Lateral Strength of Cost Effective Un-Reinforced Brick Masonry Wall Panels

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ABSTRACT
The present research is focuses on load bearing brick masonry walls such as one brick thick brick masonry cavity walls and solid wall of reduced thickness using conventional solid bricks.

Keywords: masonry wall, English and Flemish bond, lateral stiffness and brick masonry

I. INTRODUCTION

The types of conventional and low cost masonry that have been considered in the present study are: (i) conventional brick masonry in English bond referred in the paper as Type A; (ii) solid wall of reduced thickness masonry in English bond referred as Type B; and (iii) Rat-Trap brick masonry in Flemish bond referred as D.

The brick masonry Type A and B are solid, whereas Types D is hollow. The English bond in brick masonry has alternate courses of header and stretcher, whereas, Flemish bond has alternate header and stretcher bricks in every course. In brick masonry Type A, bricks in every course are flat; in Type B one brick is flat and one on-edge in every course. In masonry Type D, bricks in every course are on-edge bricks. All the three types of brick masonry can be seen in Fig. 1.

The saving in the cost and merits of such type of construction are:

i) Use of one brick thick cavity wall and solid wall of reduced thickness results in the saving of bricks by 25% and 16% respectively.

ii) Reduction in the number of bricks reduces the quantity of mortar and results in the reduction of dead load of the superstructure, thus reducing the cost of foundation.

iii) The cost of brick masonry walls is about 35% and that of the plastering is about 10% of the total cost of building, thus the saving in the cost of building due to the saving in the number of bricks, masonry mortar and plastering used as well as due to reduced cost of foundation is about 20-25%. Though there will be some increase in the cost of labour because of the specialized construction but the mason has to handle less number of bricks, therefore, the net increase in the cost of labour is almost nil which has also been observed in practice.

iv) Cavities in one brick thick cavity walls act as an insulator and reduce the chiseling work done for electrification purposes.

Alshebani and Sinha [1] carried out a series of laboratory tests on half scale brick masonry panels subjected to uniaxial cyclic loading. Forty-two square panels were tested under cyclic loading until failure for two cases of loading: (i) Normal to the bed joint; and (ii) parallel to the bed joint. Failure due to cyclic compression was usually characterized by a simultaneous failure of brick units and head joints or by splitting in the bed joints depending on whether the panel was loaded normal or parallel to the bed joint, respectively. The characteristics of the stress-strain relationships of the two loading conditions were presented in this paper. Envelope, common point and stability point and stress-strain curves were established based on test data, and an exponential formula was found to provide a reasonable fit to the test data. It was concluded that the peak stress of the stability point curve can be regarded as the maximum permissible stress level that was found to be approximately equal to two thirds of the failure stress. It was also observed that the permissible stress level depends on the plastic strain level present in the material due to cyclic loading.
Lee et al. [2, 3] introduced a homogenization technique to investigate the elastic-brittle behaviour of masonry panels subjected to incremental lateral loading. For modeling the elastic behaviour of masonry, two successive steps of homogenization were used to obtain equivalent elastic properties. In the first step, brick units were homogenized with vertical joints to give equivalent elastic properties of a stacked system. This stacked system, in the second step, was then homogenized with the bed joints to obtain equivalent material properties for masonry. Tensile cracking was the only non-linearity considered in this paper. Cracking was judged on the basis of stresses and strength of each of the constituent materials. The cracks developed, if any, are also homogenized with the homogenized masonry and equivalent non-linear stress-strain relationships for cracked masonry were derived. The constitutive model was incorporated in a three-dimensional finite element code. It has been verified and validated with experimental data on the response of a set of laterally loaded rectangular masonry panels with and without openings. It was considered that the model can be used for predicting the physical behaviour of laterally loaded panels of arbitrary geometry and boundary conditions.

Thurlimann and Guggisberg [4] tested eight brick masonry panels, loaded with a vertical normal force and transverse bending moments in two directions in a specially designated rig. Thus failure criterion for laterally loaded masonry walls was investigated experimentally.

There has been considerable controversy over which is the most appropriate theory for predicting the transverse lateral strength of masonry walls, which has centered on the methods of analysis, without giving sufficient consideration to the derivation of the material properties. Fried et al. [5] compared the results of combining different methods of analysis and material properties to predict wall strength. Actual wall test results from various sources were used in the comparisons. Research into the relationships between various techniques for determining material properties were discussed and the need for researchers to record certain basic properties of the material being used in the masonry research for flexure was emphasized.

Lawrence and Cao [6] identified and discussed the distinct point of cracking in masonry walls under uniformly distributed out-of-plane lateral loads. Most investigators have concentrated on ultimate load prediction. But this study focuses on the load at which first crack forms. Because this load marks a significant change in behaviour and representing serviceability condition for design, should be studied as a first stage in developing a rational analysis of panel behaviour. A method of analysis based on elastic plate theory for the prediction of loads to cause first cracking in wall panel was presented. A range of practical wall dimensions were covered for supports on three or four sides and the analytical predictions were compared with the results of 32 full scale tests on clay brick walls.

II. EXPERIMENTAL PROGRAM

2.1 Materials used

2.1.1 Bricks

Full size hand moulded burnt clay traditional solid bricks have been used in the present study. The average size of brick is 228x114x76 mm respectively having frog of size 170x60x8 mm on one bed face only. The shape of frog was rectangular with rounded corners. These bricks were moulded manually in the laboratory from the brick-earth and were burnt properly in brick-kiln. A schematic view of the brick is shown in Fig. 2. Samples of bricks were tested for crushing strength and moisture absorption as per Bureau of Indian Standards (BIS) specifications [7, 8]. The test results obtained are as follows:
Weight of brick
Crushing strength on bed
Coefficient of variation
Crushing strength on edge
Coefficient of variation
Efflorescence
Water absorption after 24 hrs immersion in cold water

Fig. 2 Schematic view of brick used

2.1.2 Cement

Ordinary Portland Cement (OPC) was used in the preparation of wall panels. The cement was tested for the normal consistency, compressive strength, initial and final setting time as per BIS specifications [9, 10]. The total quantity required was procured in one instalment so as to ensure uniformity. The results obtained are as follows:
Compressive strength (28 days)
Normal consistency
Initial setting time
Final setting time

2.1.3 Sand

Locally available river sand was used. The sieve analysis was carried out and percentage passing through different sizes of sieve has been plotted in Fig. 3. The grading of sand conforms to zone IV as per BIS specifications [11, 12]. The fineness modulus of sand was 1.98. Through out the experiment the same sand has been
used for making wall panels so as to achieve uniformity in cement-sand mortar as far as possible.

![Grading of fine aggregate (river sand)](image1)

**Fig. 3 Grading of fine aggregate (river sand)**

**2.1.4 Masonry mortar**

The wall panels were made in 1:6 cement-sand mortar. Different values of water-cement (w/c) ratios were tried to obtain the mortar of desired workability that was more of a qualitative judgment than a quantitative one. The w/c ratio adopted in the construction of brick masonry was taken as 0.80.

The compressive strength of mortar used was determined by testing 70.6 mm size cubes as per BIS specifications [13] under Compression Testing Machine. The tensile strength of mortar was determined using briquette under Tension Testing Machine. The bond strength of mortar on horizontal bed has been determined by detaching two bricks bonded together with the help of mortar. The bricks were at right angles to each other with equal projection on either side and the frog of both of the bricks was upward. The specimen was tested under Universal Testing Machine as shown in Fig. 4.

The same mason prepared all the wall panels so as to achieve uniform workmanship. The thickness of mortar was kept uniform at \( D/6 \), where \( D \) is the thickness of brick, thus its value for model bricks was 6 mm and that for the full size bricks was 12 mm. The properties of the mortar used were as follows:

- **Compressive strength at 28 days** = 7.11±0.75 MPa
- **Coefficient of variation** = 10.66%
- **Tensile strength at 28 days** = 0.78±0.06 MPa
- **Coefficient of variation** = 7.76%
- **Bond strength** = 0.14 MPa
- **w/c ratio** = 0.80

![Testing of specimen for bond strength](image2)

**Fig. 4 Testing of specimen for bond strength**

**2.2 Masonry wall panels**

The wall panels of size 1200×1000 mm were constructed using masonry Type A, B and D with full size bricks. The construction of wall panels was in accordance with the specifications of IS: 2212-1962 [14]. The wall panels were checked for verticality during construction. The thickness of the wall panels built with three types of masonry A, B and D were 228, 190 and 228 mm respectively.

The wall panels were cured for 10 days before testing [14]. A horizontal force was applied at the top of the wall with the help of a hydraulic jack of 100 kN capacity having a least count of 0.5 kN. A rectangular plate of 200 mm height and width equal to the width of wall panel was used to transmit the lateral load from hydraulic jack to the wall panel. The load was applied in increments of 0.5 kN till the failure of the wall panel. The load was in plane and horizontal throughout the test [15].

The wall panels were fixed and the other three edges were free.

Three dial gauges were placed on the vertical edge opposite to the loaded edge of the wall – one each at the top, mid height and bottom. The dial gauge affixed at the bottom was used for checking the fixidity of the wall panel.
at the base. Four sets of Demac gauges named D1 to D4 were affixed, two each along both the diagonals. The readings of dial and Demac gauges were taken at each load increment and crack patterns were also recorded. The test setup for wall panel under static lateral load is shown in Fig. 5.

![Test setup for wall panel under static lateral load](image)

III. EXPERIMENTAL OBSERVATIONS AND ANALYSIS

3.1 Lateral strength of wall panels

The experimental results of Type A, B and D brick masonry wall panels tested under lateral loads are given in Table 1 and their failure pattern is shown in Fig. 6. The deformation of diagonals of the wall panels given in the table is the average of the two Demac gauges readings along a diagonal. The ultimate shear strength of brick masonry is calculated on the basis of net cross-sectional area. Though the ultimate lateral load for masonry Type B and D is 29% and 38% less than that of masonry Type A respectively, whereas, shear strength of masonry Type B and D is 13% and 6.5% less than that of masonry Type A respectively. The reduction in shear strength for masonry Type B is due to the non-uniform distribution of load on mortar bed. The ultimate shear strain is maximum for masonry Type D which shows that this type of masonry is more ductile under lateral load as compared to other types of masonry.

The wall panels of masonry Type A and B failed due to sliding at the base along the horizontal mortar bed (Figs. 6 (a) and (b)) which is because of the masonry being stronger along the diagonals. Whereas the wall panel of masonry Type D failed in diagonal tension by the development of cracks along the diagonal passing through horizontal and vertical mortar joints (Fig. 6 (c)) because this type of masonry is relatively weaker in tension along its diagonals. The reduction in tensile strength along the diagonal is because of the vertical mortar joint being relatively weaker because the height of vertical mortar joint in masonry Type D is more as compared to masonry Type A. The cracks in the wall panels of all types of brick masonry got developed only at the failure load and there was no any visible crack at lesser magnitude of load.

The lateral load is plotted against horizontal deflection at the top and mid height of the wall in Figs. 7 and 8 respectively. The initial slope of the load deflection curve for masonry Type A is steeper as compared to other masonry types. The initial slope of the load deflection curve for masonry Type D is steeper than masonry Type B. The deflection at failure for masonry Type D is much larger than other types of masonry thus showing large amount of ductility against lateral loads.

The diagonal compression and extension at failure in walls of masonry Types A and B are almost same and their magnitude is quite small. Whereas, in the wall of masonry Type D, diagonal extension at failure is large due to development of diagonal tension cracks. The magnitude of diagonal compression in masonry Type D is quite small.

![Failure pattern of different types of masonry wall panels under static lateral load](image)

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![Failure pattern of different types of masonry wall panels under static lateral load](image)
3.2 Lateral stiffness of wall

Considering a wall of height $H$, length $L_w$ and thickness $t_w$ as shown in Figs. 9 and 10. Two different cases of openings are considered – one in which there is a door and a ventilator (Fig. 9) and second in which there is a window (Fig. 10). Some other cases of openings are also covered such as wall without opening and wall with a door opening without ventilator. The openings are assumed to be centrally placed. The sizes of openings are: door ($L_1 \times H_1$), ventilator ($L_2 \times H_2$) and window ($L_3 \times H_3$).

The base of the wall is considered as fixed because of its connection with massive footing. The top of the wall is also considered as fixed but free for lateral displacement because of its connection with the slab at the top. The wall is given unit lateral displacement at the top by applying a horizontal force for the purpose of calculating the lateral stiffness of wall. The total strain energy of the wall, $U$, for this mode of deformation can be calculated from the summation of the strain energy due to bending moment and shear:

$$U = \int_{x=0}^{L_w} \frac{M^2}{2EI} \, dx + \int_{y=0}^{y_f} y^2 \frac{q^2}{2G} \, dx$$

The magnitude of shear stress, $q$, for different segments of the wall is calculated from the relation:

$$q = \frac{P}{I_2} (Ay)$$  \hspace{1cm} \text{(2)}$$

which is given in Table 2.

<table>
<thead>
<tr>
<th>Type of walls</th>
<th>Wall segment</th>
<th>Shear stress, $q$</th>
<th>Limit of $y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall having door and ventilator as shown in Fig. 9</td>
<td>AC</td>
<td>$\frac{P}{2I_1} \left( \frac{L_2^2}{4} - y^2 \right)$</td>
<td>$\pm \frac{L_1}{2}$ to $\pm \frac{L_w}{2}$</td>
</tr>
<tr>
<td></td>
<td>CD</td>
<td>$\frac{P}{2I_1} \left( \frac{L_2^2}{4} - y^2 \right)$</td>
<td>$0$ to $\pm \frac{L_w}{2}$</td>
</tr>
<tr>
<td></td>
<td>DB</td>
<td>$\frac{P}{2I_1} \left( \frac{L_2^2}{4} - y^2 \right)$</td>
<td>$\pm \frac{L_2}{2}$ to $\pm \frac{L_w}{2}$</td>
</tr>
<tr>
<td>Wall having window as shown in Fig. 10</td>
<td>AE and CB</td>
<td>$\frac{P}{2I_1} \left( \frac{L_3^2}{4} - y^2 \right)$</td>
<td>$0$ to $\pm \frac{L_w}{2}$</td>
</tr>
<tr>
<td></td>
<td>EG</td>
<td>$\frac{P}{2I_1} \left( \frac{L_3^2}{4} - y^2 \right)$</td>
<td>$\pm \frac{L_3}{2}$ to $\pm \frac{L_w}{2}$</td>
</tr>
</tbody>
</table>

![Fig. 7 Load deflection curves for different wall panels at top](image)

![Fig. 8 Load deflection curves for different wall panels at mid height](image)

![Fig. 9 Brick masonry wall with door and ventilator](image)
Applying a horizontal fictitious load, \( P \), at the top of the wall, the bending moment and shear force at a section distant \( x \) from the base of the wall is given by:

\[
M_x = (V - P)x + M 
\]

\( \ldots (3) \)

\[
F = (V - P) 
\]

\( \ldots (4) \)

\[
\frac{\partial U}{\partial M_x} = 0 \text{ and } \frac{\partial U}{\partial P} = -1 = 0 
\]

\( \ldots (5) \)

From the above equations, we get the following two linear simultaneous equations for each case of wall opening considered in the study.

\[
\frac{1}{E_1} \left[ \frac{V}{3} + \frac{M}{H} \right] - \frac{1}{E_3} \left[ \frac{V}{3} + \frac{M}{H} \right] + \frac{1}{E_2} \left[ \frac{V}{3} + \frac{M}{H} \right] - \frac{1}{E_2} \left[ \frac{V}{3} + \frac{M}{H} \right] = 0 
\]

\( \ldots (6) \)

\[
\frac{1}{E_1} \left[ \frac{V}{4} + \frac{M}{H} \right] + \frac{1}{E_2} \left[ \frac{V}{4} + \frac{M}{H} \right] - \frac{1}{E_2} \left[ \frac{V}{4} + \frac{M}{H} \right] - \frac{1}{E_2} \left[ \frac{V}{4} + \frac{M}{H} \right] = 0 
\]

\( \ldots (7) \)

The above equations may be solved to get the value of \( M \) and \( V \) hence the lateral stiffness of the wall for the two cases of wall openings.

The lateral stiffness of walls of different types of masonry tested experimentally has been calculated from Eqs. (6) to (9) and the values are given in Table 3. The thickness of wall for different types of masonry is taken as the effective thickness of wall. The lateral stiffness of wall of masonry Type A is less due to lesser value of modulus of elasticity as compared to other masonry types. It is observed from the table that the influence of shear deformation on the lateral stiffness of different types of masonry wall is 50.90%.

The lateral stiffness of a typical wall, 3 m high, 3 m long and 0.228 m thick of masonry Type A, has been calculated for different cases of door, window and ventilator openings and the same are given in Table 4. The size of doors, window and ventilator are given in the table.

It is observed from Table 4 that the consideration of ventilator just above the door increases the stiffness of wall by merely 0.63% with shear deformation as compared to the case when the ventilator is at the top of the wall. Two widths of window opening, 40% and 60% of length of wall, have been considered in Table 5. A comparison of stiffness shows that 50% increase in the width of window reduces the stiffness by 18.28% with shear deformation. The presence of opening such as a window of size 1.8×1.95 m reduces the stiffness of wall without opening by 58.58% with shear deformation. The consideration of shear deformation reduces the stiffness of wall by 42% to 74% for the cases considered in the table.
Table 3 Lateral stiffness of different types of brick masonry walls without opening

<table>
<thead>
<tr>
<th>Type of masonry</th>
<th>Lateral stiffness of wall without opening (GN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without shear</td>
</tr>
<tr>
<td>A</td>
<td>108.74</td>
</tr>
<tr>
<td>B</td>
<td>127.39</td>
</tr>
<tr>
<td>D</td>
<td>139.71</td>
</tr>
</tbody>
</table>

Table 4 Lateral stiffness of brick masonry wall with different cases of opening

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Particulars</th>
<th>Lateral stiffness of wall (GN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Without shear</td>
</tr>
<tr>
<td>1.</td>
<td>Wall without opening</td>
<td>63.0</td>
</tr>
<tr>
<td>2.</td>
<td>Wall with door and ventilator (D = 1.2 x 0.15 m; V = 1.2 x 0.45 m)</td>
<td>59.5</td>
</tr>
<tr>
<td>3.</td>
<td>Wall with door and ventilator (D = 1.2 x 0.15 m; V = 1.2 x 0.45 m; ventilator just above door)</td>
<td>60.3</td>
</tr>
<tr>
<td>4.</td>
<td>Wall with window (W = 1.2 x 1.95 m)</td>
<td>61.9</td>
</tr>
<tr>
<td>5.</td>
<td>Wall with window (W = 1.8 x 1.95 m)</td>
<td>58.5</td>
</tr>
</tbody>
</table>

IV. CONCLUSIONS

On the basis of test results obtained by testing brick masonry wall panels and analysis the following conclusions have been drawn:

i) The ultimate lateral load carrying capacity for wall panel of brick masonry Type B and D is 29 and 38 percent less than that of masonry Type A respectively.

ii) The shear strength of wall panel for brick masonry Type B and D is 13 and 6.5 percent less than that of masonry Type A respectively.

The peak lateral deflection of wall panel of masonry Type B and D is 77 and 82 percent higher than the peak deflection of wall panel of masonry Type A respectively.

The peak lateral deflection of wall panel of brick masonry Type D is 3 percent higher than wall panel of brick masonry Type B.

The effect of inclusion of shear deformation in the calculation of lateral stiffness of different types of masonry wall without any structural opening is 50 percent.

If a ventilator is provided above a door opening (both placed at mid length of wall), the effect of change in the position of ventilator on the lateral stiffness of wall is almost negligible.

The presence of opening such as a window of size 1.8 x 1.95 m in a wall panel of 3 x 3 m in size reduces the lateral stiffness of wall by 58 percent.

The wall panels of masonry Type A and B failed due to sliding at the base along the horizontal mortar bed. Where as the wall panel of masonry Type D failed in diagonal tension by the development of cracks along the diagonal passing through horizontal and vertical mortar joints.

This can be concluded that the masonry Type B is stronger in carrying lateral load as compared to masonry Type D but the difference is only 12 percent. Whereas, the ultimate shear strain is maximum for masonry Type D which shows that this type of masonry is more ductile under lateral load as compared to other types of masonry. The presence of opening as well as the consideration of shear deformation considerably reduces the stiffness of wall.

REFERENCES

ACKNOWLEDGEMENT

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NOMENCLATURE

\( L \) length of brick  
\( B \) width of brick  
\( D \) thickness of brick  
\( P \) horizontal force applied at the top of wall to give unit lateral displacement  
\( U \) strain energy  
\( M_s \) bending moment at a section distant \( x \) from base  
\( M \) fixed end moment  
\( F \) shear force  
\( V \) support reaction  
\( q \) shear stress intensity at a section  
\( z \) width of the fibre at a distance \( y \) from neutral axis  
\( y \) distance of fibre under consideration from neutral axis  
\( y_t \) distance of the fibre in tension zone under consideration from neutral axis  
\( y_c \) distance of the fibre in compression zone under consideration from neutral axis  
\( A \bar{y} \) moment of area of the portion which is between the fibre under consideration and the extreme of fibre  
\( L_w \) length of wall  
\( H \) height of wall  
\( t_w \) thickness of wall  
\( L_1 \) width of door  
\( H_1 \) height of door  
\( L_2 \) width of ventilator  
\( H_2 \) height of ventilator  
\( L_3 \) width of window  
\( H_3 \) height of window  
\( I \) second moment of area of wall about neutral axis  
\( I_1 \) second moment of area of wall for the portion having door opening about neutral axis  
\( I_2 \) second moment of area of wall for the portion having ventilator opening about neutral axis  
\( I_3 \) second moment of area of wall for the solid portion without opening about neutral axis  
\( I_4 \) second moment of area of wall for the portion having window opening about neutral axis  
\( E \) modulus of elasticity of brick masonry  
\( G \) shear modulus of brick masonry