6. Investigation into the failure mechanism of brick masonry loaded in axial compression.

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Introduction

Structural engineers often hesitate to employ reinforced or unreinforced brick masonry as a structural material. This is not surprising. Despite the use of masonry over thousands of years, its potentials hardly have been utilized and our knowledge of its structural behavior is still quite limited. The prediction of masonry strength from known characteristics of bricks and mortar used in a masonry unit is rather unreliable. Therefore, acceptance of brick masonry units often require experimental determination of the compressive strength of a particular type of masonry rather than to predict it from known properties of its constituents. Because of these uncertainties, the allowable stresses for masonry are rather conservative; thus, the use of brick masonry as a load-bearing material may then become uneconomical.

In previous investigations\(^1,2\), for a given slenderness ratio of the test piece and given coring pattern of the bricks, the masonry strength increased as the standard compressive strength of bricks and mortar increased. However, even if the strengths of mortar and bricks are approximately equal, the strength of the masonry is smaller than the strength of its constituents. Poor workmanship and low workability of the mortar generally result in masonry strength reduction. Furthermore, thick mortar joints reduce the masonry strength, and masonry strength is influenced by the water absorption of the bricks. However, these relationships exhibit unusually larger scatter.

From observations of brick failure mode, it was concluded that the failure of masonry loaded in compression is initiated by vertical cracking or splitting of the bricks. Therefore, various attempts have been made to relate the compressive strength of masonry to the tensile strength of the bricks.\(^3\)

Since a multitude of parameters govern the compressive strength of brick masonry, a reasonably accurate estimate of the masonry compressive strength is possible only if these parameters are considered simultaneously, and if the failure mechanism of masonry is taken into account. In the following, this failure mechanism will be studied and, based upon this discussion, a procedure will be developed which may enable us to predict strength and behavior of masonry units from characteristic properties of its constituents which can be determined in simple tests.

The Stress State in Brick Masonry Subjected to Uniaxial Compression

Brick masonry is a two-phase material, both phases not only have different strengths but also different deformation characteristics. In general, the uniaxial compressive strength and the modulus of elasticity of the mortar are considerably lower than the corresponding values of the bricks. Therefore, if the mortar could deform freely, its lateral strains would be larger than the strains in the bricks. This is especially true if the external load approaches the uniaxial compressive strength of the mortar. However, because of bond and friction between brick and mortar, the mortar is confined. Thus, an internal state of stress is developed which consists of axial compression and lateral tension in the brick and triaxial compression in the mortar (Figure 6-1). It is only because of this triaxial state of compression that a masonry unit can be subjected to external stresses which exceed the uniaxial compressive strength of the mortar.

Even if care is taken in laying bricks, not all bricks will be evenly supported by their mortar bed. Then, in addition to the external load and the internal stress state described above, the
bricks are subjected to flexural and shear stresses. Insufficient filling of the mortar joints or varying thickness of bricks and joints give rise not only to these flexural stresses, but they also result in an uneven distribution of the external load. Then, stress concentrations are developed in the bricks which may be considerably larger than the nominal average stress on which all calculations of masonry strength are generally based.

**Results from an Experimental Investigation**

With this concept in mind, the author has investigated the failure mechanism of clay brick masonry units while working at the Laboratory for Building Materials at the Technical University of Munich. A detailed description of this investigation is reported in Reference 4.

Most of the masonry specimens tested in this investigation consisted of five layers of bricks (Specimen Type B in Figure 6-2). The thickness of the mortar joints was 0.47 inches and 0.24 inches, respectively. The bricks, 9.2 by 4.2 by 2.7 inches, had a standard compressive strength of 5300 psi according to the German Specification DIN 105. The flexural strength of the bricks was 780 psi, their tensile splitting strength amounted to 410 psi. The major parameters in this study were type and strength of the joint mortar. Either lime mortars, lime-cement mortars or cement mortars were used. Their compressive strength was determined from prismatic specimens 1.6 by 1.6 by 4.1 in. and ranged from 21 psi for the lime mortar to 3500 psi for the high strength cement mortars. Additional data are summarized in Table 6-1.

Numerous strain measurements over a gage length of 2 in. at the surfaces of several bricks were carried out to study the state of stress acting in the bricks if the masonry unit was subjected to an axial load (Figure 6-2).

In evaluating the strain measurements it was assumed that the stresses in the bricks acting in the horizontal x-direction are linearly distributed over the height of the brick. Then the stress $\sigma_x$ can be separated into two components: (a) the flexural stresses $\sigma_{xM}$ and the normal stresses $\sigma_{xN}$ which are constant over the height of a brick. The stresses $\sigma_{xN}$ can be attributed to differences in lateral strains between the mortar and the bricks. The flexural stresses may be caused by an uneven support of the bricks as described earlier.

For two specimens the distribution of lateral stresses $\sigma_{xN}$ and $\sigma_{xM}$ and of the longitudinal stresses $\sigma_y$ across the width of a brick is given in Figures 6-3 and 6-4. These results confirm the original concept of the stress state in masonry. Lateral tension, whose magnitude increases as the external load is increased, was observed in the bricks. Despite the extreme care taken in manufacturing the masonry samples, the flexural stresses and an almost random distribution of the stresses in the direction of the external load could not be avoided.

Vertical cracking was observed in the bricks at loads considerably below the failure load. In most cases initial cracking occurred in sections in which the sum of the stresses $\sigma_x = \sigma_{xM} + \sigma_{xN}$ reached a maximum.
### Table 6-1
Summary of Test Results

<table>
<thead>
<tr>
<th>Specimen Nr.</th>
<th>Type</th>
<th>Mortar Type</th>
<th>$f'_{m}$</th>
<th>$f'_{m}$ Calc.</th>
<th>$U_{u}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/1</td>
<td>A</td>
<td>lime cement</td>
<td>410</td>
<td>5.1 x 10^5</td>
<td>2210</td>
</tr>
<tr>
<td>1/2</td>
<td>B</td>
<td>lime cement</td>
<td>410</td>
<td>5.1 x 10^5</td>
<td>2370</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>cement</td>
<td>410</td>
<td>5.1 x 10^5</td>
<td>2930</td>
</tr>
<tr>
<td>3/1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3460</td>
</tr>
<tr>
<td>3/2</td>
<td>B</td>
<td>cement</td>
<td>3500</td>
<td>3.1 x 10^6</td>
<td>3100</td>
</tr>
<tr>
<td>3/3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3290</td>
</tr>
<tr>
<td>4/1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3600</td>
</tr>
<tr>
<td>4/2</td>
<td>B</td>
<td>cement</td>
<td>3500</td>
<td>3.5 x 10^6</td>
<td>4850</td>
</tr>
<tr>
<td>4/3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3320</td>
</tr>
<tr>
<td>5/1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1060</td>
</tr>
<tr>
<td>5/2</td>
<td>B</td>
<td>lime</td>
<td>21</td>
<td>9.4 x 10^4</td>
<td>1370</td>
</tr>
<tr>
<td>5/3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1830</td>
</tr>
<tr>
<td>6/1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1570</td>
</tr>
<tr>
<td>6/2</td>
<td>B'</td>
<td>lime</td>
<td>21</td>
<td>9.4 x 10^4</td>
<td>1490</td>
</tr>
<tr>
<td>6/3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1530</td>
</tr>
</tbody>
</table>

Joint thickness: specimens A, B: 0.47 in.
Specimens B': 0.24 in.

To express analytically the nonuniformity of the stresses in the direction of the external load $\sigma_y$, the nonuniformity coefficient, $U$, was introduced. This coefficient is the ratio between the maximum normal stress observed within one brick to the average normal stress acting on the masonry. The coefficient of nonuniformity is a function of the applied load. At low stresses, $U$ decreases as the external load increases: local “yielding” or crushing of the mortar at points of high stress concentration results in a more even distribution of stresses. As failure approaches, the nonuniformity coefficient rapidly increases (Figure 6-5).

The coefficient of nonuniformity at failure is also a function of strength and workability of the mortar. As the mortar strength increases the coefficient $U$ decreases (Figure 6-6). It is likely that $U$ is also a function of the workability of the mortar. It should be larger for mortars with low workability than for mortars with high workability, since workable mortars result in more uniform joints and, thus, in a more uniform support of the brick. However, this tendency cannot be clearly deduced from the available data.

If the local stress concentrations in the bricks were the only parameter affecting the compressive strength of various masonry units made from the same types of bricks, the failure should occur as soon as the maximum local stress $\sigma_{ym}$ exceeds the compressive strength of the brick, where $U$ is the nonuniformity coefficient and $\sigma_{ym}$ is the applied stress.
average stress. In Figure 6-7 this maximum stress observed in masonry units made of different types of mortar is given as a function of the compressive strength of the mortar. Figure 6-7 shows, however, that as the compressive strength of the mortar increases, the maximum local stress in the brick at failure also increases. On a phenomenological basis this tendency can be explained as follows: low strength mortars develop larger lateral tensile stresses in the bricks than do the high-strength mortars. In general, the compressive strength of brittle materials in a given longitudinal direction decreases as simultaneously acting tensile stresses in lateral directions increase. Consequently, the maximum stress which the brick can sustain decreases as the mortar strength decreases.

An Analytical Procedure to Predict the Strength of Clay Brick Masonry Loaded in Compression

Figure 6-8 shows the development of stresses as they may occur in a single brick within a masonry unit subjected to axial compression. It is assumed that the lateral tensile stresses in the x and z directions, $\sigma_x$ and $\sigma_z$, are equal. In Figure 6-8 these stresses are given as a function of the local maximum stresses, $\sigma_y$, which act in the direction of the external load. The stresses $\sigma_y$ can be computed from the average masonry stresses, $\sigma_{ym}$, and the coefficient of nonuniformity $U$. Line A in Figure 6-8 represents the failure criterion for the triaxial strength of bricks and indicates the combinations of compressive stresses $\sigma_y$ and lateral tensile stresses $\sigma_x$ and $\sigma_z$ which will cause local failure or cracking of the brick. For $\sigma_x = \sigma_z = 0$, $\sigma_y$ is equal to the uniaxial compressive strength of the
If the external load is increased beyond the load at first cracking, then stresses in an uncracked section of the brick may develop along line $B_2$. As soon as line $B_2$ intersects the failure criterion line $A$, the second crack is formed. This process of cracking continues, and the brick may be split into small elements. Excessive cracking also results in an increase of the coefficient of nonuniformity (see test results in Figure 6-5).

Under the best conditions, failure of the masonry occurs when the lateral tensile strength of the brick is smaller than the stress which is necessary to sufficiently confine the mortar. Therefore, the intersection of the failure criterion line $A$ and the minimum lateral stress line $C$ corresponds to the ultimate load of the masonry unit.

In Figure 6-8 the parameters which are known to affect the compressive strength of brick masonry are considered:

1. The uniaxial compressive strength of the brick.
2. The biaxial tensile strength of the brick.
3. The failure criterion for bricks under a triaxial state of stresses as represented by line $A$.
4. The uniaxial compressive strength of the mortar which corresponds to the onset of line $C$ in Figure 6-8.
5. The behavior of the mortar under a state of triaxial compression, determining the shape and inclination of line $C$.
6. The coefficient of nonuniformity.

Failure of the masonry may occur before line $A$ intersects with line $C$: the stress state at the surface of the brick and the mortar joints is only biaxial, so the mortar is not sufficiently confined; therefore, spalling of the surface layers of the brick may occur at lower stresses and may result in a rapidly progressing failure.

The following equation is an attempt to express the failure criterion described above in an analytical form. No information on the behavior of bricks under triaxial stresses was available. Therefore, it was assumed that the failure criterion line $A$ as shown in Figure 6-8 corresponds to a straight line. Then, line $A$ can be expressed by the following equation:

$$
\sigma_x = \sigma_z = f'_{bt} \left[ 1 - \frac{\sigma_y}{f'_b} \right]
$$

in which $\sigma_x, \sigma_z, \sigma_y$ = stresses in $x, y$ or $z$-direction

- $f'_b$ = uniaxial compressive strength of brick
- $f'_{bt}$ = strength of brick under biaxial tension

Line $C$ corresponds to the minimum lateral tensile stress which has to act in the brick to sufficiently confine the mortar. It depends on the behavior of the mortar under triaxial compression. No corresponding tests have been carried out in this investigation. Therefore, it was assumed that the strength of the mortar under triaxial compression is similar to the strength of concrete under triaxial compression. Richard Brandtzaeg and Brown in their investigation of the triaxial...
strength of concrete found that the triaxial strength of concrete can be approximated by the following expression:

\[ f'_t = f'_c + 4.1\sigma_2 \]  

(6-2a)

In which:
- \( f'_t \) = compressive strength of a laterally confined concrete cylinder
- \( f'_c \) = uniaxial compressive strength of concrete cylinder
- \( \sigma_2 \) = lateral confinement of cylinder

If Equation 6-2 is valid for mortars, then the minimum lateral confinement of the mortar joint is:

\[ \sigma_{xj} = \frac{1}{4.1} (\sigma_y - f'_j) \]  

(6-2b)

In which:
- \( \sigma_{xj} \) = lateral compressive stress in mortar joint
- \( \sigma_y \) = local stress in y-direction
- \( f'_j \) = uniaxial compressive strength of mortar

For simplicity let us assume that the lateral stresses \( \sigma_x \) in bricks and mortar joints are uniformly distributed over the height of bricks and mortar. Then from the equilibrium condition it follows that

\[ \sigma_{xb} \cdot b = \sigma_{xj} \cdot j \]  

(6-3)

In which:
- \( \sigma_{xb} \) = lateral tensile stress in bricks
- \( \sigma_{xj} \) = lateral compressive stress in mortar joint
- \( b \) = height of brick
- \( j \) = thickness of joint

Substituting Equation 6-3 in Equation 6-2a we obtain an expression for Line C in Figure 6-8

\[ \sigma_x = \frac{j}{4.1b} (\sigma_y - f'_j) \]  

(6-4)

From Equation 6-1 and 6-4 the magnitude of the maximum local stress at failure, \( \sigma_y \), can be determined. It corresponds to the point of intersection of lines A and C:

\[ \sigma_y = \frac{f'_b \cdot a}{f'_bt + a \cdot f'_b} \]

where \( a = \frac{j}{4.1b} \)

Using the nonuniformity coefficient at failure \( U_u \), the average masonry stress at failure can be expressed as

\[ \sigma_{ym} = f'_m = \frac{\sigma_y}{U_u} \]

Then we obtain as a general expression for the axial compressive strength of masonry:

\[ f'_m = \frac{f'_b}{U_u} \cdot \frac{f'_bt + a \cdot f'_j}{f'_bt + a \cdot f'_b} \]  

(6-5)

This expression depicts the known relationships between the compressive strength of masonry and various parameters: masonry strength increases with increasing compressive strength of bricks and mortar, with increasing tensile strength of bricks, and with decreasing ratio of joint thickness to height of brick. It should be realized, however, that \( U_u \) is not a constant but depends on a number of parameters including the joint thickness and the mortar strength.

**Conclusions**

Equation 6-5 was used to evaluate the results of this investigation. The biaxial tensile strength of the bricks or the relationship between uniaxial tensile strength and biaxial tensile strength were unknown. Therefore, it was assumed that
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the biaxial tensile strength of the brick was equal to its uniaxial tensile strength. Furthermore, it was assumed that the uniaxial compressive strength of the bricks is equal to its standard strength. In Figure 6-9 the masonry strength computed from Equation 6-5 is compared to the experimental results: the compressive strength of the test specimens could be predicted within a range of ±20% of the actual values. For the higher strength mortars, the computed values generally were too low; however, they were too high for the low-strength mortars. This may be due to an erroneous assumption of the failure criterion for bricks and mortar under triaxial stress states. The relationship given by Richart, Brandtzaeg and Brown is empirical and is not necessarily the same for all types of mortars. Nevertheless, this rational approach in the prediction of the compressive strength of masonry units appears to be promising. Before a general applicability of Equation 6-5 could be recommended, various characteristic properties of masonry have to be established which were normally not investigated in previous studies. These are:

1. The coefficient of non-uniformity, \( U \), as a function of (a) quality of workmanship, (b) type and compressive strength of mortar, (c) type of bricks, (d) pattern of masonry unit and coring of bricks, and (e) thickness of joints.

2. The behavior of bricks and mortars subjected to defined triaxial stress states.

3. A relationship between the strength of bricks under biaxial tension, uniaxial tension and flexure.

Then an approach as outlined in the foregoing may enable us to safely predict the compressive strength of masonry from properties of its constituents which can be easily determined in standard tests.

Notations

- \( a \) Coefficient to evaluate Equation 6-5
- \( b \) Height of brick
- \( E \) Modulus of elasticity
- \( f'_{c} \) Uniaxial compressive strength of brick
- \( f'_{bt} \) Biaxial tensile strength of brick
- \( f'_{c} \) Compressive strength of standard concrete cylinder
- \( f'_{j} \) Uniaxial compressive strength of joint mortar
- \( f'_{m} \) Compressive strength of masonry unit
- \( f'_{l} \) Compressive strength of standard concrete cylinder which is confined by a stress \( \sigma_2 \)
- \( j \) Thickness of mortar joint
- \( \sigma_x, \sigma_y, \sigma_z \) Stresses in x, y and z-direction
- \( \sigma_{xy} \) Stress in brick acting in x-direction
- \( \sigma_{yj} \) Stress in mortar joint acting in x-direction
- \( \sigma_{ym} \) Average masonry stress in y-direction
- \( \sigma_2 \) Confining pressure of a concrete cylinder
- \( U \) Nonuniformity coefficient
- \( U_u \) Nonuniformity coefficient at failure

References

Remarks

By Bob D. Campbell
Bob D. Campbell & Company, Structural Engineers

I was impressed by the mutual support of papers 2 and 7 of the third session (chapters 6 and 11). Professor Hilsdorf’s paper, “An Investigation Into the Failure Mechanism of Brick Masonry Loaded in Axial Compression” clearly answered the question of “Why” the tangent modulus of elasticity increased with load on the stress-strain curve of “Experimental Investigation on the Structural Performance of Brick Masonry Prisms” by Dr. Rao. This increase was not necessarily slackness of experimental set up, nor was it densification of mortar, per se, as Dr. Rao proposes. It more likely is a picture of the mortar shifting from uniaxial compression to the triaxial compression condition reported by Professor Hilsdorf.

At the start of the loading it appears the tangent modulus is the result of the combination of the shortening of the brick plus that of the mortar in uniaxial compression. The final Tangent modulus is more nearly that of the brick alone. That is, with a true triaxial compression condition Poisson’s ratio is zero, and the mortar, so confined, is infinitely stiff. See Figure 6-A herewith.

The curved transition between the two end conditions is the interesting part of the graph. It appears to be a “picture” of that which is taking place, and I feel it should be closely analysed as future research in the interaction of brick and mortar.

I would like to commend the whole conference and these two authors in particular for the contribution to a more complete understanding by the practicing professions in masonry construction of many of the actions of brick, mortar, concrete, etc. when combined.