BASIC PROPERTIES OF CLAY-UNIT MASONRY STACK-BOND PRISMS IN COMPRESSION

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SUMMARY

This paper presents results of analysis and experimentation to study the behavior of clay-unit masonry under uniaxial compressive loadings. A theory is developed to determine strength and deformations of stack-bond prisms. Tests of individual brick and mortar specimens are done to determine material properties of the constituents for input to the computational model. Results of the analysis are compared with measured strengths and deformations of masonry prisms. Conclusions of the study indicate that behavior of masonry in compression is largely dependent on the nonlinear properties of the mortar.

INTRODUCTION

Design of load-bearing clay-unit (brick) masonry buildings to withstand vertical loading and lateral loading due to earthquake or wind depends, in part, on the knowledge of behavior and failure mode of masonry in compression. Present design procedures in many ways consider masonry to be a homogeneous material, and do not reflect adequately or account for the performance of masonry as affected by the properties of its constituents. The purpose of the study described in this paper was to examine strength and deformational properties of masonry in detail so that future design procedures may be improved.

THEORIES FOR MASONRY BEHAVIOR UNDER COMPRESSIVE LOADINGS

Hilsdorf (2)* proposed a theory in which the strength of solid-unit stack-bond masonry prisms is limited by the strength of the mortar as described by the Coulomb criteria. Alternatively, Khoo and Hendry (3) have suggested that failure of prisms is defined by a maximum lateral tensile strain criterion for brick units. The strain criterion was established by a series of tests of brick coupons under combined tension and compression. Their theory relates unit lateral strain to triaxial stress conditions in the mortar bed joints and relies upon strain compatibility between units and mortar. Shrive and Jessop (4), assuming linear elastic properties (E and ν) for both units and mortar, developed an expression for lateral stress in the unit as a function of prism compressive stress. They found poor correlation between predicted and measured prism strengths which is not surprising as

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*Numbers in parentheses denote references found at the end of the paper.

they did not consider either nonlinear mortar effects or the biaxial failure envelope of the brick units.

A deformation failure theory (1) has been developed which incorporates the observed, nonlinear, dilatant behavior of mortar and the linear-elastic behavior of the brick units. In equation [1] an increment of lateral brick stress is expressed as a function of an increment of prism compressive stress and the elastic and geometric properties of the brick units and mortar bed joints.

$$\Delta_{xb} = \frac{\Delta\sigma\left[\nu_b - \frac{E_b}{E_m(\sigma_1,\sigma_3)}\,\nu_m(\sigma_1,\sigma_3)\right]}{1 + \frac{E_b}{E_m(\sigma_1,\sigma_3)}\,\frac{t_b}{t_m}} \qquad [1]$$

where Δ_{xb} = an increment of lateral stress in the clay unit

$\Delta\sigma$ = an increment of prism compressive stress

ν_b = Poisson's ratio of the unit (brick)

E_b = modulus of elasticity of the unit

ν_m = Poisson's ratio of mortar as a function of principal stresses

E_m = modulus of elasticity of mortar as a function of principal stresses σ_1 and σ_3

t_b = thickness (height) of a masonry unit

t_m = thickness of a mortar bed joint

A computer routine, incorporating Eq. [1] was written to evaluate unit and mortar stresses for incrementally increasing prism compressive load. At the beginning of a load step, values of Poisson's ratio and Young's modulus are determined based on the mortar's stress state (σ_1,σ_3) at the end of the previous step. Prism failure is defined to occur whenever the stress state in the mortar or the unit exceeds the applicable failure envelope.. The failure envelopes considered were straight-line envelopes (Coulomb) for both the brick and masonry as well as the nonlinear envelopes which were determined experimentally for the mortar as described below.

BRICK PROPERTIES

Biaxial tension-compression tests of clay units (brick) were conducted to simulate the state of stress of units in a prism under compression and thereby define a biaxial failure envelope. A test apparatus (Fig. 1) was developed which applies tensile force through aluminum brushes to reduce lateral interface shear stresses. Compressive force, perpendicular to the tensile force, was applied by a standard testing machine with greased teflon sheets interposed to minimize brick-platen interface friction.

A nondimensionalized plot of results (Fig. 2) shows that all of the data falls in a narrow band, regardless of brick type. Test results of

Khoo on one-third scale bricks (3) are also shown. The line of best fit through all of the data points is concave. This suggests that the tensile load has a stronger influence on the compressive strength than the widely used straight line criterion of Coulomb.

MORTAR PROPERTIES

A series of triaxial compression tests was conducted using 4 in. x 2 in. diameter cylinder mortar specimens made of $1:\frac{1}{4}:3$, $1:\frac{1}{2}:4\frac{1}{2}$, 1:1:6, and 1:2:9* proportions to simulate the state of stress in a horizontal mortar bed joint. A triaxial test cell was used to determine the stress-strain characteristics of the mortar under lateral pressures ranging from 30 psi to 1500 psi as the compressive stress was increased to mortar failure.

A typical set of stress-strain curves for the $1:\frac{1}{4}:3$ mortar are shown in Fig. 3. These tests, and similar tests done on the other mortar types, led to a better understanding of the characteristics of mortar in triaxial compression. All four mortar types exhibited increasingly nonlinear behavior with increasing confining pressure. The strength and strain at ultimate increased with confining pressure. The elastic modulus, and Poisson's ratio were dependent on the amount of axial stress, confining pressure, and the mortar type. The data from these tests were reduced to represent behavior of the mortar under all stress states encountered in the computer routine.

PRISM PROPERTIES

A series of compression tests were conducted using five-unit stack-bond prisms. Tests were done for all combinations of two brick types and four mortar types. The prisms were capped and loaded using a greased teflon sheet to reduce interface friction. The axial deformation of the prisms was measured with LVDT's attached to the prism (Fig. 4).

DISCUSSION

Calculated lateral stresses of the unit and mortar are shown in Fig. 6 as a function of prism compressive stress. Both the straight-line (Coulomb) and the measured nonlinear envelope for brick type 1 as well as failure envelopes for two mortars are shown. Failure is defined to occur when the stress state of either the brick or mortar falls outside their respective envelopes.

The nonlinear, dilatant behavior of the mortar is clearly shown in Fig. 6. The brick unit provides sufficient confining (lateral) stress to the mortar such that mortar does not initiate failure of the prism. The non-linear behavior of the mortar also causes the brick tension-compression stress curves to be nonlinear. As shown in Fig. 6, these curves intersect the brick unit failure envelope at points well below what would have been predicted assuming the mortar to be a linear-elastic material.

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*Denotes parts by volume of portland cement, hydrated lime, and masonry sand.

The calculated prism strengths (Table 1) were consistently lower than measured strengths. The failure strengths predicted using the computer routine are based on occurrence of the initial tensile crack in the brick unit. Observations of prism failure have shown that the initial vertical tensile cracks in the brick units occur at approximately 80 to 85% of the prism ultimate stress. The computer routine did successfully predict the changes in prism strength for the different mortar types.

The measured and calculated prism stress-strain plots are shown in Fig. 5(a,b). The measured plots are the extremes of the experimental data and show good correlation with calculated values. Prisms made with the 1:2:9 mortar behaved nonlinearly, while those with 1:½:4½ mortar behaved essentially linearly.

CONCLUDING REMARKS

The research has shown that the strength and deformation of masonry in compression may be determined from a careful evaluation of both the mortar and brick properties. Using the theory presented in this paper, a lower bound on the compressive strength of stack-bond prisms associated with initial lateral cracking may be calculated. Deformational characteristics of the test prisms could also be revealed by the computational model.

Tests of full-size brick units subjected to biaxial compression-tension stresses corraborated the failure envelope proposed by previous investigators (3). The straight-line relationship between uniaxial tension and compressive strengths as prescribed by Coulomb was found to be unconservative.

Tests of mortar cylinders subjected to triaxial states of stress indicated significant nonlinear deformational characteristics which were dependent on the mortar type and the lateral confining pressure.

Deformation and strength of masonry prisms in compression were dependent on the nonlinear characteristics of the mortar, particularly for loading states near ultimate.

The theory and experimentation described in this paper should form the basis for a future study of the behavior of masonry subjected to repeated loadings.

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Table 1. Measured and Calculated Prism Strengths

Brick Type	Mortar Type	Prism Strength (psi)		
		Measured	Calculated	
			(1)	(2)
1	1:¼:3	6989	4965 (71%)*	5345 (76%)
	1:½:4½	5931	4175 (70%)	4460 (75%)
	1:1:6	4713	3735 (79%)	4042 (86%)
	1:2:9	4334	2620 (60%)	2711 (63%)
2	1:¼:3	5461	3455 (63%)	4209 (77%)
	1:½:4½	5025	3180 (63%)	3689 (73%)
	1:1:6	3919	2560 (65%)	3042 (77%)
	1:2:9	2863	1980 (69%)	2275 (79%)

(1) Measured brick failure envelope.

(2) Coulomb straight line failure envelope.

*Figures in brackets are percentage of measured strength.

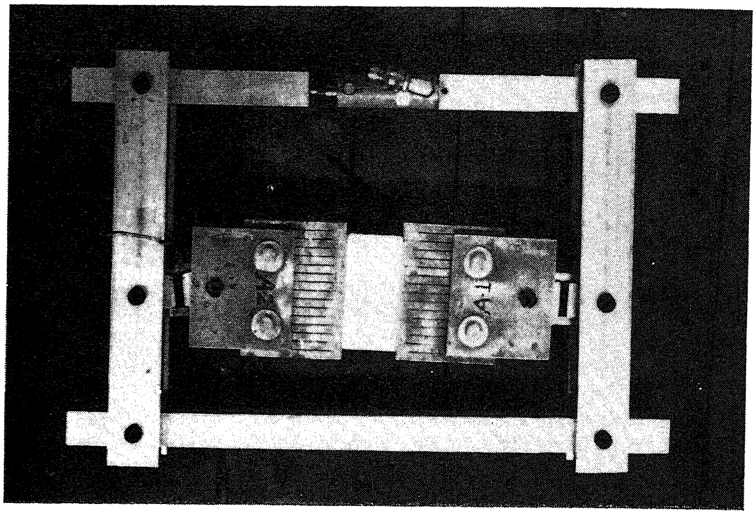


Fig. 1. Biaxial Tension-Compression Brick Test Apparatus.

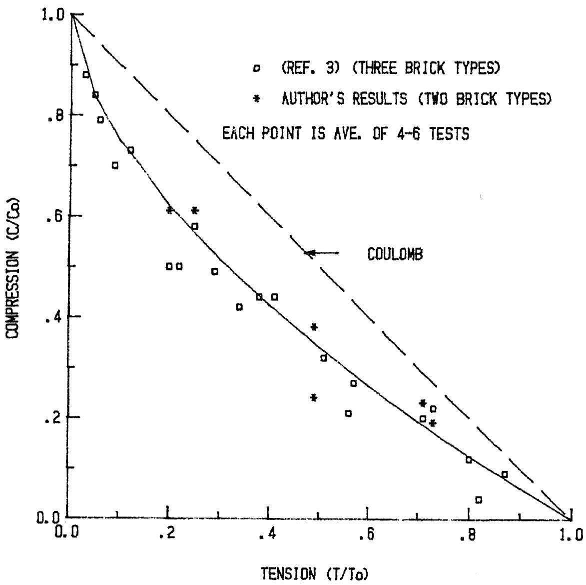


Fig. 2. Nondimensionalized Plot of Biaxial Tension-Compression Brick Tests.

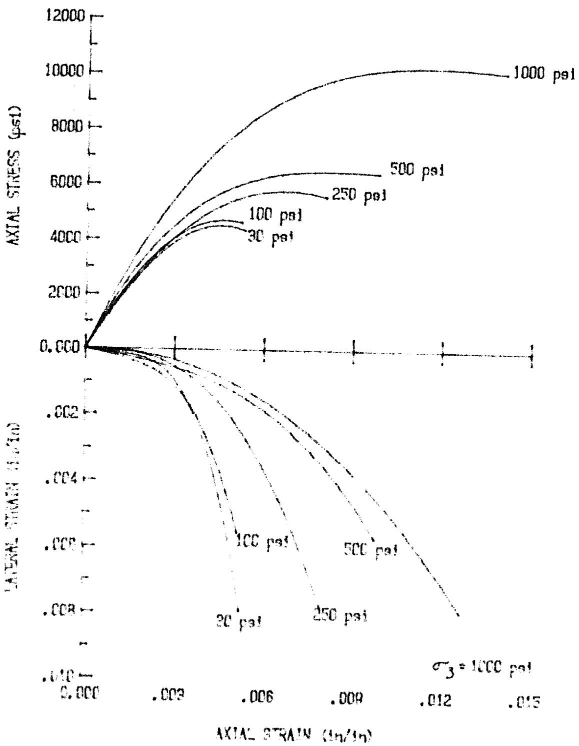


Fig. 3. Stress-Strain Plots for 1:¼:3 Mortar.

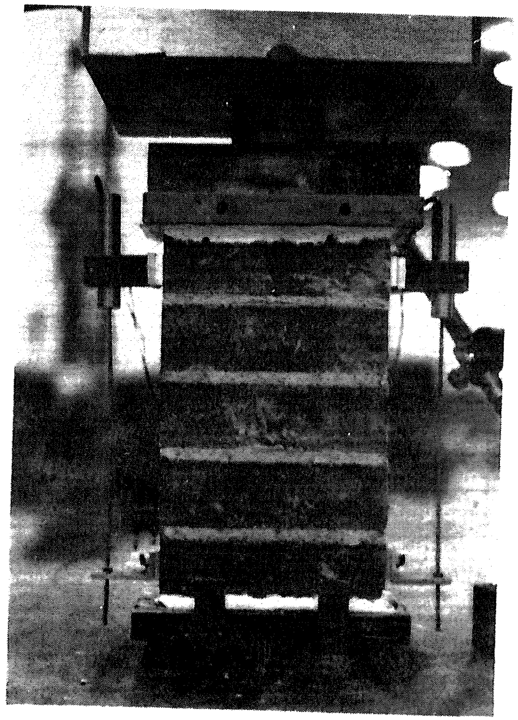
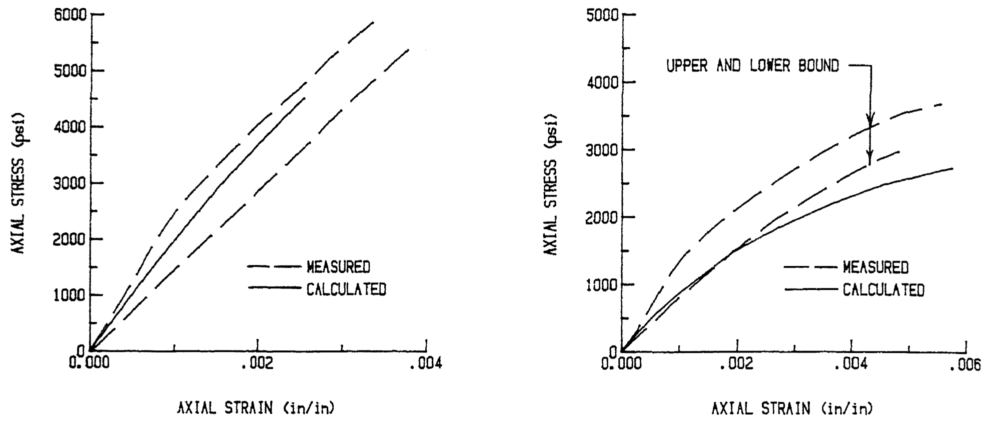


Fig. 4. Typical Prism Test with LVDT's Attached.



a) 1:½:4½ Mortar b) 1:2:9 Mortar

Fig. 5. Stress-Strain Plots for Brick Type 1 Prisms Made with 2 Mortar Types.

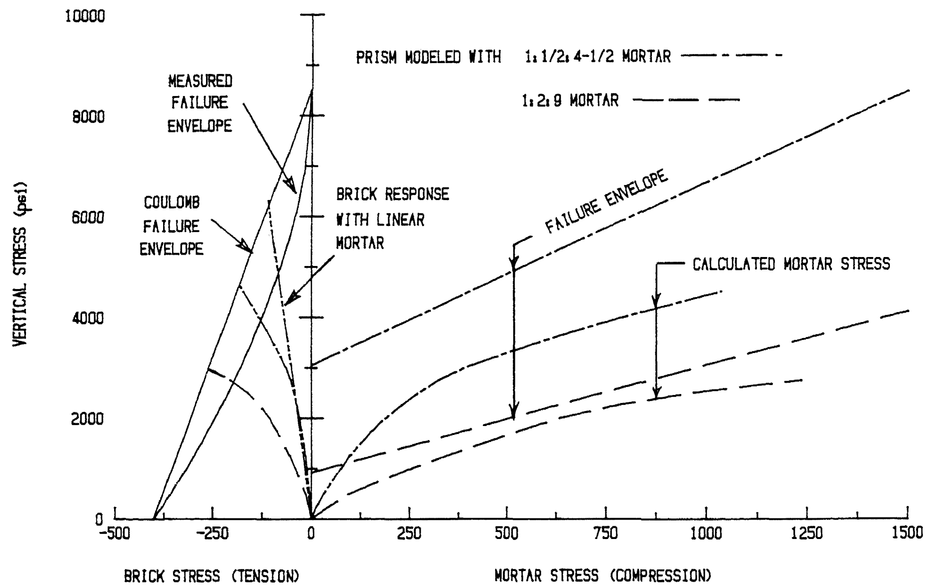


Fig. 6. Calculated Stress Paths of the Brick and Mortar for Prisms Modeled with Brick Type 1.