7). This forces the tension failure to occur in the bricks rather than by shear-debonding around the bricks. For axial tension the bed joint is under shear along the joint combined with tension normal to it which causes debonding failure to occur at lower levels (1).

The difference between the failure modes for the two test techniques serves to emphasize the anisotropic nature of masonry and to indicate the importance of the stress field. This illustrates the significance of the type of test used to attempt to provide data to predict the behaviour of the walls.

3.2 Tensile Strength of Masonry

Table 3 contains the summary of the test results for principal tension oriented at angle θ of 0°, 45°, and 90° from the bed joint direction. Both the splitting tension and axial tension results are included. In the case of the axial tension, the only complete series is for Type S mortar. Limited results for other mortars are presented for comparison. Tests were also done for other orientations of the bed joint and these are plotted later.

The test results for all of the splitting tension tests and for the complete set of axial tension tests are shown in Figure 5. This clearly indicates the sensitivity of tensile strength to orientation of the stress. Also the very significant influence of the stress field is apparent.

Figure 6 is a sketch of the interaction of shear and normal stresses along the bed joint at failure. Point B represents the conditions for splitting tension failure at $\theta = 45^{\circ}$ and point A represents the comparable failure condition for axial tension. If the failure is considered to be a shear failure along the bed joint, the influence of the magnitude of either tensile or compressive stress normal to the bed joint can be seen to be substantial. Beyond some level of compression, the shear-slip mode of failure will no longer dominate and will be replaced by tensile failure passing through the mortar and brick. Obviously the transition point will depend both on the bond strength and on the tensile strength of the brick.

The full set of results for the axial tension tests for Type S mortar are presented in Figure 7. A straight line through the approximate mean values for the orientations of the bed joints is also shown. Recognizing the rather large variability of the tensile strengths, it seems that the straight line approximation for the shear-tension interaction curve is reasonable.

4. CONCLUSIONS

1. Masonry is known to be an anisotropic material and the results presented in this paper again confirm the characteristic dependence of the tensile strength on the orientation of tensile stresses.
2. In addition to the above anisotropic effect, it was shown that for any particular direction of tensile stress, the stress field is a controlling factor in determining the apparent tensile strength.
3. For tensile test data to be correctly interpreted for design purposes, it is suggested that the combined stress conditions (normal and parallel to the bed joint) must be considered. This implies the need for development of failure criteria to account for these combined stress conditions.

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TABLE 1 - BRICK PROPERTIES

Gross Area	19,380 mm^2
Net Area	153,900 mm^2
Initial Rate of Absorption	1.94 $kg/m^2/min$
Compressive Strength (tested flatwise)	128.7 MPa
Compressive Strength (tested endwide)	68.8 MPa
Flexural Tensile Strength (based on net area)	11.9 MPa

TABLE 2 - MORTAR PROPERTIES

Mortar Type	Proportions by Volume (weight)				Compressive Strength (MPa)
	Cement	Lime	Sand	Water	
M	1	0.25 (0.10)	2.81 (2.98)	(0.64)	22.4
S	1	0.5 (0.21)	4.0 (4.24)	(0.90)	14.0
N	1	1.25 (0.53)	6.75 (7.16)	(1.50)	6.5

TABLE 3: TEST RESULTS

Test Type	Mortar Type	Orientation	No. of Specimens	Tensile Strength, N/mm^2	C.O.V.
Axial Tension	S	0	3	1.36	15.5
		45	3	0.50	28.8
		90	4	0.45	19.9
	M	0	3	1.06	4.2
		45	-	-	-
		90	-	-	-
	N	0	5	1.17	40.5
		45	-	-	-
		90	3	0.47	51.2
Splitting Tension	S	0	3	2.35	19.9
		45	3	2.57	34.9
		90	3	1.35	11.8
	M	0	3	2.09	9.5
		45	3	2.17	10.0
		90	3	1.01	23.7
	N	0	3	1.85	11.3
		45	3	1.87	15.9
		90	3	0.87	17.0

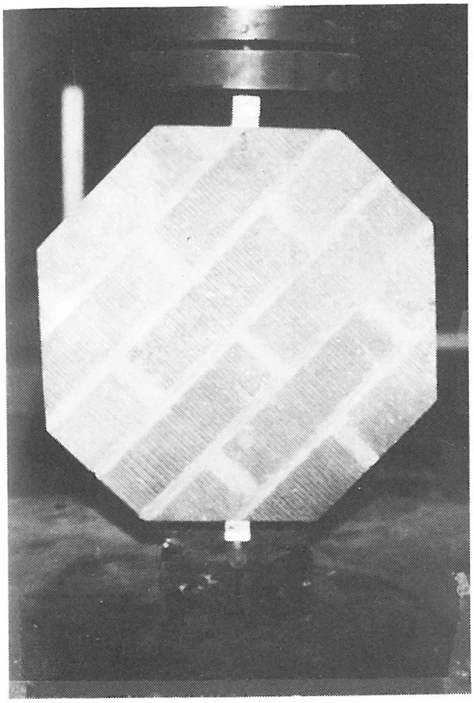


FIGURE 1 SPLITTING TENSION TEST

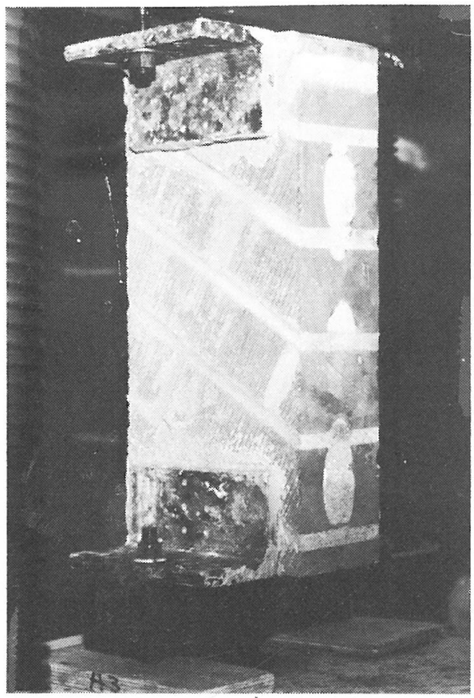
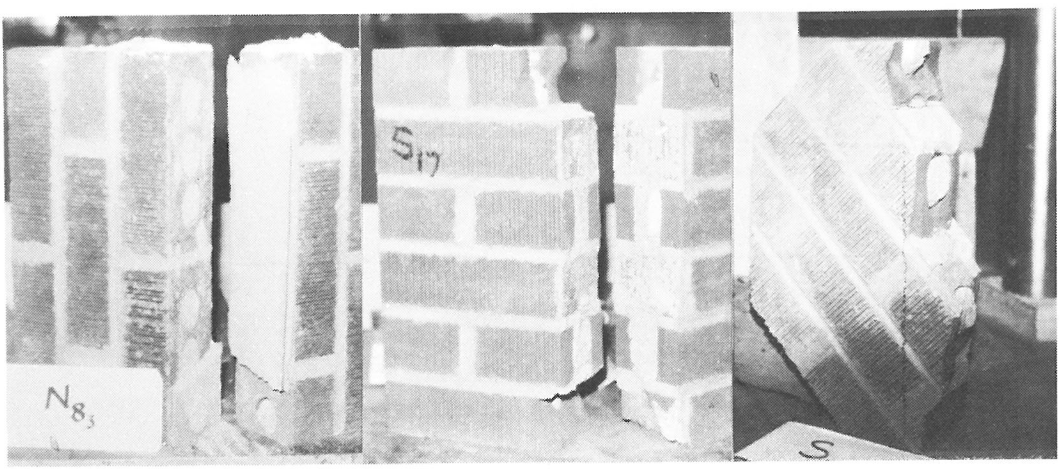
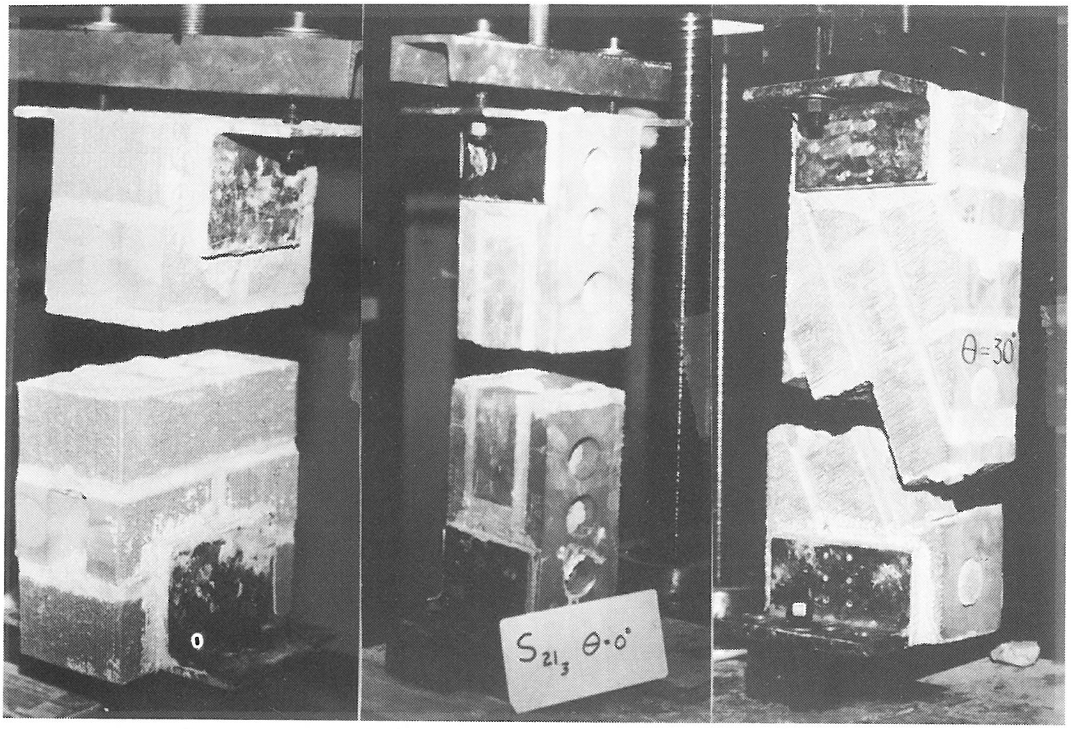


FIGURE 2 AXIAL TENSION TEST



a) Normal to Bed Joint b) Parallel to Bed Joint c) At 45° from Bed Joint

FIGURE 3 FAILURE MODES FOR SPLITTING TENSION



a) Normal to Bed Joint b) Parallel to Bed Joint c) At Angle θ from Bed Joint

FIGURE 4 FAILURE MODES FOR AXIAL TENSION

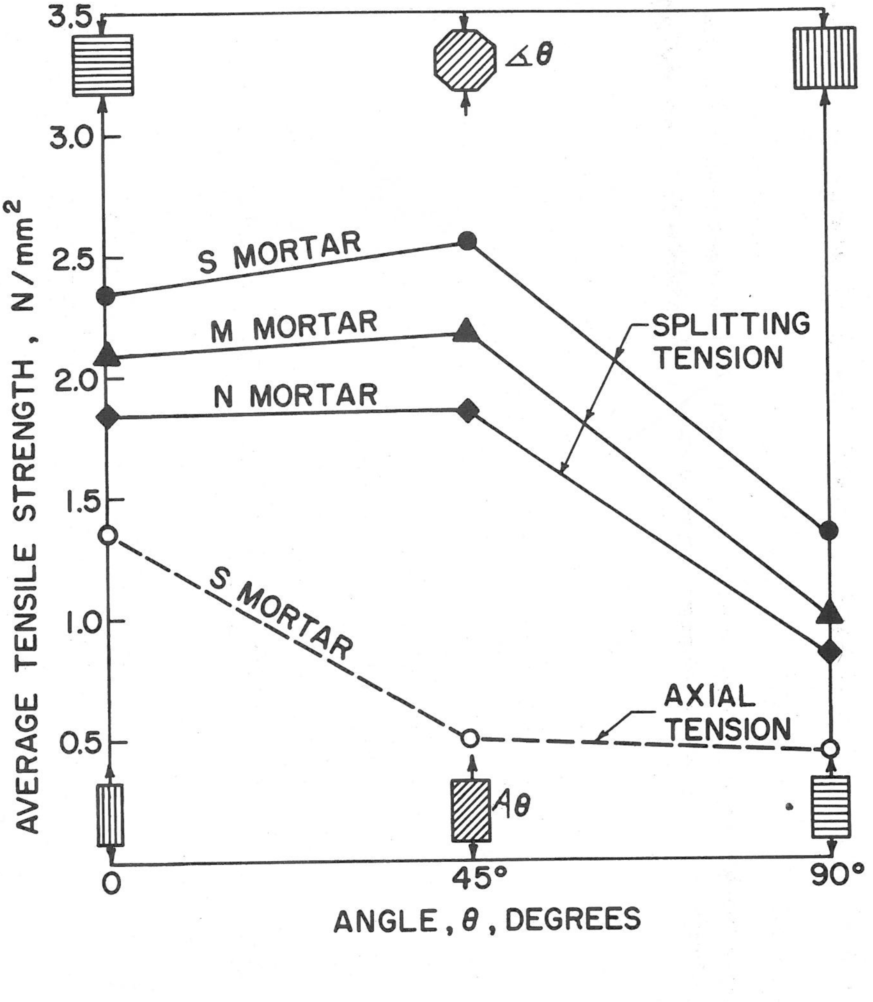


FIGURE 5 TENSILE TEST RESULTS

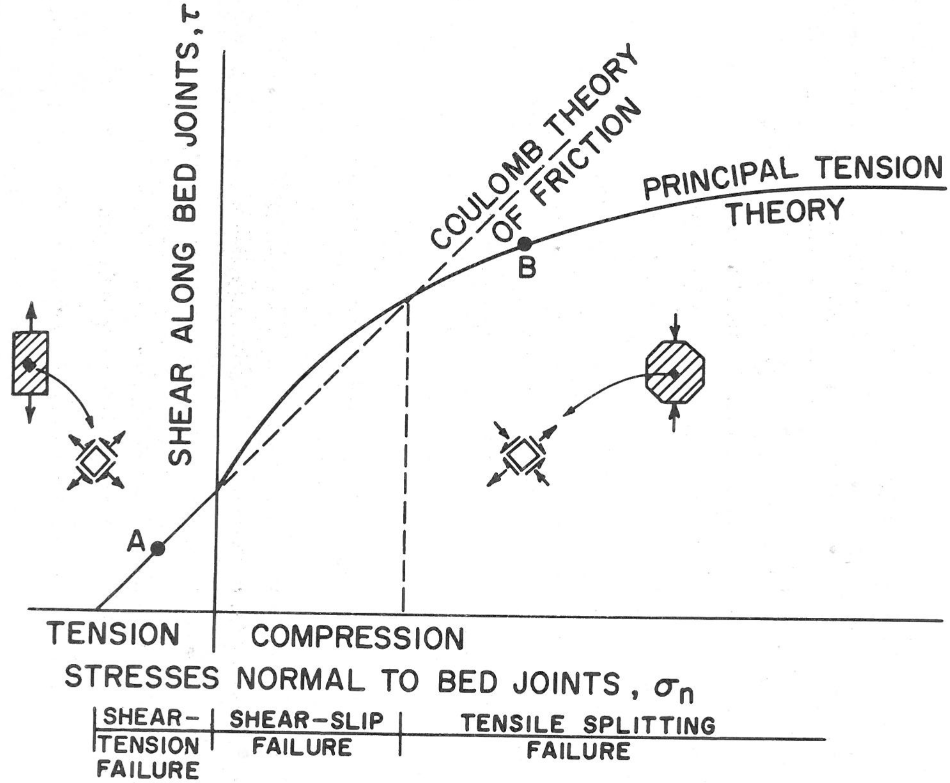


FIGURE 6 INTERACTION DIAGRAM FOR SHEAR AND NORMAL STRESSES ALONG THE BED JOINT

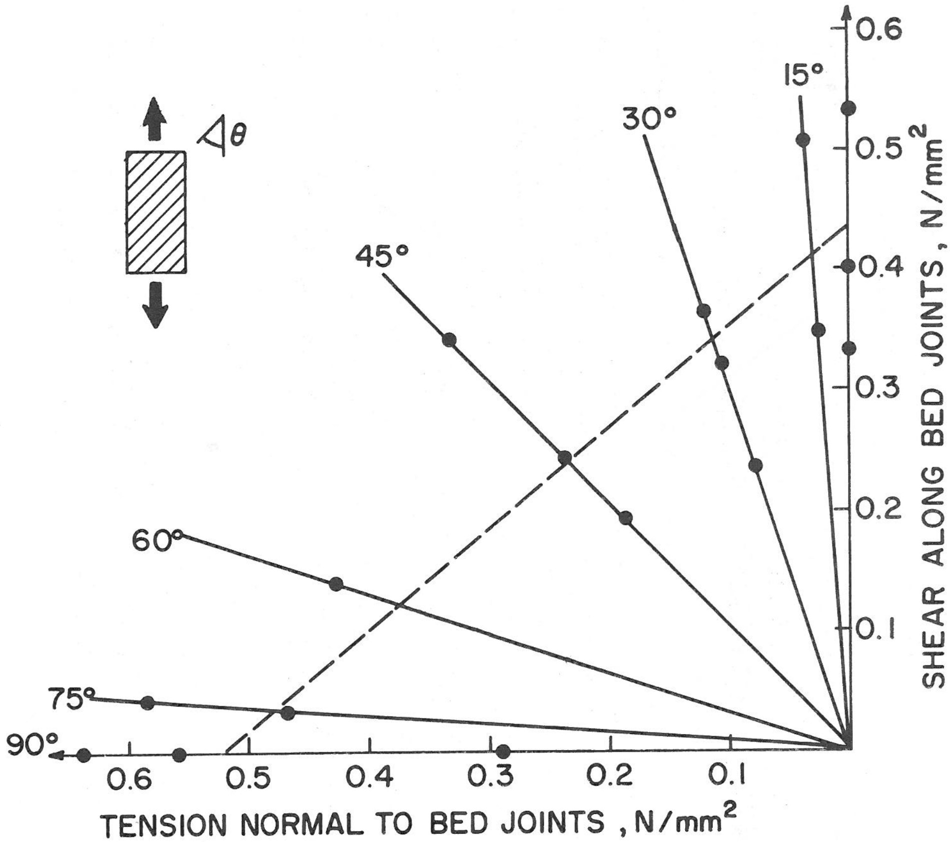


FIGURE 7 RESULTS FROM AXIAL TENSION TESTS