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SHEAR STRENGTH ANALYSIS FOR CLAY BRICK MASONRY WALLS

S B Lee and G T Suter
Department of Civil and Environmental Engineering
Carleton University, Ottawa, Ontario, Canada K1S 5B6

ABSTRACT

Shear strength is an important material property for masonry structures, especially for seismic design and performance analysis of structures in earthquakes. Because of its importance, there have been a large number of projects and studies involving shear behaviour of masonry structures and structural members including static and dynamic tests, numerical analyses, case studies and concept discussions. This paper makes a contribution to that body of knowledge.

Based on the analysis of a series of test results on clay brick masonry shear walls, the paper provides a discussion of theories and presents equations for the calculation of shear resistance of both unreinforced and horizontally reinforced clay brick masonry walls.

INTRODUCTION

In many countries, masonry is one of the main forms of building construction. It is therefore very important to optimise its structural performance, especially in earthquake zones or where strong winds exist.

Damage to structures in earthquakes is primarily caused through horizontal loads (Fig. 1), as indicated in the Kobe earthquake in Japan [Fleming, 1995] a few years ago. Although there have been some reported cases of vertical movements [Li, 1986], most codes of practice on seismic design only consider horizontal loading effects. In these circumstances the shear strength of masonry walls is obviously significant.

In non-seismic areas the shear behaviour of masonry structures is important if high wind loads are applied where the walls parallel to the direction of the wind sustain high horizontal loads.

In the current calculation of shear resistance for masonry walls, the expressions usually include a portion provided by masonry and a portion provided by reinforcement in the case of reinforced masonry as shown in the following form:

$$V = V_m + V_r$$

Here, V is the shear resistance of the wall; V_m is the shear resistance provided by masonry; and V_r is the shear resistance provided by reinforcement. The portion of shear resistance provided by masonry is usually a function of the shear or tensile strength of masonry and of precompression on the structural member, such as,

$$\tau = \tau_0 + \mu\sigma_0$$

Here, τ is the overall shear strength; τ_0 is the initial shear strength; μ is the coefficient of friction; and σ_0 is the precompression stress. The compressive strength of masonry is often involved either directly or indirectly.

In most building standards and codes of practice, tensile and shear strengths of masonry are only concerned with mortar; however, actual test results suggest otherwise. From comparing the behaviour of reinforced and unreinforced masonry shear walls, horizontally reinforced masonry should not primarily use the strength of reinforcement as an additional portion of the shear resistance as suggested by current equations. What actually happens is that the reinforcement brings those unused portions of unreinforced masonry walls into play and thus contributes to a better performance; of course, additional ductility and crack control are further contributions of the reinforcement.

In order to examine the effects of horizontal shear loads on masonry, the results of shear tests on 59 brickwork walls are analysed. Using this analysis and suggestions from other researchers, the causes of shear failure as well as a method of predicting the ultimate shear resistance of brickwork walls are considered.

DESCRIPTION OF TESTS

The tests were carried out in China [Zhou et al. 1987 and Zhou et al. 1987]. All the walls were solid and had a thickness of 240 mm. The percentage of horizontal reinforcement in joints varied from zero to 0.2% and mortar strength ranged from 0.54 to 22.7 N/mm^2. The spacing of horizontal reinforcing steel was typically two bars in every 2, 4 or 7 layers of masonry. All the walls were constructed using 240×120×53 mm (length × width × height) units, which had a standard compressive strength of 10 N/mm^2. Details of the walls are given in Table 1 and in the references [Zhou et al, 1987]. The walls were supported top and bottom but without in-plane supports as shown in Fig.1.

In Table 1, those specimens marked with a "*" are walls with reinforced concrete tie columns at each end. Details of R.C. tie columns and the relation with the clay brick masonry wall are shown in Fig.2. The R.C. tie columns and R.C. girth beams form a light frame system which would provide extra support for a masonry structure and this system has been extensively used in earthquake regions in China. The interactive layout prevents the separation of the columns from the wall because there are no weak shear planes between them. The R.C. tie columns also provide reliable end anchorage for horizontal reinforcement in the joints.

In general, cyclic horizontal loads caused by external forces are applied to brick masonry walls between floors as shown in Fig.1. Consequently the testing rig was designed to simulate this loading and horizontal cyclic loads were applied in all the tests.

CRACK PATTERNS

Both the reinforced and unreinforced walls were loaded cyclically, the maximum load of each cycle being increased by a uniform amount. The cracking load was defined as the load when the first crack, or cracks, on the wall were observed. All specimens failed with a shear pattern of cracks. In general, a few larger cracks were noted in the unreinforced masonry walls, these usually being one or two principal diagonal cracks with some smaller ones at right angles to these. More diagonal cracks in both directions occurred in the reinforced masonry walls; the more reinforcement the wall had, the better distributed the cracking became. Fig.3 shows the crack patterns of two typical walls.

No obvious separation was observed between the wall and the R.C. tie columns when present. The behaviour of the R.C. tie columns was deemed satisfactory during the loading process.

The test results indicated that stresses in the horizontal reinforcing steel bars were very low before the initial crack appeared, but they increased suddenly after the wall cracked, especially where the reinforcement crossed cracks. However, until the specimens failed at last, only a small portion of the strength of the reinforcing steel was used in the loading process.

DISCUSSIONS OF BEHAVIOUR UNDER SHEAR LOADING

Previous test experience with both horizontally reinforced and unreinforced walls [Zhou et al, 1987 and Zhou et al, 1987] indicates that masonry walls showed initial cracks in the central part of the wall when subjected to horizontal cyclic loads. Then cracks extended in the diagonal directions, ultimately splitting the wall into four sections.

In order to establish which factors affect the shear resistance, the horizontal load / horizontal cross section area of the wall was defined and termed as "the overall shear stress", τ_{ov}. This parameter was only utilised to enable influences on the shear resistance to be determined. It is not suggested the term has significance in terms of shear stress.

Shear Resistance and Strength of Masonry

Fig.4 shows the relationship between the strength of mortar and the overall shear stress at ultimate load. Fig.5 shows the relationship between the compressive strength of masonry and the overall shear stress. Here, the compressive strength of masonry is the value of average strength and it is the result of the following equation [National Standard of China, 1988].

$$f_m = k_1 f_1^{\alpha} (1 + 0.07 f_2) k_2$$

where, f_m is the average compressive strength of masonry; k_1 is 0.78 for clay brick masonry; f_1 is the average compressive strength of the masonry unit; α is 0.5 for clay brick masonry; f_2 is the average compressive strength of mortar; k_2 is usually 1.0 and, for clay brick masonry, $k_2 = 0.6 + 0.4f_2$ when $f_2 < 1.0$.

It is clear that the shear resistance steadily increases with increasing mortar strength as well as with increasing masonry compressive strength within the range of the tests.

Shear Resistance and Vertical Compressive Stress

Many authors [Amrhein, 1973], [Haseltine et al, 1981], [Hendry, 1983] and [Hamid et al, 1994] have indicated that the vertical compression on masonry plays a critical role in determining shear resistance. Fig.6 shows the relationship between the vertical compressive stress and the overall shear stress at the ultimate load of the 59 test walls. Included on the figure are the mean values of similar walls (marked by "x"), which generally increase as the vertical compressive stress increases.

Shear Resistance and Reinforcement

Fig.7 shows the relationship between the amount of reinforcement and the overall shear stress at ultimate load. The figure indicates no obvious relationship between the shear resistance and the percentage of reinforcement. In order to have a clearer view without the influence of other factors, an adjustment process was used to distinguish the effects of masonry strength and vertical compression. Thus Fig.8 shows that there is still no obvious overall strength increase or decrease due to the change in the amount of reinforcement. There are, however, two points which need further discussion. Means of similar walls (marked by "x") are included on Figs.7 and 8.

First, the specimens with R.C. tie columns at each end exhibited an almost straight line when the overall shear resistance was plotted against the percentage of reinforcement. To illustrate this, four walls identical in all respects except for their reinforcement were selected. A plot of the overall shear resistance vs the percentage of reinforcement is given in Fig.9. In contradiction to the finding above that the influence of reinforcement on shear resistance is negligible, this graph indicates that the amount of reinforcement in these walls has a definite influence on the shear resistance. In these walls, the R.C. tie columns and horizontal reinforcement would have provided better containment than in other walls. In such cases, any slight movement caused by external loads would cause an immediate response from the horizontal reinforcement because of the better anchorage provided by the R.C. columns. Thus, the better the anchorage of the reinforcement, the more it may contribute to the load carrying capacity of brickwork shear walls.

Secondly, Fig.10 shows the relationship between curvature, ϕ, and shear resistance for different groups of tested specimens where each group consists of specimens with a similar amount of reinforcement. It is evident that reinforced walls have a better ability to deform and, within limits, increases in reinforcement lead to improved deformation capacities. This is obviously useful for the energy absorbing capacity of masonry walls and will lead to better inelastic performance for a relatively brittle material.

Shear Resistance and Height / Length Ratio

Fig.11 shows the relationship between the overall shear stress and the height/length ratio. It can be seen that, in general, shear strength decreases with increasing h/l ratio. Means of similar walls (marked by "x") are included on the figure.

ANALYSIS AND PREDICTION OF SHEAR RESISTANCE

Theoretical Basis

Two theories dealing with the shear failure of unreinforced masonry structures are discussed. These are the Maximum Principal Stress theory and the Coulomb-Mohr or Internal Friction theory. In the analysis of the shear failure process of brickwork masonry walls, each is applicable but at different stages. Until initial cracking occurs, no surfaces along which friction can occur exist. Therefore, the Maximum Principal Stress theory should be used up to cracking after which both theories could be applicable because new cracks would still be occurring and old cracks would provide shear resistance by friction between cracked surfaces. However, a horizontally reinforced masonry shear wall will behave differently.

If in Fig.12, we assume that element 23 is the weakest element in an unreinforced masonry shear wall, then the initial crack will originate somewhere in the element if the wall is under biaxial stresses. Therefore, this element will not maintain its stiffness. The consequent redistribution of load will result in neighbouring elements bearing extra forces. The cracked element will push its neighbouring elements which may in turn cause horizontal cracks between elements 26 and 27, and between elements 22 and 23. As a second possibility in Fig.12, part of the cracked element 23 is pushing its neighbouring element 22 causing horizontal cracks and tensile forces to develop in element 22 with the potential for it to crack. In the masonry wall, this means the cracks will gradually develop in the diagonal directions after the initial crack forms, with the wall finally loosing its capacity for shear resistance.

But a reinforced masonry shear wall will behave differently. Horizontal bars will bind the masonry elements together and reduce the relative displacement between cracked parts of a cracked element. Neighbouring elements will not bear the extra forces from the cracked elements to the same degree because the stiffer steel bars will distribute these additional loads away. Consequently, element 23 will no longer be the weakest one after the initial crack occurs and other weaker elements will crack resulting in the steel bars in their locality distributing extra loads away from the cracked element. Through this process, there will be a distribution of cracks over the entire wall, the precise pattern depending on the arrangement of the reinforcement and the actual location of weak elements. The strength of masonry is not significantly increased with horizontal reinforcement but the reinforcement enables the entire wall to be utilised. Consequently, the strength of the reinforcement is not usually critical, its correct placement and distribution being far more important.

From the above discussion, it is thought that the Maximum Principal Stress theory will be more suitable for describing the ultimate shear resistance of horizontally reinforced masonry walls. Fig.13 shows a wall under horizontal shear load and constant vertical compressive stress. Considering a typical element from the wall, the principal tensile stress is

$$\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau^2}$$

Since $\sigma_x = 0$ and $\sigma_y = -\sigma_0$, where σ_0 is the stress due to the constant vertical load, then

$$\sigma_1 = -\frac{\sigma_0}{2} + \sqrt{\left(\frac{\sigma_0}{2}\right)^2 + \tau^2}$$

Letting $\sigma_1 \leq R_t$, where R_t is the tensile strength of masonry, when $\sigma_1 = R_t$,

$$\tau = R_t \sqrt{1 + \frac{\sigma_0}{R_t}} \qquad (1)$$

Prediction of Ultimate Shear Resistance

It is possible to produce curves to represent those testing points in Figs.4 to 6 using Eq.1, thus relating theory to practice. Eq.1 may therefore be used to determine the shear stress in a brickwork wall. However, the calculation of the ultimate shear resistance still requires the effect of the height/length ratio to be included as indicated in Fig.11. Assuming the calculation of shear resistance would be adjusted by a function of the panel's height/length ratio, the following formula is indicated.

$$V_u = F \cdot A \cdot \tau \qquad (2)$$

where V_u is the ultimate shear resistance; F is a function of the height/length ratio; A is the plan area of the wall; and τ is the shear stress obtained from Eq.1 above.

As the influence of horizontal reinforcement on the shear resistance is negligible (with the exception of walls with well anchored reinforcement), its effect will not be included in this formula.

To determine R_t, the tensile strength of masonry, a formula based on tests was used:

$$R_t = 0.079 f_m$$

where f_m is the compressive strength of masonry (N/mm^2). Using these results, empirical relationships between the actual h/l ratio of the panel and F can be derived. The following equation was used:

$$F = 1.2 - 0.2\,(h/l) \qquad (3)$$

In Eq.2, the cross sectional area A includes the equivalent effect of R.C. tie columns. The following formula is used when R.C. tie columns are involved:

$$A = A_j + \eta_g \frac{G_h}{G} A_h$$

where, A_j is the net cross section area of masonry wall; $\eta_g = 0.22$ when h/l ≥ 0.5 and $\eta_g = 0.2$ when h/l < 0.5; G_h is the shear modulus of concrete using 40% of E value of concrete; G is the shear modulus of masonry using 30% of E value of masonry; and A_h is the cross section area of R.C. tie columns.

Fig.14 and Table 1 show a comparison between test results and calculated ultimate shear resistance using Eqs.1, 2 and 3. While there is some scatter about the 45^0 equality line, there is an overall good agreement between tested and predicted shear capacities. Clearly, more results are needed at loads between 500 and 800 kN.

CONCLUSIONS

The shear resistance of brickwork shear walls under horizontal cyclic loading is affected by several factors. These are the strength of masonry, the vertical compressive stress on the panel, and the height/length ratio of the wall.

The shear resistance increases with increasing strength of masonry and with increasing vertical compressive stress on the wall, but may decrease with an increase in the height/length ratio of the wall.

The effect of horizontal reinforcement on the shear resistance is negligible. However, for walls with reinforced concrete tie columns or other means of containment, the shear resistance increases steadily with increasing amounts of reinforcement. Horizontal reinforcement always improves the deformational behaviour and the capacity for energy absorption of masonry.

A technique for predicting the shear resistance of unreinforced and horizontally reinforced brickwork walls is presented.

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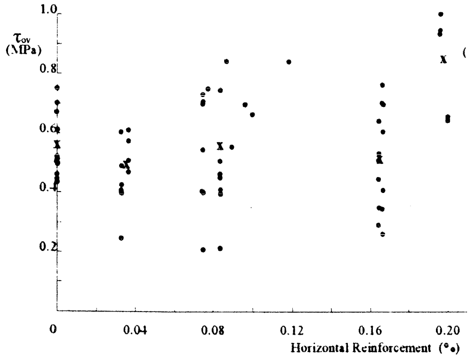

Fig.7 Relationship between Shear Resistance and Amount of Horizontal Reinforcement

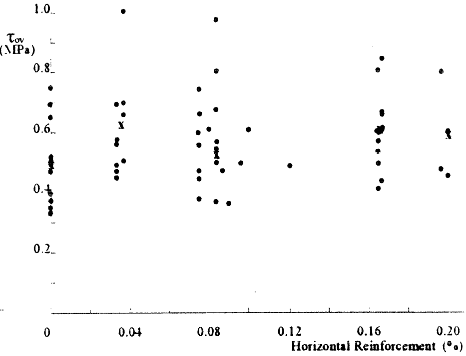

Fig.8 Relationship between Shear Resistance and Amount of Horizontal Reinforcement After Adjustment

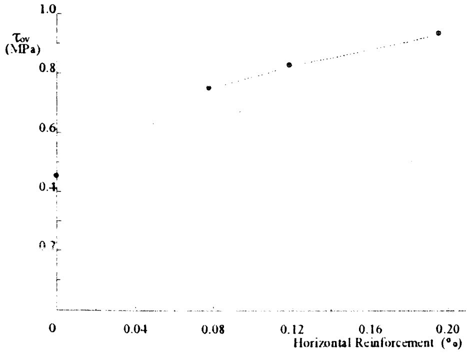

Fig.9 Relationship between Shear Resistance and Amount of Horizontal Reinforcement for An Identical Group of Walls with R.C. Tie Columns

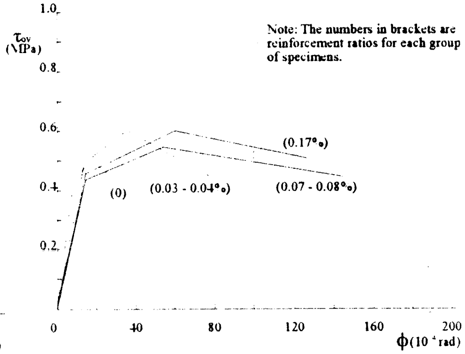

Fig.10 Relationship between Shear Resistance and Deformation Capacity

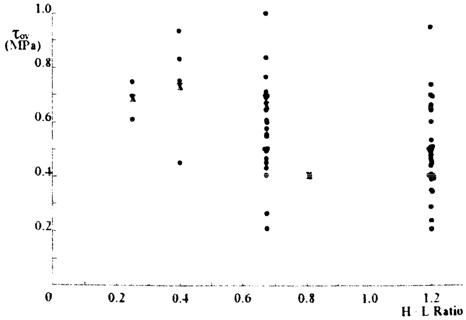

Fig.11 Relationship between Shear Resistance and Height/Length Ratio

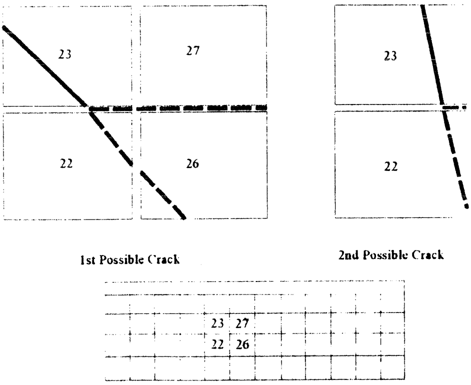

Fig.12 Theoretical Crack Patterns

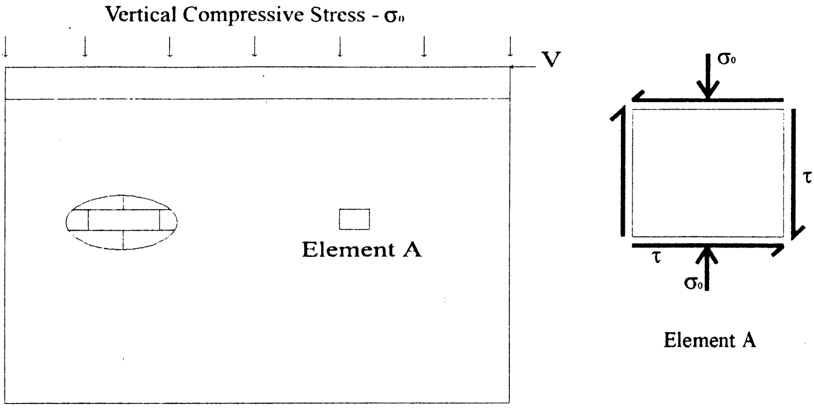

Fig. 13 Analytical Model of a Brick Wall

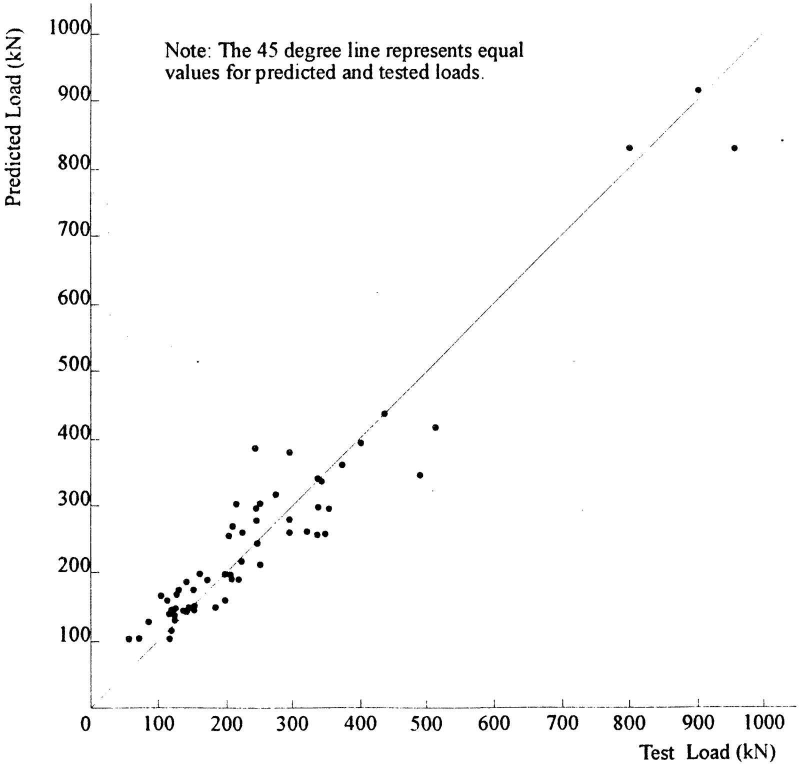

Fig. 14 Comparison between Predicted and Actual Test Loads