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SHEAR THEORY AND STRENGTH OF PERFORATED BRICK MASONRY UNDER SHEAR-COMPRESSION COMBINED LOADING

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Abstract

Through the shear strength test of three-perforated-brick models under different N/N_u ratios which is defined as the ratio of working compressive stress and compressive strength, the failure mode and theory under shear-compression combined loading have been studied primarily. After regressive analysis of the test data, the calculating formula of combined shear strength is obtained. The comparison of formula between perforated and solid brick masonry shows the influence of brick's holes upon combined shear strength. In the end, the complement and development to shear theory and strength calculating method are presented.

Key words

perforated brick, combined loading, failure theory, shear strength.

1 Foreword

The calculating formula of combined shear strength of masonry given by Wankang. Luo et al (1997) has been adopted by the Masonry Code of China. Without the limitation of Mohr's and Coulomb's theory, this formula presents the combined shear strength of masonry more accurately. The study of straight line shear strength of perforated brick masonry has show that holes influence distinctly on shear ability and failure theory. The pure shear strength f_{vo} of perforated brick masonry is made up of cohesive shear strength and pin key shear strength. Under shear-compression loading, some questions about shear ability of perforated brick masonry, such as how holes act on shear strength, what about it's failure mode, and whether the shear strength calculating formula of solid brick masonry is applicable to perforated brick masonry, need to be answered through experimental study.

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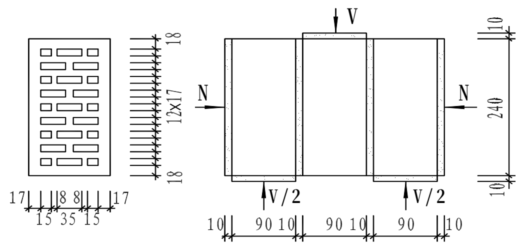
2 General situation of experiment

Ninety pieces of three-brick specimens are made out of KP1 type fired shale perforated bricks with the hole ratio of 26.3% (it's dimension see Figure 1 a) and three kinds of mortar whose respective strength is M2.5 M7.5 and M15. Specimen's dimension and loading mode are shown in Figure 1 b. The average compressive strength of material and masonry is summarized in Table 1.



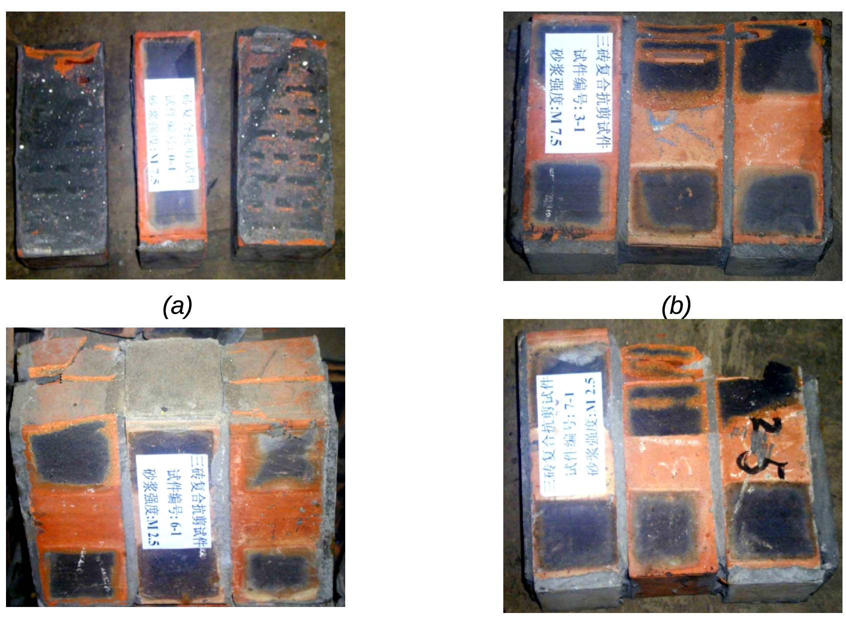
(a) (b)

Figure 1 Dimension of brick and specimen and loading mode

Table 1 Average compressive strength of material [N/mm^2]

Strength of brick (f_1^t)	20.4		
Mortar type	M2.5	M7.5	M15
Strength of mortar f_2^t	8.62	18.72	33.52
Strength of masonry f_m^t	8.58	12.37	17.90

3 Experimental result and theoretical analysis



(a) (b)

(c) (d)

Figure 2 Failure modes of combined shear of perforated brick masonry

3.1 Failure mode

The same with solid brick, perforated brick masonry has three kinds of failure modes: shear-friction, shear-compression and inclined compression. But due to the holes of bricks, the failure modes of perforated brick masonry are somewhat different from the solid brick masonry's.

①Shear-friction failure: when the ratio N/N_u is small and the strength of mortar is low, masonry fails along the straight line of mortar layer (see Figure 2 a). Here the pin keys of mortar layer in the brick's holes have been cut off. On this kind of condition, the anti-shear capability of masonry is low.

②Shear-compression failure: with the increase of N/N_u and mortar's strength, the middle piece of brick's vertical rib detaches from block. This kind of failure is the result of double direction stress. Under combined loading, horizontal expansion of top of middle brick is big, a big horizontal expansion due to the breakaway of vertical rib from lateral rib. Once the vertical rib breaks away, it's unsupported length increases greatly and in a very short time unstable failure happen(see Figure 2 b).

③ Inclined compression failure: when N/N_u increases to a very high level, in the stress that the specimen bears, the compression occupies the main part. Then the specimen cracks along the direction of holes(see Figure 2 c and 2 d).

3.2 Experimental data

Testing values of combined shear strength of perforated brick masonry are presented in Table 2.

Table 2 Testing and average values(f_v^t)of combined shear strength of perforated brick masonry[N/mm²]

N/N_u	M2.5(8.62 N/mm²)				M7.5(18.72 N/mm²)				M15(33.52 N/mm²)			
	No.1	No.2	No.3	$f_{v,m}^t$	No.1	No.2	No.3	$f_{v,m}^t$	No.1	No.2	No.3	$f_{v,m}^t$
0	—	0.81	1.11	0.96	1.06	0.95	—	1.01	1.16	1.06	1.00	1.07
0.1	1.22	0.94	—	1.08	1.05	1.22	1.08	1.12	1.25	1.55	1.58	1.46
0.2	1.48	1.28	1.13	1.30	1.02	1.56	1.60	1.39	1.58	1.15	1.70	1.47
0.3	1.70	0.98	1.21	1.31	1.14	2.18	1.05	1.46	1.80	1.66	1.55	1.67
0.4	1.60	1.18	1.24	1.35	1.67	1.97	1.37	1.67	1.61	1.59	2.05	1.75
0.5	1.50	1.54	1.63	1.56	1.61	1.85	1.74	1.73	1.30	2.03	1.60	1.64
0.6	1.60	1.36	1.23	1.38	1.75	1.50	1.83	1.69	1.15	1.87	1.71	1.58
0.7	1.45	0.97	1.05	1.16	1.49	1.43	—	1.46	—	1.13	1.05	1.09
0.8	0.87	1.28	1.31	1.15	1.92	1.16	1.25	1.44	1.07	—	—	1.07
0.9	1.13	0.84	—	0.99	1.28	1.32	1.36	1.32	0.69	—	—	0.69

3.3 Regression of experimental data

3.3.1 Regression of experimental data of perforated brick masonry

Regard the pure shear strength f_{v0}^t on condition that N/N_u = 0 in Table 2 as the contrastive parameter, then list in Table 3 the average values of f_v^t / f_{v0}^t (V_u/V_0) corresponding to the three kinds of strengths of mortar. The shear-compression equation which has two parts can be got from regression of data in table 3.

the ascending part ($0 \le N/N_u \le 0.5$) is expressed as a quadratic paracurve:

$$V_u/V_0 = 1.005 + 2.082\,N/N_u - 1.702(N/N_u)^2 \quad (1)$$

the descending part ($0.5 \le N/N_u \le 1.0$) is expressed as a cubic paracurve:

$$V_u/V_0 = 14.514 - 56.984\,N/N_u + 82.330(N/N_u)^2 - 39.870(N/N_u)^3 \quad (2)$$

Table 3 The relative values of shear strength of perforated brick masonry experiment

N/N_u	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
$f_v^t/f_{v0}^t(V_u/V_0)$	1	1.199	1.370	1.457	1.566	1.624	1.531	1.222	1.210	0.993

3.3.2 Regress of combined shear strength data of common solid brick masonry

Also regard f_{v0}^t as the contrastive parameter and carry out regression analysis on the experimental data (Wankang.Luo et al 1997). The shear-compression equation can be presented as below:
the ascending part ($0 \le N/N_u \le 0.6$) is expressed as a quadratic paracurve:

$$V_u/V_0 = 1.055 + 10.446 N/N_u - 9.143(N/N_u)^2 \tag{3}$$

the descending part ($0.6 \le N/N_u \le 1.0$) is expressed as a cubic paracurve:

$$V_u/V_0 = 78.081 - 316.811 N/N_u + 442.207(N/N_u)^2 - 204.500(N/N_u)^3 \tag{4}$$

3.3.3 Comparison of averaged values for combined shear strength and shear theory between perforated and solid brick masonry

With the introduction of $V_0 = f_{v0,m}^t A$ $V_u = f_{v,m}^t A$ $N = s_{0k} A$ $N_u = f_m^t A$ and the shear-compression strength ratio $m = \frac{V_0}{N_u} = \frac{f_{v0,m}^t}{f_m^t}$, the regressive equations 1 to 4 change into the shear-friction theory mode as below:

$$f_{v,m}^t = f_{v0,m}^t + m s_{0k} \tag{5}$$

Where the μ is the changing friction coefficient, which is defined as the influence coefficient of shear-compression combined loading in Chinese code.
① For the perforated brick masonry, the average value formulas of shear strength can be got from equation 1 and 2.
the ascending part ($0 \le s_{0k}/f_m^t \le 0.5$):

$$f_{v,m}^t = 1.005 f_{v0,m}^t + m_1 s_{0k} \tag{6}$$

$$m_1 = (2.082 - 1.702\frac{s_{0k}}{f_m^t})m \tag{7}$$

the descending part ($0.5 \le s_{0k}/f_m^t \le 1.0$):

$$f_{v,m}^t = 1.005 f_{v0,m}^t + m_2 s_{0k} \tag{8}$$

$$m_2 = [13.509\frac{f_m^t}{s_{0k}} - 56.984 + 82.330\frac{s_{0k}}{f_m^t} - 39.870(\frac{s_{0k}}{f_m^t})^2]m \tag{9}$$

Keep the m_2 values on N/N_u =0.5 and 1.0 two points, abridge the quadratic curve (formula 9) to a beeline crossing the two points as below:

$$m_2 = (3.479 - 4.494\frac{s_{0k}}{f_m^t})m \tag{10}$$

②For the solid brick masonry, the average value formulas of the shear strength can be got from equation 3 and 4.
the ascending part ($0 \le s_{0k}/f_m^t \le 0.6$):

$$f_{v,m}^t = 1.055 f_{v0,m}^t + m_1 s_{0k} \tag{11}$$

$$m_1 = (10.446 - 9.143\frac{s_{0k}}{f_m^t})m \tag{12}$$

the descending part ($0.6 \le s_{0k}/f_m^t \le 1.0$):

$$f_{\mathrm{v,m}}^{\mathrm{t}} = 1.055 f_{\mathrm{v0,m}}^{\mathrm{t}} + m_2 \sigma_{0\mathrm{k}} \tag{13}$$

$$m_2 = [78.081 \frac{f_{\mathrm{m}}^{\mathrm{t}}}{\sigma_{0\mathrm{k}}} - 316.811 + 442.207 \frac{\sigma_{0\mathrm{k}}}{f_{\mathrm{m}}^{\mathrm{t}}} - 204.500 (\frac{\sigma_{0\mathrm{k}}}{f_{\mathrm{m}}^{\mathrm{t}}})^2] m \tag{14}$$

Abridge formula 14 to a linear equation:

$$m_2 = (14.121 - 15.144 \frac{\sigma_{0\mathrm{k}}}{f_{\mathrm{m}}^{\mathrm{t}}}) m \tag{15}$$

③To compare the combined shear strength of perforated brick masonry with that of solid brick masonry, introducing the shear-compression strength ratio $m = \frac{V_0}{N_{\mathrm{u}}} = \frac{f_{\mathrm{v0,m}}^{\mathrm{t}}}{f_{\mathrm{m}}^{\mathrm{t}}}$ into the regress expression and adopting the value $f_{\mathrm{v0,m}}^{\mathrm{t}} = 0.18\sqrt{f_2}$ (Shihong.Qin et al 2004a), then the expressions of shear strength average value of perforated brick masonry compared with mortar strength as below.

the ascending part:

$$\frac{f_{\mathrm{v,m}}^{\mathrm{t}}}{\sqrt{f_2}} = 0.181 + 0.375 \frac{\sigma_{0\mathrm{k}}}{f_{\mathrm{m}}^{\mathrm{t}}} - 0.306 (\frac{\sigma_{0\mathrm{k}}}{f_{\mathrm{m}}^{\mathrm{t}}})^2 \tag{16}$$

the descending part:

$$\frac{f_{\mathrm{v,m}}^{\mathrm{t}}}{\sqrt{f_2}} = 2.612 - 10.257 \frac{\sigma_{\mathrm{ok}}}{f_{\mathrm{m}}^{\mathrm{t}}} + 14.819 (\frac{\sigma_{0\mathrm{k}}}{f_{\mathrm{m}}^{\mathrm{t}}})^2 - 7.177 (\frac{\sigma_{0\mathrm{k}}}{f_{\mathrm{m}}^{\mathrm{t}}})^3 \tag{17}$$

The same, adopting $f_{\mathrm{v0,m}}^{\mathrm{t}} = 0.125\sqrt{f_2}$ according to the code of China, and the corresponding expressions of solid brick masonry can be shown as below.

the ascending part:

$$\frac{f_{\mathrm{v,m}}^{\mathrm{t}}}{\sqrt{f_2}} = 0.132 + 1.306 \frac{\sigma_{0\mathrm{k}}}{f_{\mathrm{m}}^{\mathrm{t}}} - 1.143 (\frac{\sigma_{0\mathrm{k}}}{f_{\mathrm{m}}^{\mathrm{t}}})^2 \tag{18}$$

the descending part:

$$\frac{f_{\mathrm{v,m}}^{\mathrm{t}}}{\sqrt{f_2}} = 9.760 - 39.601 \frac{\sigma_{\mathrm{ok}}}{f_{\mathrm{m}}^{\mathrm{t}}} + 55.276 (\frac{\sigma_{0\mathrm{k}}}{f_{\mathrm{m}}^{\mathrm{t}}})^2 - 25.562 (\frac{\sigma_{0\mathrm{k}}}{f_{\mathrm{m}}^{\mathrm{t}}})^3 \tag{19}$$

④From comparison of $\frac{f_{\mathrm{v,m}}^{\mathrm{t}}}{\sqrt{f_2}} \sim \frac{\sigma_{0\mathrm{k}}}{f_{\mathrm{m}}^{\mathrm{t}}}$ curves of combined shear in Figure 3, we can

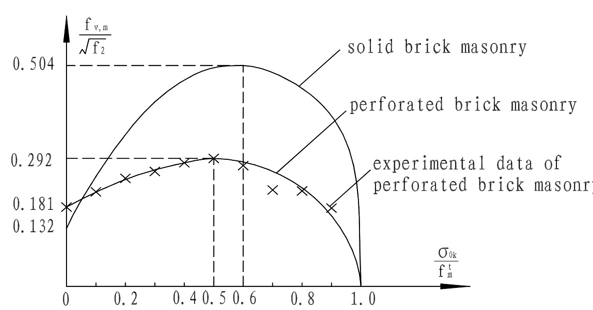


Figure 3 Comparison of shear-compression combined relative curve between perforated and solid brick masonry

learn that the shear-compression relative laws of perforated and solid brick masonry are similar. But because the existence of mortar pin keys that embedded in holes of

brick, when $\frac{s_{0k}}{f_m^t} = 0$, the $f_{v,m}^t$ of perforated brick masonry is bigger than that of solid brick masonry. While the peak value of $f_{v,m}^t$ of perforated brick masonry is smaller than that of solid brick masonry. This indicates that on net section of perforated brick masonry, the increase speed of friction which is created by compressive stress is much smaller than that of solid brick masonry. Further more, the compression does not redound to the increase of pin key’s shear strength, so it is not safe to calculate the shear strength of perforated brick masonry with the formula which is applicable to solid brick masonry.

3.3.4 The comparison of changing friction coefficient (μ) between perforated and solid brick masonry

Base on the previous study, with the substitution of $f_{v0,m} = 0.18\sqrt{f_2}$ (Shihong.Qin et al 2004a) and $f_m = 0.28 f_1^{0.87}(1+0.07 f_2)$ (Shihong.Qin et al 2004b), the value of *m* can be calculated by the formula as below:

$$m = \frac{f_{v0,m}}{f_m} = \frac{0.18\sqrt{f_2}}{0.28 f_1^{0.87}(1+0.07 f_2)} \qquad (20)$$

For perforated brick, with the adoption of f_1 and f_2 of all strength levels, the average value of $\overline{m} = 0.0858$ can be got. With the introduction of $\overline{m}$, formula 7 and 10 change into the forms as below:

$$m_1 = 0.179 - 0.146\frac{s_{0k}}{f_m^t} \quad \text{(the ascending part)} \qquad (21)$$

$$m_2 = 0.298 - 0.386\frac{s_{0k}}{f_m^t} \quad \text{(the descending part)} \qquad (22)$$

The same, for solid brick masonry, according to Code for Design of Masonry Structures, adopt $f_{v0,m} = 0.125\sqrt{f_2}$ and $f_m = 0.78\sqrt{f_1}(1+0.07 f_2)$. With the introduction of $\overline{m} = 0.0626$, formula 12 and 15 change into the forms as below:

$$m_1 = 0.654 - 0.572\frac{s_{0k}}{f_m^t} \quad \text{(The ascending part)} \qquad (23)$$

$$m_2 = 0.884 - 0.948\frac{s_{0k}}{f_m^t} \quad \text{(The descending part)} \qquad (24)$$

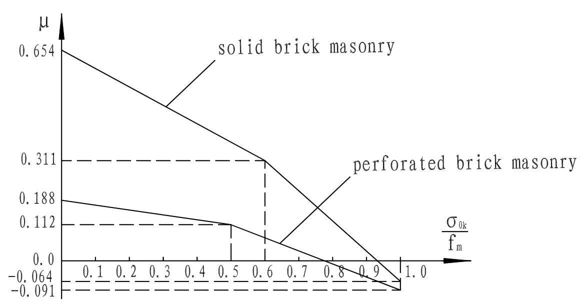


Figure 4 The comparison of μ between perforated and solid brick masonry

The comparison of changing friction coefficient (μ) of two kinds of brick masonries see figure 4. From comparison we can learn that the value of μ of perforated brick

masonry is much lower than that of solid brick masonry. This indicates the existence of holes greatly reduces the frictional shear capability which is created by compression.

4 Conclusions

The shear-compression relative law of perforated brick masonry is similar to that of solid brick masonry. But because the straight line shear strength of perforated brick masonry is higher than that of solid brick masonry, the initial point of relative curve of perforated brick masonry is higher. In addition, because the net area of perforated brick is small, compressive stress contributes a little to increase of frictional shear effect and does no contribution to pin key's shear effect, so the curve of perforated brick masonry is flat and the peak point is lower than that of solid brick masonry.

The peak s_{0k}/f_{m} value of solid brick masonry combined curve is 0.6. While the value of perforated brick masonry is 0.5.

When perforated brick masonry fails along straight or stair line, the average value can be calculated by formula 6 7 8 and 10.

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