Effect of Opening on the Lateral Stiffness of Masonry Walls with and without Ties

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ABSTRACT: *In this study, lateral response of masonry walls with openings is studied. The numerical modeling and analysis is followed and the developed models are validated using available experimental results. Samples selected for validation analysis include two masonry walls confined with reinforced concrete perimeter ties and one masonry wall with no ties. Validity of the numerical models has been established against the experimental samples within Abaqus software using nonlinear static analysis. Variation in the size, location and aspect ratio of the opening are taken into account and the lateral stiffness and strength of the walls are calculated. In addition, a series of equations have been developed based on strength of materials for simple calculation of lateral stiffness, strength and ductility of masonry walls with opening. This has the important advantage of avoiding complex and time consuming 3D nonlinear finite element analysis for the same purpose. To do this task, three different cases of failure are accounted for the walls including: when presence of the opening is not effective, when behavior of the two piers besides the opening is governing, and when the overhead lintel governs the lateral behavior of wall. Each of the mentioned cases are in turn divided into other sub-cases and several nonlinear finite element analyses have been undertaken. Results of the developed analytical equations are compared and calibrated with those of the finite element analysis and desirable accuracy of the relations developed in this study is confirmed.

1. INTRODUCTION

There have been several research works for quantifying the lateral behavior of masonry walls with openings in masonry buildings. Qamaruddin [1] presented a method for calculating the in-plane stiffness of masonry walls with openings. In his method, the wall was simulated using a number of flexible beams under the lateral load. Shariq et al. [2] studied the effect of openings on the seismic performance of masonry walls. They concluded that the maximum tensile stress happens in narrower walls while the maximum shear stress occurs in longer walls. Kuroki et al. [3] investigated different methods of strengthening for the masonry walls with openings using added reinforced concrete elements. They performed a number of experiments on the masonry walls for this purpose. The test results exhibited the fact that it was possible to increase the shear strength of the walls with openings to a level even larger than that of the solid wall using the added concrete elements. Sarrafi and Eshghi [4] devised a number of masonry wall samples being similar in pattern to the walls being customary in Iran and conducted experiments on them. As a result, they determined the cracking strength, the ultimate lateral strength, the ductility capacity, and the energy absorbed by the wall samples. Ganz et al. [5] tested a number of masonry walls under different loads. Moreover, they analyzed the tested walls using the finite element method and

the macro approach. They compared the analyses and testing results and exhibited the similarities. In this research, a semi-analytical equation has been developed for determining the lateral stiffness of masonry walls having openings, using the analytical approach.

2. METHODOLOGY

A masonry wall with opening is shown in Fig. 1. This wall is divided into three segments and its lateral stiffness is sum of the deformations related to bending and shear actions. The flexural and shear energies are calculated for the wall segments using Eqs. (1-3):
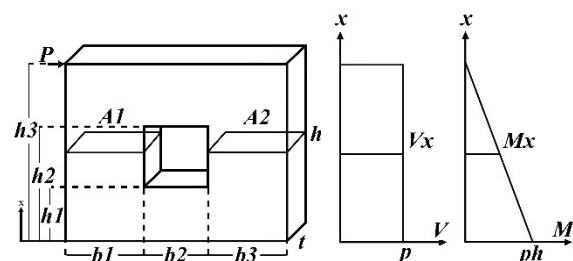

Fig. 1. Schematic view of a masonry wall having an opening and distribution of internal actions along its height.

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$$U_I = \frac{p^2 h_1 b^2 (1+v)}{10 EI_w} + \frac{p^2}{2 EI_w}(h^2 h_1 + \frac{h_1^3}{3} - h h_1^2) \qquad (1)$$

$$U_{II} = \frac{p^2 b^3 b_1 (1+v)}{10 EI_w (b_1 + b_3)^2}(h_2 - h_1) + \frac{p^2 b^3 b_3 (1+v)}{10 EI_w (b_1 + b_3)^2}$$

$$(h_2 - h_1) + \frac{p^2}{2 EI_{op}}((h^2 h_2 + \frac{h_2^3}{3} - h h_2^2) \qquad (2)$$

$$-(h^2 h_1 + \frac{h_1^3}{3} - h h_1^2))$$

$$U_{III} = \frac{p^2 b^2 (1+v)}{10 EI_w}(h_3 - h_2)$$

$$+ \frac{p^2}{2 EI_w}((h^2 h_3 + \frac{h_3^3}{3} - h h_3^2) - (h^2 h_2 + \frac{h_2^3}{3} - h h_2^2)) \qquad (3)$$

In the above equations, U_I, U_{II} and U_{III} are the energies absorbed by the lower, intermediate, and upper parts of the wall, respectively; h_1, h_2, and h_3 are the heights attributed to the parts below and over the opening and the whole wall, respectively. Moreover, I_w and I_{op} are the moments of inertia of the solid and opening parts of the wall, respectively, E is the modulus of elasticity and v is the Poisson's ratio of the wall material. To simplify the procedure, $\frac{h_1}{h}$, $\frac{h_2}{h}$, and $\frac{h_3}{h}$ are replaced by α_1, α_2, and α_3. Then:

$$U = \frac{p^2 b^2 (1+v)}{10 EI_w}(h - h_{op} + \frac{b h_{op}}{b - b_{op}})$$

$$+ \frac{p^2 h^2}{6E} \left\{ \begin{array}{l} \frac{1}{I_w}\left[h_1 (3 + \alpha_1^2 - 3\alpha_1) \right] \\ + \frac{1}{I_{op}}\left[h_2 (3 + \alpha_2^2 - 3\alpha_2) - h_1 (3 + \alpha_1^2 - 3\alpha_1) \right]) \\ + \frac{1}{I_w}\left[h_3 (3 + \alpha_3^2 - 3\alpha_3) - h_2 (3 + \alpha_2 - 3\alpha_2) \right]) \end{array} \right\} \qquad (4)$$

Using Eq. (4), the lateral stiffness of the masonry wall with opening is calculated using Eq. (5):

$$\frac{1}{K} = \frac{b^2 (1+v)}{5 EI_w}(h - h_{op} + \frac{b h_{op}}{b - b_{op}})$$

$$+ \frac{h^2}{3E} \left(\begin{array}{l} (\frac{h_1}{I_w} - \frac{h_1}{I_{op}})(3 + \alpha_1^2 - 3\alpha_1) \\ + (\frac{h_2}{I_{op}} - \frac{h_2}{I_w})(3 + \alpha_2^2 - 3\alpha_2) + \frac{h_3}{I_w} \end{array} \right) \qquad (5)$$

The lateral stiffness of the concrete ties around the wall is calculated at the top of the wall by analyzing it as a moment frame using Fig. (2).

Then, the stiffness matrix of the concrete tie will be:
Using the relations between the rotations of the nodes and the lateral displacement under a lateral load, and a coefficient of 0.3 for the moment of inertia of the cracked sections, the

$$k = \begin{bmatrix} \frac{24EI}{h^3} & \frac{6EI}{h^2} & \frac{6EI}{h} \\ \frac{6EI}{h} & \frac{4EI}{h} + \frac{4EI}{L} & \frac{2EI}{L} \\ \frac{6EI}{h} & \frac{2EI}{L} & \frac{4EI}{h} + \frac{4EI}{L} \end{bmatrix} \qquad (6)$$

$$K = (24 - (\frac{36h^2}{2h^2 + \frac{3h^3}{L}}))\frac{0.3EI}{h} \qquad (7)$$

lateral stiffness of the tie is calculated to be as follows:
The total lateral stiffness is the sum of the masonry parts and the concrete tie calculated in the above.

3. DISCUSSION AND RESULTS

A wall having dimensions equal to 5m in length, 3m in height and 30 cm in thickness is considered. It is under a uniform gravity line load of 2 t/m. The lateral stiffness of the wall is calculated using the finite element method and compared with the above analytical relations. Then the lateral stiffness (K) is calculated using the analytical ones corrected as follows:

$$K = \frac{K_{wall} + K_{tie}}{1 + \beta_1} \qquad (8)$$

where K_{wall} and K_{tie} are the lateral stiffness of the wall itself (reciprocal of Eq. 5) and the tie system (Eq. 7), respectively, and β_1 is ratio of the difference of the analytical and finite element values of the lateral stiffness to the later one. It is proved to be calculated using Eq. (9):

$$\beta_1 = ax^3 + bx^2 + cx + d \qquad (9)$$

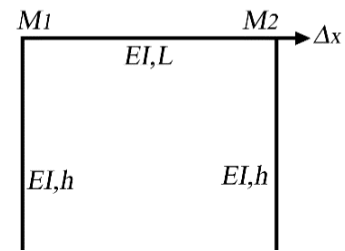in which x showing the number attributed to the location

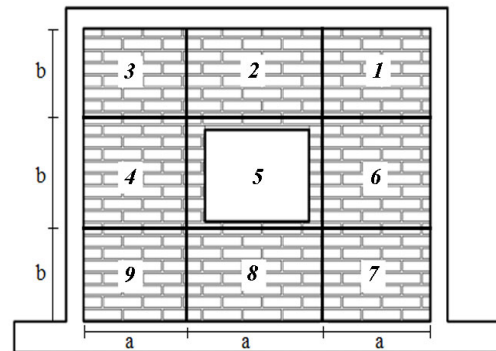**Fig. 2. The concrete tie system.**

Fig. 3. Possible locations of the opening (locations 1-9).

of the opening in the wall, as shown in Fig. 3.

Coefficients of Eq. (9) are calculated as follows:

$$a = -0.1536\gamma + 0.0172, R^2 = 0.92 \tag{10}$$

$$b = 2.3598\gamma - 0.2642, R^2 = 0.93 \tag{11}$$

$$c = 209.82\gamma^2 - 101.9\gamma + 10.654, R^2 = 1 \tag{12}$$

$$d = 20.397\gamma - 1.9893, R^2 = 1 \tag{13}$$

where γ is ratio of opening area to the total wall area.

4. CONCLUSIONS

In this paper, lateral stiffness of a masonry wall having an opening was calculated. Nine different locations were considered for the opening and different ratios were considered for the area of the opening to the whole wall. It was simple and accurate enough to correct the analytical equations using a correction factor derived from the finite element analysis. The correction factor varied with location and relative area of the opening.

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