FAILURE MODES FOR ECCENTRICALLY LOADED CONCRETE BLOCK MASONRY WALLS

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May 1991

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INTRODUCTION

Axially loaded masonry walls tend to fail by vertical splitting which results from the differences in physical properties of mortar and masonry units. Analytical evaluations of the compressive strength of axially loaded masonry have been proposed by Hilsdorf (1) and Francis (2). When the vertical load is applied eccentrically the maximum vertical stress at failure is observed to be significantly higher than that obtained for axial load. This apparent increase in compressive strength is attributed to the stress gradient on the cross section resulting from the presence of moment.

In this study, the effects of loading conditions on the failure mode are investigated and results from tests on prisms and full scale walls are reported.

BEHAVIOUR OF CONCRETE MASONRY

Extensive experimental research has been conducted in recent years to investigate the behaviour of axially loaded masonry. Most notable is the work of Thomas (3) and Hendry (4).

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The splitting failure of axially loaded masonry is well documented. In the development of an analytical model, Hilsdorf (1) assumed that the tensile stress in the masonry units, resulting from the confinement of the mortar joint, is uniform over the height of the unit. The state of stress assumed by Hilsdorf is shown in Figure 1. However, a finite element analysis using quadratic serendipity elements shows that the stress distribution is not uniform but varies along the height of the unit, as shown in Figure 2.

The behaviour of axially loaded masonry depends largely on the elastic properties of the masonry units and the mortar. The compressive strength of the mortar is usually less than that of the unit and as a result the mortar is crushed before the strength of the units is reached. As crushing occurs, there is increased tendency for the mortar to expand in the lateral direction. This effect can be simulated by an increase in Poisson's ratio. Theoretically the value of the Poisson's ratio should be less than 0.5. However, when the compressive strength of the mortar is exceeded, there is an increase in the volume of the mortar due to the creation of voids and cracks, resulting in quasi-Poisson's ratio values greater than 0.5. The values of this ratio for lime mortars reported in the literature varies from 0.2 to more than 1.0. Hilsdorf (5) states that Poisson's ratio increases rapidly as the uniaxial strength of the mortar is approached, and at failure values exceeding 1.0 have been observed. Lateral tensile stresses in the masonry unit in a uniaxially loaded masonry assembly obtained from a finite element analysis are directly proportional to lateral expansion as shown in Figures 3 and 4.

When a masonry assembly is subjected to a combination of axial load and moment, rotations take place principally in the mortar joints and the resulting stress on the masonry units has a lateral component as shown in Figure 5. As a result of the applied moment and due to initial imperfections, shear stresses occur along the wall height. Figure 6 shows a free body diagram of a wall section. Thürlimann (6) observed that in masonry walls subjected to bending and a small axial compression load the angle of rotation is concentrated in one mortar joint and in such a case the crack width between mortar and the unit is large. Under bending and a large compression load, the rotation occurs over several mortar joints. For both cases a wedge type deformation results and because of the presence of shear as indicated in Figures 5 and 6 the lateral tensile stresses in the unit are reduced and failure of the unit is changed from splitting to crushing. Figure 7 shows the maximum tensile stress within a masonry unit as a function of the ratio of the minimum and maximum stresses at the two faces of the wall. It has been indicated in Figure 2 that the maximum tensile stress in the unit reduces rapidly from the edge of the unit to the center and only a small shear is necessary to oppose the splitting action and to change the mode of failure to that of crushing. For example, consider a wall mode of masonry units with a compressive strength of 2500 psi and a tensile strength of 320 psi for which the eccentricity of vertical load is t/70. The ratio of minimum stress to maximum stress (f_{min}/f_{max}) in the units is 0.85. From Figure 7 it is observed that the tensile stresses when f_{min}/f_{max} is 0.85 in a unit along lines A and B are reduced from 320 to 275 psi and from 170 to 160 psi, respectively. No large reduction occurs along line C. Although this analysis indicates tensile failure is imminent at C, at the same time the compressive stress on the mortar joint in the vicinity of C is so large that spalling occurs in the mortar and the bond is destroyed thereby reducing any tendency for splitting of the unit. Failure of the unit will occur when the maximum compressive stress reaches the compressive strength.

For eccentricities of load larger than t/70, masonry walls with normal mortar joints will always fail when the compressive strength of the unit is reached. In practice, because of initial crookedness, difficulties in positioning load precisely, etc., it is reasonable to consider that compressive failure will occur whenever the eccentricity of vertical load is of the order of t/20 or greater. For abnormal mortar joints the limits on eccentricity of load to cause crushing will be different. In walls with very thick mortar joints the failure of the wall will be caused by failure of the mortar alone.

EXPERIMENTAL INVESTIGATION

Twelve, five-block high prisms were built using Type S mortar. Solid block units and fully bedded construction were used in order to conform as closely as possible with the assumptions made in the finite element analysis.

Fifteen short wall specimens were built using 8 x 8 x 16 two-core concrete block units. These specimens were 2 1/2 blocks in length and 5 blocks high (8 x 40 x 40). Nine of these specimens contained joint reinforcement in the form of #9 gauge wire in every joint.

All short wall specimens were built by an experienced mason, and were cured in a laboratory environment at 32% relative humidity and 70°F temperature.

The specimens were at least 28 days or older at the time of testing. The vertical loads were applied at equal eccentricities at top and bottom of 0, t/6 and t/3, with pinned ended conditions.

MATERIAL TEST RESULTS

Based on tests on ten masonry units with h/t equal to 2, the compressive strength of the units was found to be 2000 psi. The compressive strength of the mortar was 750 psi based on tests on ten 2-inch cubes cured in the same environment as the prisms. Tests on fifty moist cured 2-inch cubes, results in a compressive strength of 2545 psi.

The compressive strength of the hollow masonry units based on net cross sectional area was 2350 psi. The maximum strength obtained in testing concrete block units was 3890 psi and the minimum 1850 psi.

WALL TEST RESULTS

Typical failures of axially loaded walls are shown in Plates 1 and 2. Failures of eccentrically loaded walls are shown in Plates 3 and 4. The change in the mode of failure from splitting along the height of the wall to crushing of the units is clearly shown in Plates 3 and 4.

The test results are summarized in Tables 1 and 2. The average compressive stress at failure for the three axially loaded solid block walls was 1650 psi. For specimens loaded at eccentricities of t/20, t/12 and t/6 the corresponding compressive stress at failure was 2150, 2000 and 2010 psi respectively. The average compressive stress at failure for the eccentrically loaded specimens was 2080 psi which compares favorably with the compressive strength of the units.

For specimens consisting of hollow block units and no joint reinforcement, the average compressive stress at failure was 2320 psi when axially loaded at an eccentricity of t/6, and 3600 psi when loaded at an eccentricity of t/3.

The average vertical stress values at failure for specimens containing joint reinforcement were as follows: 2000 psi for axially loaded specimens, 2770 psi for specimens loaded at an eccentricity of t/6 and 2500 psi for specimens loaded at an eccentricity of t/3. The reduction in the vertical stress at failure for specimens containing joint reinforcement is attributed to the stress concentration in the mortar joint created by the presence of the steel (8).

The average vertical stress at failure for the eccentrically loaded hollow block walls was 3360 psi for the plain wall specimens and 2610 psi for specimens containing joint reinforcement. These values are higher than the mean compressive strength of the units. It is believed that this difference is due to factors such as the extent of mortar penetration, the variation in the block thickness with height, and the method of construction (minimum surface area of block bearing on maximum surface area of the block below). Table 3 gives a summary of the test results obtained from tests on hollow block wall specimens.

CONCLUSIONS

Eccentrically loaded concrete masonry walls fail when the compressive strength of the masonry unit is reached. The mode of failure will change from splitting to crushing when the eccentricity of the vertical load is of the order of t/20. The actual failure stress, calculated on the basis of net cross-sectional area may vary as a result of variations in the block thickness and type of construction.

ACKNOWLEDGEMENTS

This study was performed in the Department of Civil Engineering at the University of Alberta. Financial assistance from the Masonry Research Foundation of Canada, the Prairie Masonry Research Institute and the National Research Council of Canada is acknowledged.

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TABLE 1 - TEST RESULTS FOR SOLID MASONRY PRISMS

WALL	ECCENTRICITY OF VERTICAL LOAD	FAILURE LOAD kips	MAXIMUM COMPRESSIVE STRESS ksi
1	0	214.5	1.80
2		218.3	1.83
3		159.9	1.34
4	t/20	195.1	2.13
5		202.0	2.20
6		193.7	2.11
7	t/12	208.9	2.63
8		144.3	1.82
9		143.6	1.81
10	t/6	112.5	1.89
11		102.3	1.72
12		145.0	2.43

TABLE 2 - TEST RESULTS FOR AXIALLY LOADED HOLLOW BLOCK SHORT WALLS

SPECIMEN	JOINT REINFORCEMENT	LOAD AT FAILURE kips	STRESS AT FAILURE BASED ON MORTAR BEDDED AREA psi	STRESS BASED ON GROSS AREA psi
3	nil	215.5	2150	710
4	nil	249.1	2490	820
Average		232.3	2320	760
5	flattened*	234.8	2350	770
6	#9 gauge wire	191.1	1910	630
Average		212.9	2130	700
7	#9 gauge wire	200.0	2000	650
8		171.2	1710	560
Average		185.6	1860	610

* diameter reduced 40% by passing reinforcement through rollers.

Mortar bedded area for all above specimens was 100 in.^{2}.

TABLE 3 - TEST RESULTS FOR ECCENTRICALLY LOADED HOLLOW BLOCK SHORT WALLS

SPECIMEN	JOINT REINFORCEMENT	ECCENTRICITY	LOAD AT FAILURE kips	MOMENT AT FAILURE kip-in.	STRESS AT FAILURE BASED ON MORTARED AREA (psi)
1	nil	t/6	196.9	250.0	3540
2	nil	t/6	150.1	190.6	2690
3	nil	t/3	119.3	303.0	3090
4	nil	t/3	158.7	403.0	4110
Average					3360
5	#9 Gauge Wire	t/6	160.0	203.2	2870
6	#9 Gauge Wire	t/6	149.1	189.35	2680
7	#9 Gauge Wire	t/3	92.75	235.5	2400
8	#9 Gauge Wire	t/3	105.5	264.9	2720
9	#9 Gauge Wire	t/3	92.75	235.5	2400
Average					2610

For all above specimens mortar bedded area was 100 in.^{2}.

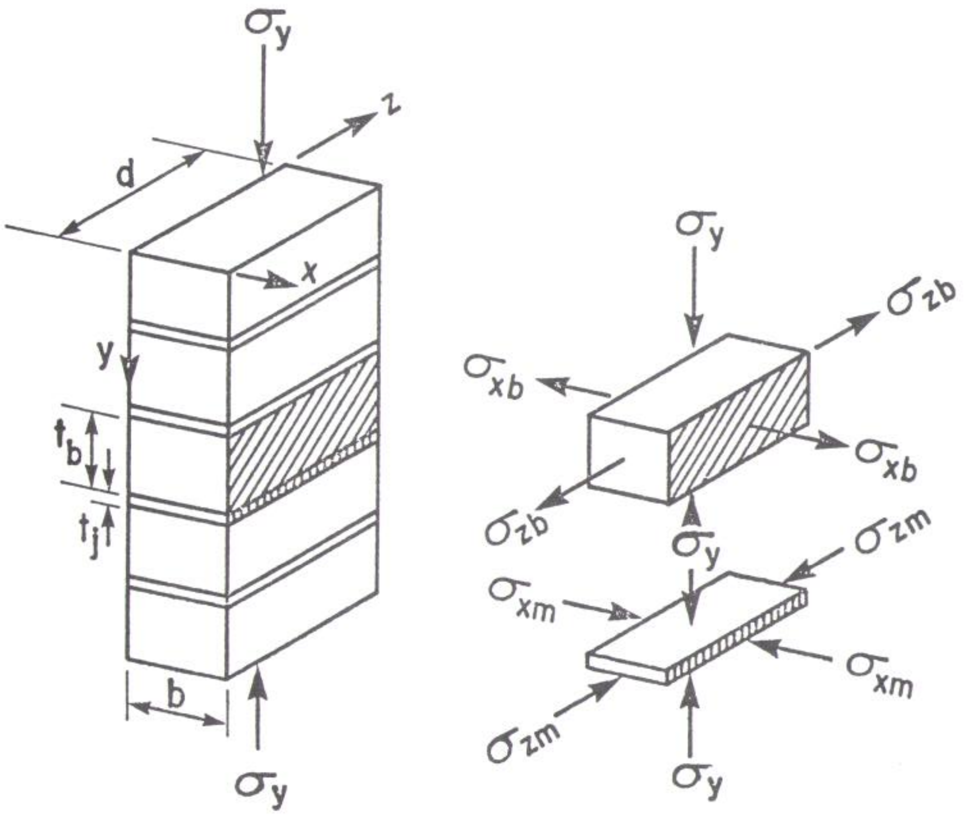

Figure 1 - State of stress in axially loaded solid block masonry

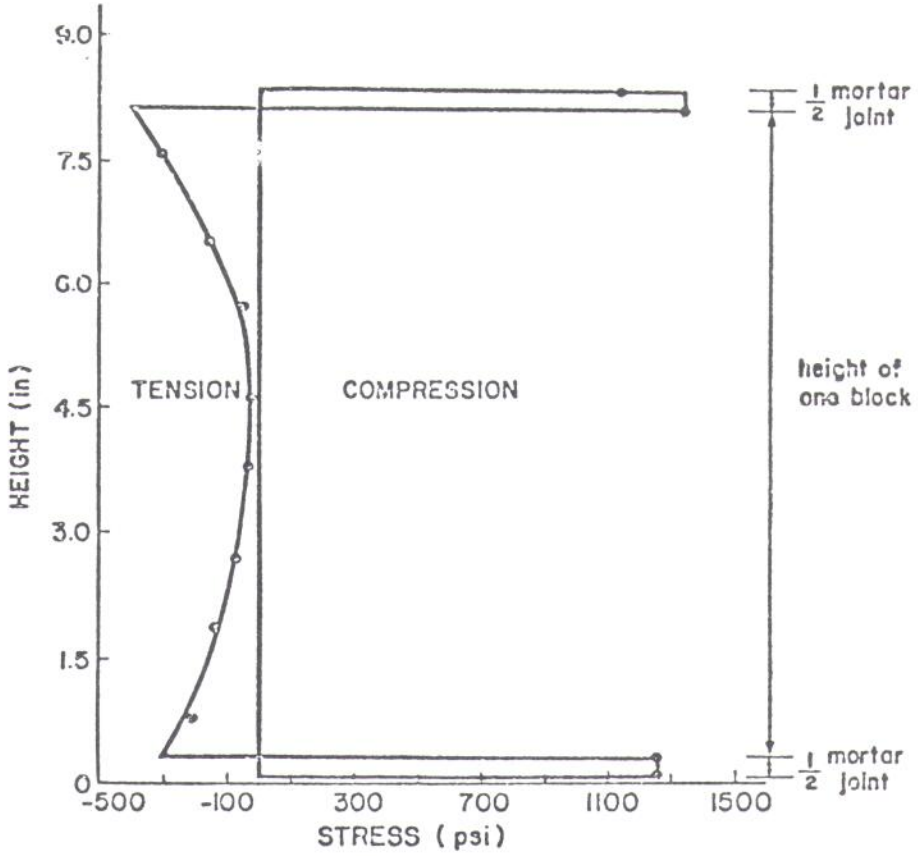

Figure 2 - Lateral stresses in
axially loaded masonry

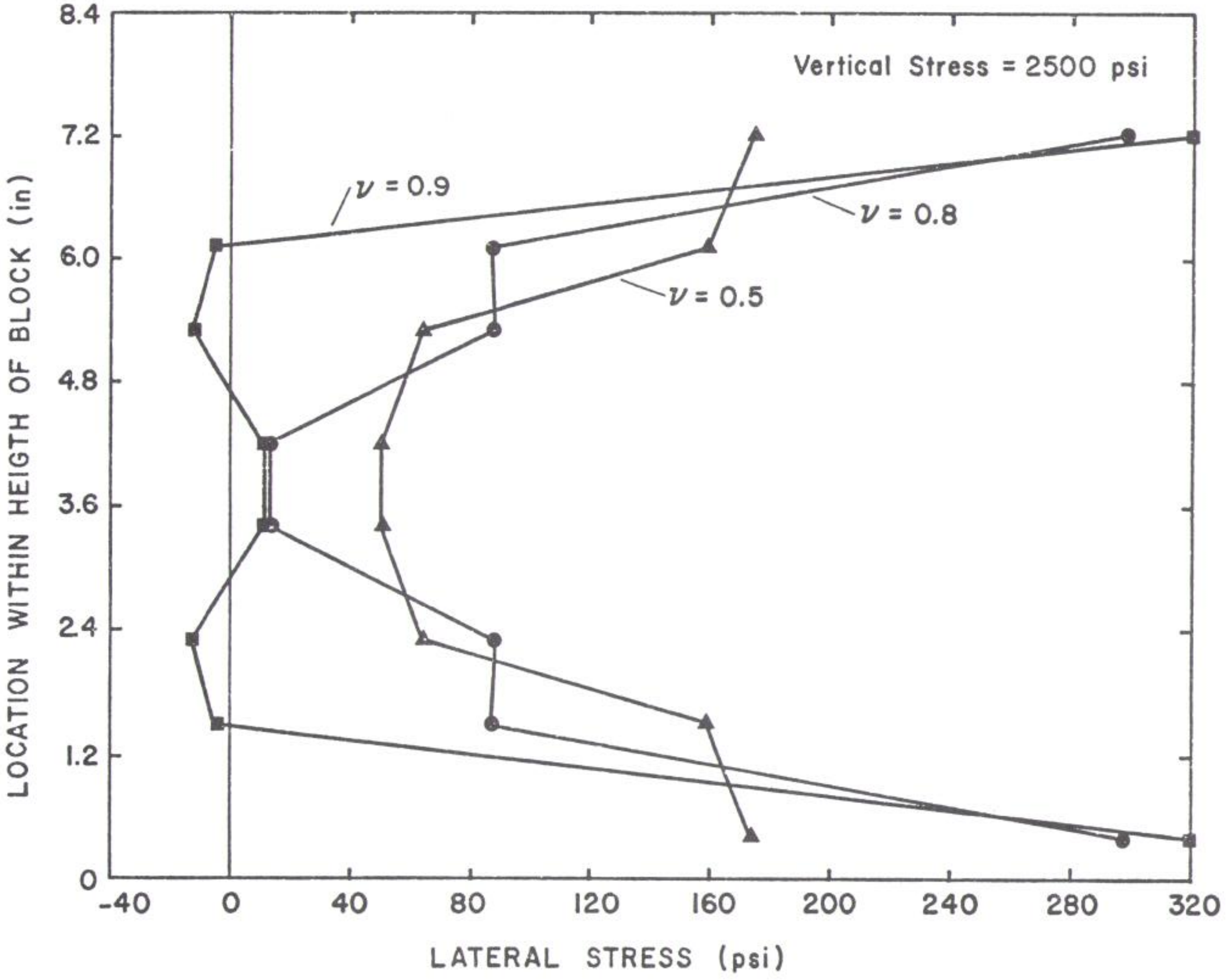

Figure 3 - Effect of Poisson's ratio on lateral tensile stress distribution

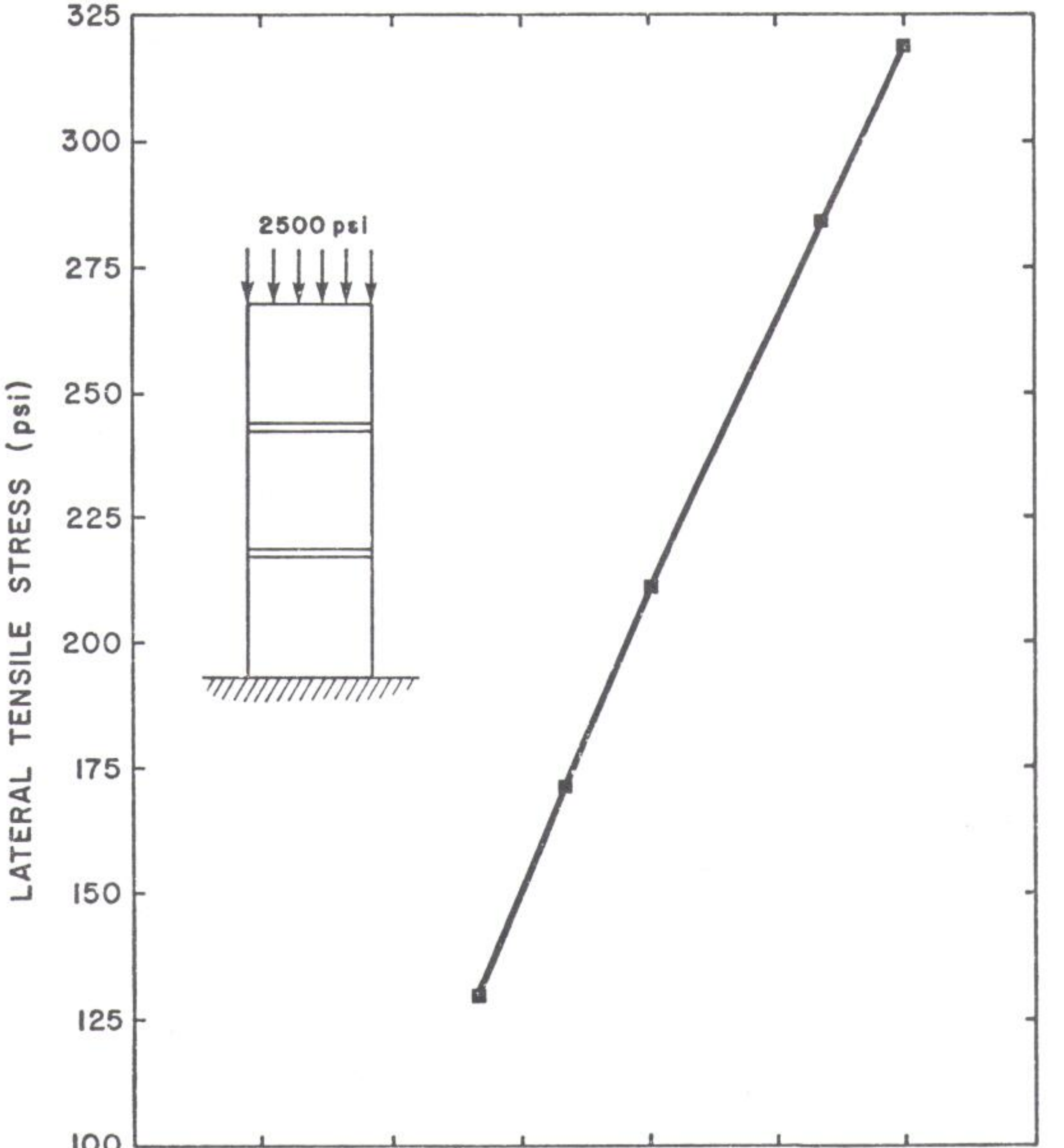

Figure 4 - Effect of Quasi-Poisson's ratio on maximum lateral tensile stress

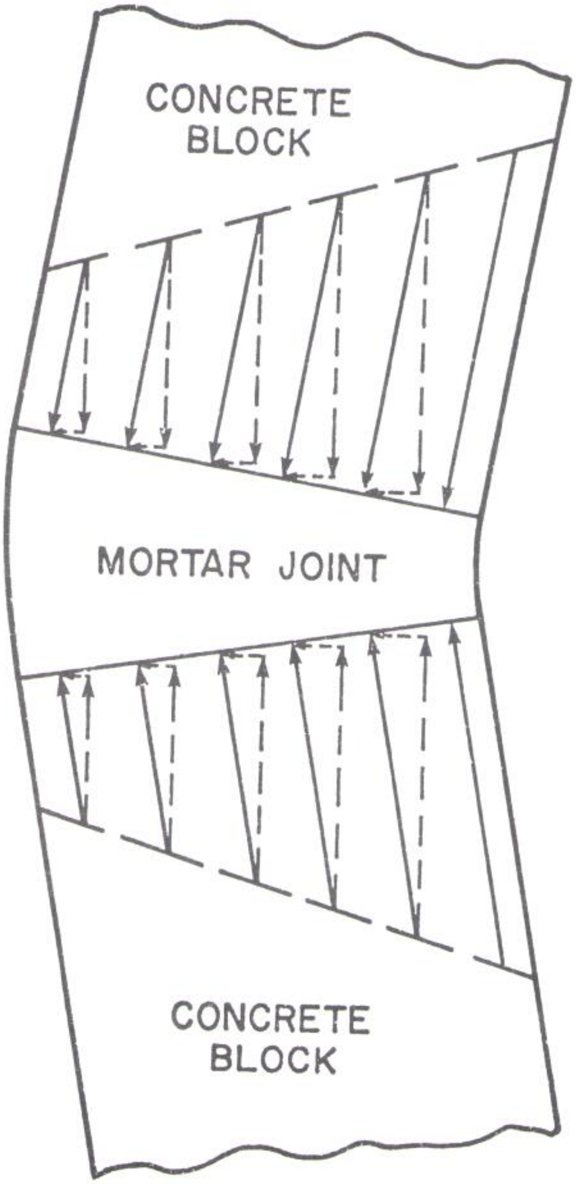

Figure 5 - Deformed mortar joint and stresses resulting from eccentric load

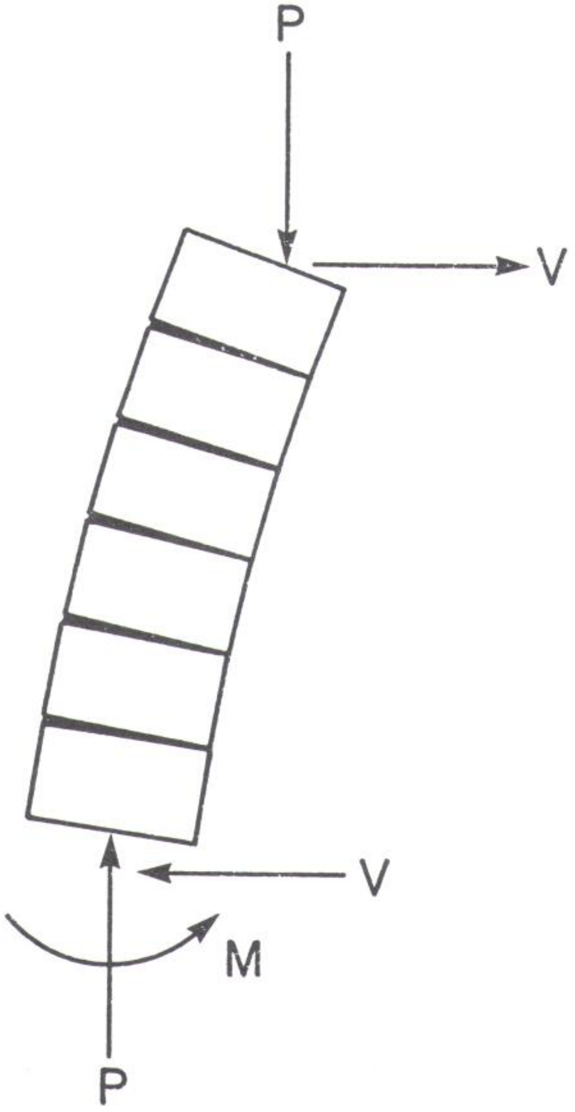

Figure 6 - Free body diagram of wall segment

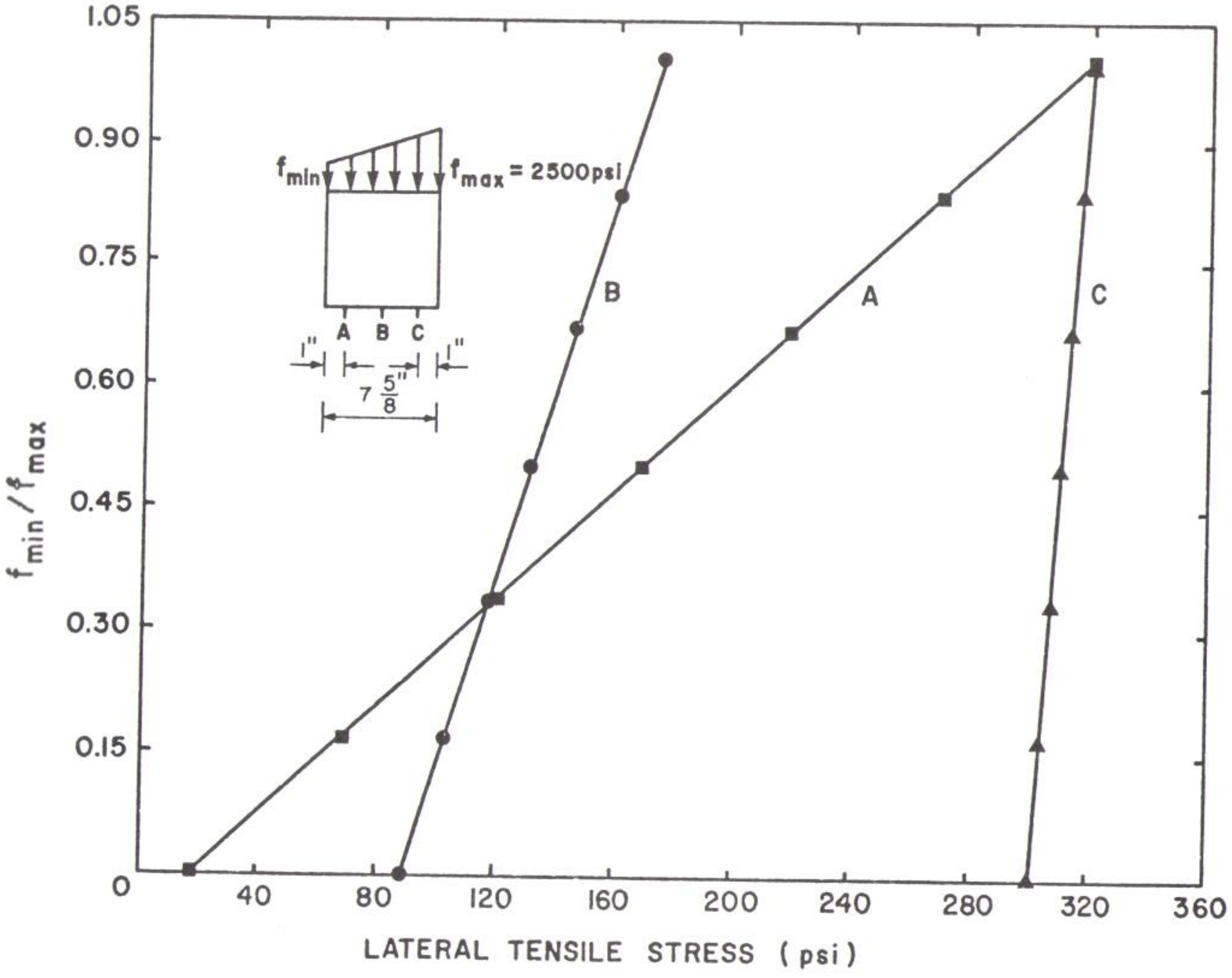

Figure 7 - Effect of vertical stress distribution on the tensile stresses along the thickness of a solid wall

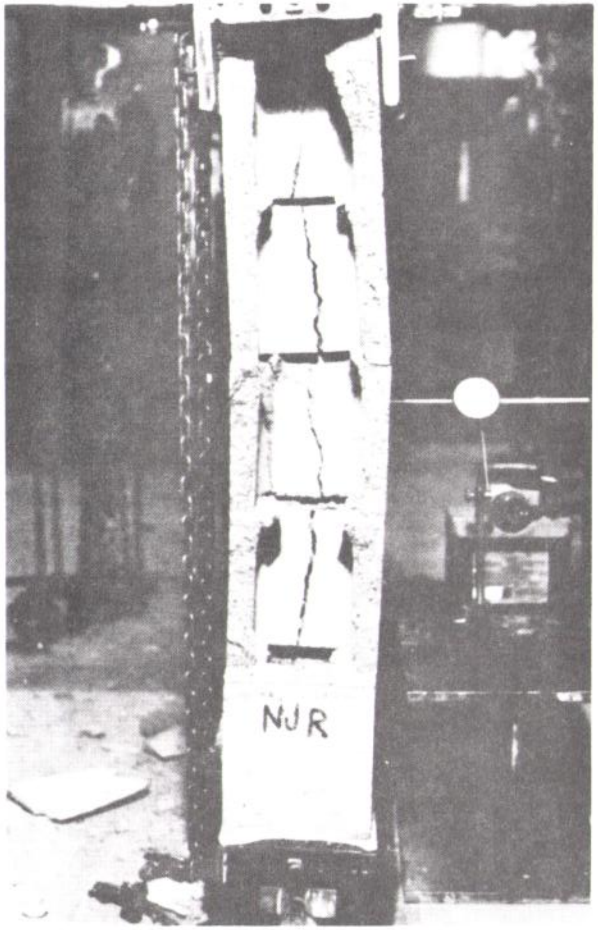

Plate 1 - Failure of axially loaded hollow concrete block masonry wall.

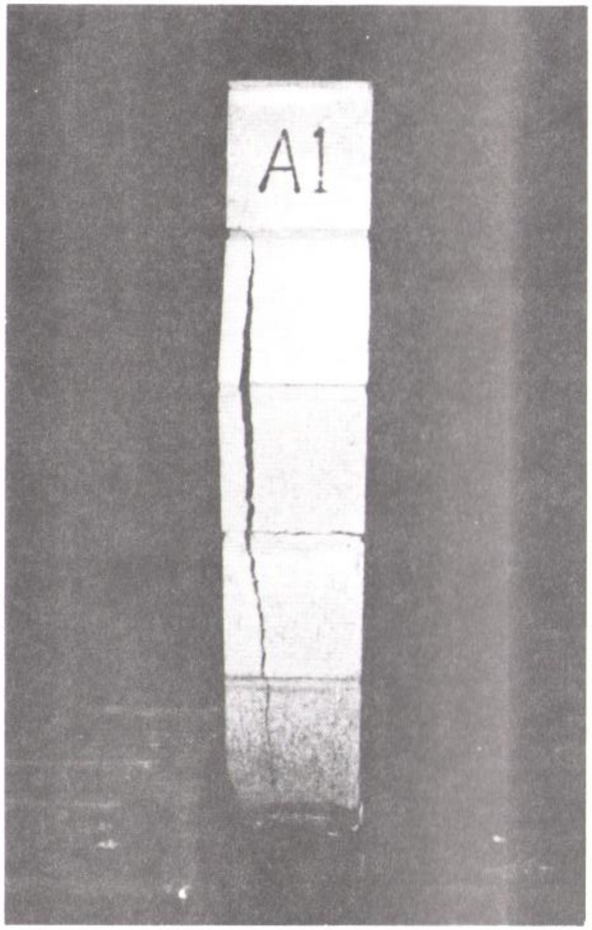

Plate 2 - Failure of axially loaded solid concrete block masonry wall.

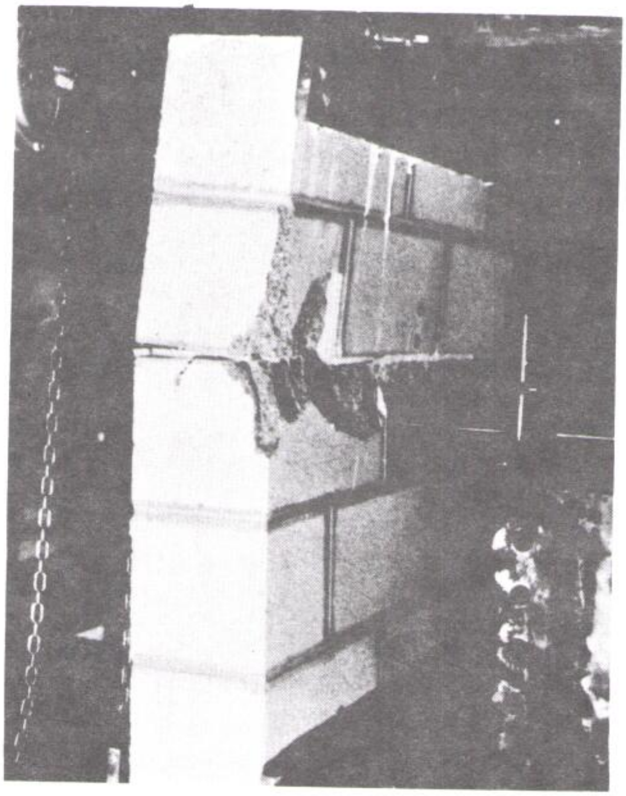

Plate 3 - Failure of eccentrically loaded hollow concrete block masonry wall

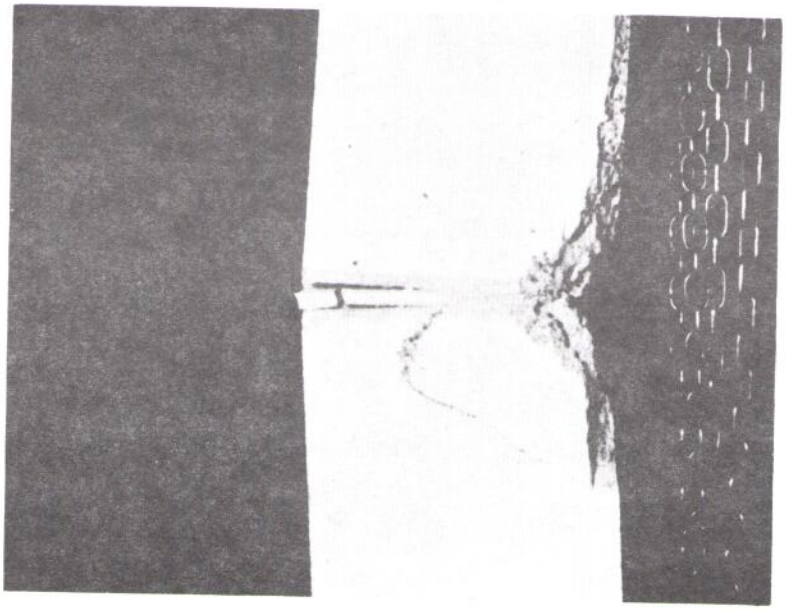

Plate 4 - Failure of eccentrically loaded solid concrete block masonry wall