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Effect of openings on lateral stiffness and strength of confined masonry walls

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Abstract. Confined masonry construction is made up of masonry walls and confining ties, which are built on all four sides of each wall. This system is a conventional form of house construction, as well as a good alternative for post-disaster reconstruction of seismically damaged and/or collapsed buildings in many countries. Window and door openings appear in many panels of confined masonry buildings, but many codes do not consider the effect of these openings in the strength and stiffness of confined masonry panels. In this study, the influence of masonry panel openings on the stiffness and strength of confined masonry walls is investigated. A finite element program, DIANA, is used for the finite element modeling of fully grouted confined masonry walls, walls with unfilled head joints, two-story walls, walls with a lintel band and walls with added vertical ties on the opening sides. All specimens have openings and are constructed according to the Iranian seismic code (Standard No. 2800-05). Models are validated by the results of the tests performed on two fully grouted one-story one-bay confined masonry walls, and a two-story one-bay confined masonry wall, constructed in Iran. Simple equations are proposed that predict the effect of central openings on the stiffness of different types of confined masonry wall and the cracking strength of fully grouted walls with openings.

1. Introduction

Masonry buildings make up a large part of residential buildings in both rural and urban areas because of their low cost and ease of construction.

Confined Masonry (CM) constructions consist of masonry walls and horizontal and vertical Reinforced Concrete (RC) ties built on all four sides of the masonry wall panel as confining elements. This structural system provides an alternative to both unreinforced masonry and frame system construction. This system could be a conventional form of new housing construction, as well as an alternative to the post-disaster reconstruction of buildings, especially for people on low incomes.

The key point regarding a CM wall is the sequence of its construction [1]. The first step is to build masonry walls with toothed age and, then, tie columns and tie beams are cast in place (Figure 1).

This construction sequence provides a stiff connection between the masonry panel and the ties, and plays an important role in the lateral resistance of CM walls. If an opening appears in the masonry panel, horizontal or vertical ties (like those shown in Figure 2) can be added to increase the lateral resistance of the CM wall (NTCM-2004 & Eurocode 6) [2,3].

CM buildings have exhibited good performance during earthquakes in the past. In 1939, an earthquake with a magnitude of M7.8 occurred in Chile, where

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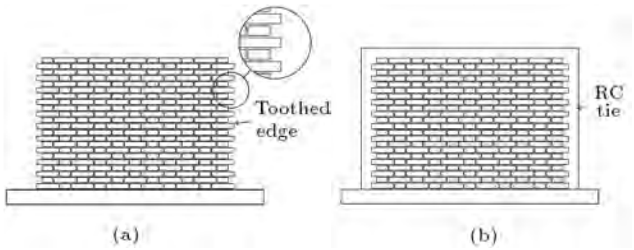


Figure 1. Construction sequence of CM walls: (a) Building masonry wall with toothed edges; and (b) casting reinforce concrete ties.

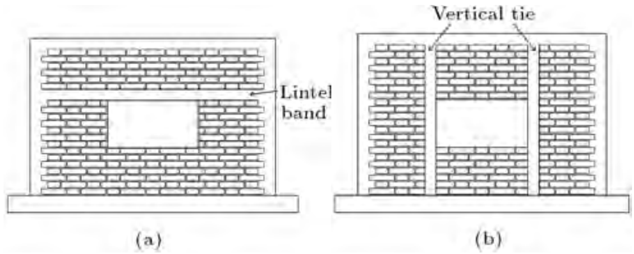


Figure 2. CM walls with additional ties. (a) CM wall with lintel band; and (b) CM wall with two added vertical ties on sides of opening.

the Modified Mercalli Intensity was estimated to be MMI=IX. In this earthquake, about 3,500 dwellings were inspected of which only 4.5% were of the CM type. 16% of the inspected CM houses and 57% of the unreinforced masonry houses collapsed or partially collapsed. On the other hand, over 50% of all inspected CM buildings had sustained the earthquake without any damage, whereas around 60% of unreinforced masonry buildings either partially or entirely collapsed [4].

More than 60% of the houses in El Salvador are built from Mixto, a type of CM with closely spaced bond beams and small panel dimensions. Mixto has a record of good performance during earthquakes, with only 8.3% experiencing damage in the 2001 earthquakes [5].

CM structures in the Tecoman-Colima earthquake of January 2003, in the coastal region of Mexico, with a magnitude of 7.6 (Ms), performed better than those built of unconfined masonry or adobe. Cracks often formed between the masonry and the confining elements, and the latter sometimes failed, but, only when the number and arrangement of confining elements were inadequate. In most instances, CM structures remained undamaged [6].

On December 26, 2003, a destructive earthquake hit Bam city in Iran. The earthquake caused the collapse of different types of buildings. Observations showed that CM buildings demonstrated good seismic performance, but, in order to have a three dimensional resisting system, tie-columns should be properly connected at all intersection points to tie-beams. If there is no suitable detailing for reinforcing bars in the concrete joints, the building cannot stand against earthquake.

Figure 3. A two-story CM building after the 2003 Bam earthquake in Iran.

Moreover, the distance between axes of two tie-columns should be limited to 5 meters [7,8].

Door and window openings are expected parts of buildings, and their effect in the overall behavior of buildings should be considered. This effect is more important in masonry systems than RC or steel structures, because masonry panels are the main parts of the resisting system in masonry buildings. Figure 3 shows a two story CM building, after the Bam earthquake, which did not suffer damage and remained intact. However, some cracks appeared in the corners of the openings and propagated to the concrete ties.

Some experimental research has been done to investigate the behavior of infills with openings [9,10] and confined masonry walls with openings [11]. An improved method for estimating the stiffness of brick masonry shear walls with openings was presented in another study [12]. Also, an attempt has been made to study the in-plane behavior of two squared confined masonry walls, with and without openings, using a numerical approach [13]. A comparison of the expressions of the strength criteria proposed by different codes is presented in [14], and a specific study on the lateral strength of confined masonry walls is reported in [15] and [16].

The aim of this paper is to investigate the effect of central openings on the stiffness and lateral strength of CM walls, and to propose simple relations to estimate the stiffness and cracking strength of such walls. In order to achieve this goal, we carried out a series of Finite Element (FE) analyses on a one-story one-bay, and a two-story one-bay, CM wall. A FE program, TNO DIANA BV (version 9.2), is used to perform the analyses. Two experimental test results are used to verify the FE models. The first test conducted on CM walls under monotonic lateral load was undertaken at the IIEES laboratory [17]. Test specimens were two half scale fully grouted CM walls made using solid clay bricks. The second test was performed on a two story half scale CM building with door and window openings [18]. Both test specimens were designed according to the Iranian seismic code provisions. After validating FE models, we analyzed CM panels with openings with varying dimensions and different types of opening ties. Finally, we introduced simple equations that estimate the lateral stiffness and cracking strength of the walls with openings.

2. Methodology

A parametric study is performed to obtain the lateral stiffness of CM walls with varying sizes of central openings. The FE method is used to analyze CM walls and the FE model is first calibrated using the results of two experimental tests conducted in Iran on one- and two-story single-bay CM walls.

The calibrated model is employed in the parametric study to determine the lateral stiffness and cracking strength of CM walls. Simple equations are proposed to obtain the same lateral stiffness as that estimated by the FE method.

In the parametric study, different sizes of opening and different types of CM wall are considered. Five sets of CM walls are analyzed and their lateral stiffness is determined by linear elastic analysis:

1. Fully grouted CM wall (CMWO-1);
2. CM walls with unfilled head joints (CMWO-2);
3. CM walls with two added vertical ties on opening sides (CMWO-3);
4. CM walls with one added horizontal tie or lintel band (CMWO-4);
5. Two-story, one-bay CM wall (CMWO-5).

Also, a set of analyses is performed on CMWO-1 type walls to estimate their cracking strength. Dimensions and material properties of the two-story model (CMWO-5) are taken similar to the two-story test specimen [18]. For the other one-story models, dimensions and material properties are taken from the one-story test specimens [17]. Central opening width ratios (L/L_o) are taken to be 0.12, 0.35, 0.59, 0.82 and 1. For each of these widths, opening height ratios (H/Ho) are considered to be 0.2, 0.3, 0.5, 0.7 and 1. For the models with added ties (CMWO-2), only opening widths of 300 mm, 450 mm, 750 mm and 1050 mm and heights of 500 mm, 1000 mm and 1500 mm are taken. Opening widths of 250 mm, 500 mm, 750 mm, 1000 mm, 1250 mm, 1500 mm, 1750 mm and 2000 mm, with a constant height of 500 mm, are considered in the CMWO-3 model. For two-story models (CMWO-5), openings in both stories are the same dimensions. Adding one bare frame and one full panel to each of the five sets of CM walls, a total of 105 models are analyzed under a combination of gravity and lateral load. All the analyses are performed using software, TNO DIANA BV (version 9.2).

3. Experimental and analytical studies

A few studies are carried out to explore the behavior of CM walls constructed according to Iranian codes and construction methods. The results of two tests used to validate the FE models in the present study are introduced here.

3.1. Experimental studies

A one-story, fully grouted clay brick wall panel (2000$\times$1315$\times$210 mm) confined by 210 mm $\times$210 mm RC bond beams and tie columns, without any opening, is tested under monotonic lateral load. The wall is made using solid fired clay bricks with dimensions of 210 $\times$ 52 $\times$ 105 mm, and 10 mm thick mortar joints. Two similar walls with the mentioned dimensions and reinforcement details presented in Figure 4 are tested in the IIEES laboratory [17].

According to the test results, shear failure was the dominant failure mode of the CM walls subjected to lateral loading. Shear failure with diagonal tension cracks was observed in both CM specimens. Shear failure occurred when the maximum principal stress developed in the wall, under a combination of vertical and horizontal loads which exceeded the tensile strength of the masonry material. The diagonal cracks passed through the mortar joints and the masonry units and then entered the connection between the RC members near the location at which lateral load was applied.

A two-story, half-scale confined masonry building was tested under cyclic loading [18]. The model had two window openings in the second story and one door and one window opening in the first story. The result of this test is used to verify the two-story FE model.

3.2. Finite element model

FE modeling of the CM walls is performed using the TNO DIANA BV (version 9.2) program. The micro modeling approach is adopted for CMWO-1 and CMWO-2 models to enable investigation of the effect of removing head joints from the model.

The walls are assumed to be made of solid fired clay bricks with dimensions of 210 mm $\times$ 52 mm $\times$ 105 mm, and 10 mm thick mortar joints having a volumetric ratio of 1:4 (cement : sand). The RC members are assumed to be those with a compressive strength equal to 28 MPa, and 4 longitudinal reinforcement bars, 10 mm in diameter, and with yield strength of 340 MPa. The RC members have stirrups (hoops) with a diameter of 6 mm and yield strength of 220 MPa. According to the Iranian seismic code (Standard No. 2800-05) [19], maximum allowable hoop spacing, within a distance of 750 mm from either end of the tie-columns and/or bond beams, is 150 mm center to center. Beyond a distance of 750 mm from the supports, maximum spacing of stirrups is 200 mm center to center. The lower RC bond beam is restrained

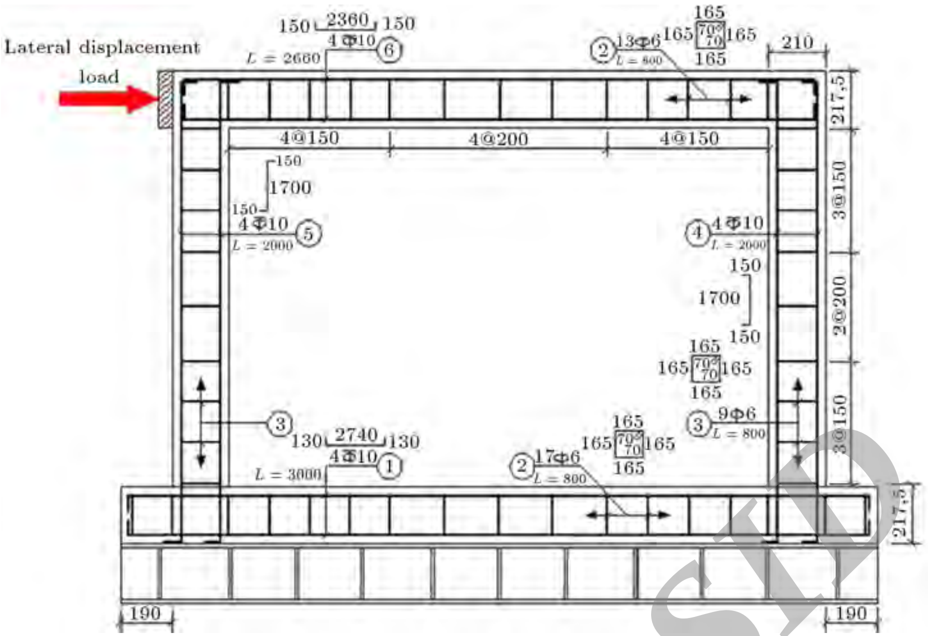


Figure 4. Specimen layout and reinforcement details [17].

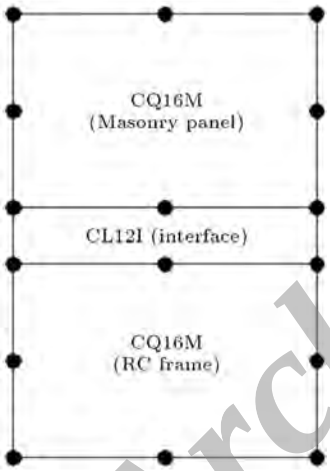


Figure 5. Elements configuration.

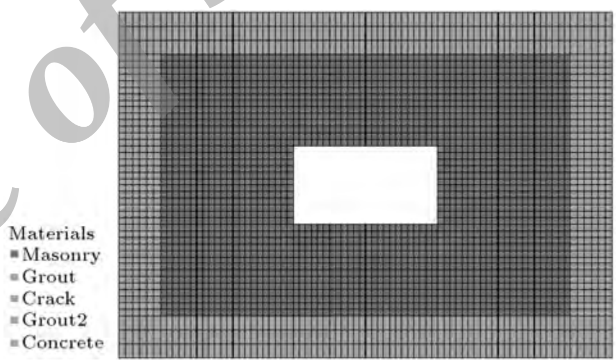


Figure 6. Finite element model of walls CMWO-1 and CMWO-2.

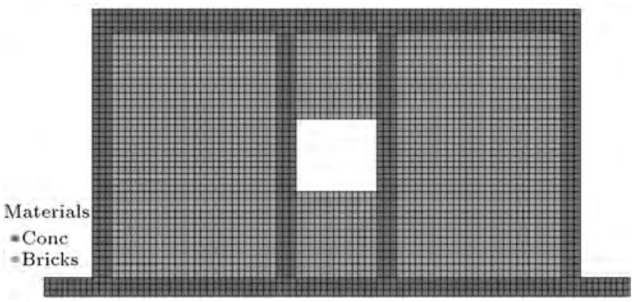


Figure 7. Finite element model of wall CMWO-3.

against the horizontal and vertical displacement. It is free to move and transfers the static monotonic lateral load to the wall.

An eight-noded quadrilateral element, CQ16M, is used to model RC bond beams, tie columns and masonry panels. The CQ16M is a regular plane stress element (sometimes called a membrane element), which must be thin, and the load must act in the plane of the element.

The CL12I line, 3 + 3 noded elements with zero width are used to model interface elements located between RC members and masonry panels [20]. The CL12I element is an interface element between two lines in a two-dimensional configuration. The configuration of combined elements is shown in Figure 5. The contact element represents a typical impenetrability constraint between adjacent bodies.

Grid patterns with mesh sizes of 20 mm for masonry and RC members are generated.

A macro modeling approach is adopted for the masonry panel of the walls CMWO-3, CMWO-4 and CMWO-5. The same elements and mesh sizes are used for this model, only interface elements are omitted. The finite element models of walls, CMWO-1 to CMWO-5, are shown in Figures 6 to 9. Elastic and

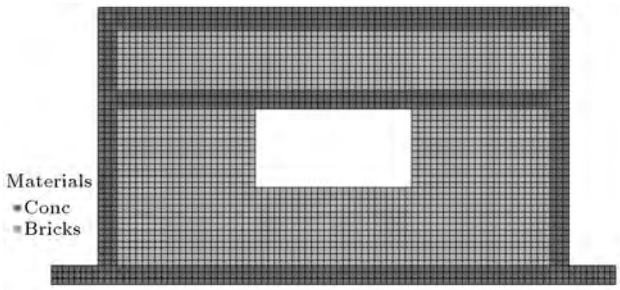


Figure 8. Finite element model of wall CMWO-4.

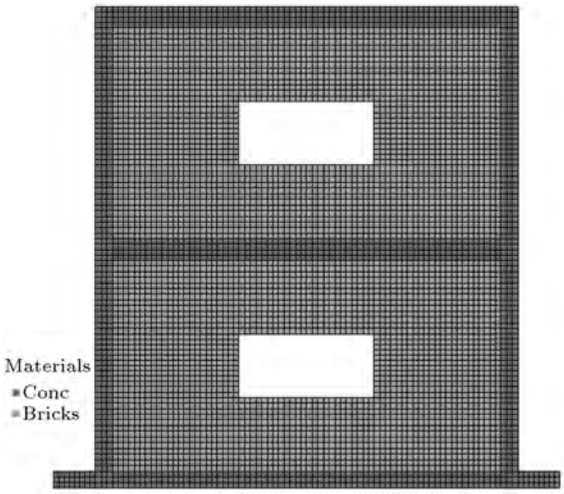


Figure 9. Finite element model of wall CMWO-5.

Table 1. Modeling parameters of bricks and middle cracks of bricks.

Masonry	Young's modulus	$E = 3500$ N/mm^2
	Poisson's ratio	u=0.15
	Mass density	1.85×10^6 kg/mm^3
Crack	Linear normal stiffness	$D_{11} = 10000$ N/mm^2
	Linear tangential stiffness	$D_{22} = 1000$ N/mm^2

inelastic parameters used for modeling are shown in Tables 1 and 2.

3.3. Verification of the FE models using test results

Verification of the FE model with test results for a one-story CM wall was performed in the previous study [13]. A lateral force-displacement curve obtained from the model is presented in Figure 10, which shows good agreement between analytical and experimental results. The same modeling parameters are used in the recent study. For two-story buildings, material properties reported in the study [18] are applied to the macro model. The amount of initial stiffness obtained from the model is 20% greater than the stiffness that test results show, which is an acceptable error value for initial stiffness.

Table 2. Modeling parameters of head and bed joints.

Grout	Linear normal stiffness	$D_{11} = 7$ N/mm^2
	Linear tangential stiffness	$D_{22} = 2.5$ N/mm^2
	Tensile strength	0.25 N/mm^2
	Fracture energy	0.0095 N/mm
	Cohesion	0.35 N/mm^2
	Tan of friction angle	0.75
	Tan of dilatancy angle	0.0001
	Residual friction coef.	0.75
	Confining normal stress	-1.3
	Exponential degradation coef.	5
	Cap critical comp. strength	8.5 N/mm^2
	Shear traction control factor	9
	Comp. fracture energy	5 N/mm
	Equivalent plastic relative disp.	0.09
	Fracture energy factor b	0.05

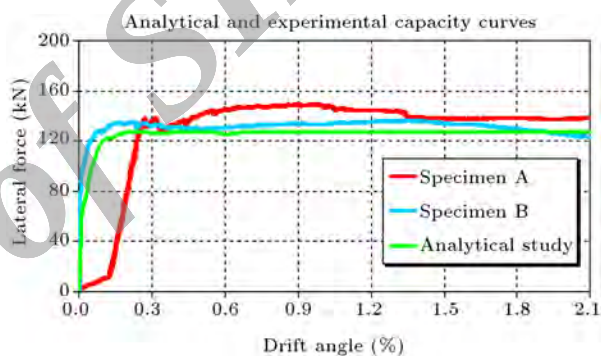


Figure 10. Lateral force-displacement curve, analytical and experimental [13].

4. Stiffness of CM walls with central openings

Window and door openings are expected parts of building walls and appear in many panels of confined masonry buildings, but many codes do not consider the effect of these openings on the strength and stiffness of CM walls.

The initial lateral stiffness of single-bay, single-story and two-story CM walls, with different sizes of central opening, is determined using the validated FE model presented in the previous section. Initial lateral stiffness is taken as the initial slope of a load-displacement curve.

A lateral point load is applied to the top level of the wall. Pushover analysis is performed using the TNO DIANA BV (version 9.2) program. Figures 11 through 15 present the deformed shape of walls: CMWO-1 to CMWO-5.

4.1. The stiffness of full panel CM wall

The stiffness of the wall depends on the dimensions, the mechanical properties of materials, and boundary conditions. The effective stiffness of a full-panel CM wall can be estimated by a simple equation, based on

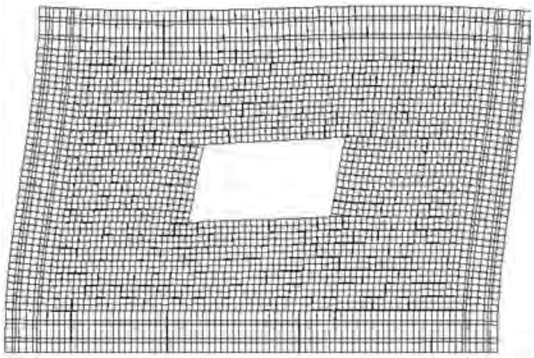


Figure 11. Deformed shape of wall CMWO-1.

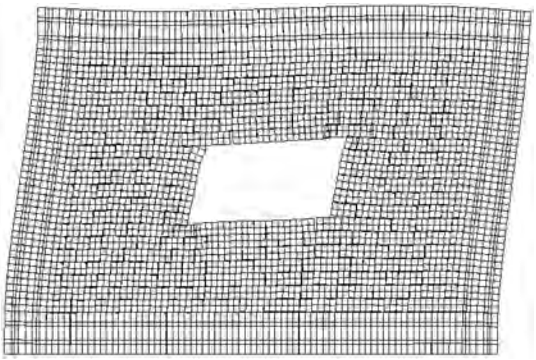


Figure 12. Deformed shape of wall CMWO-2.

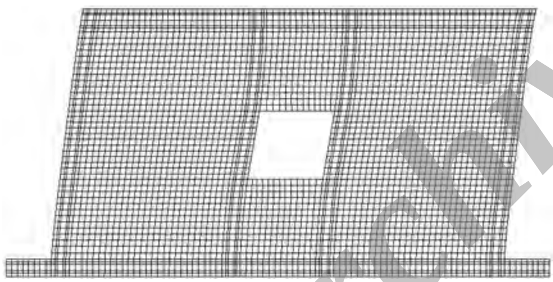


Figure 13. Deformed shape of wall CMWO-3.

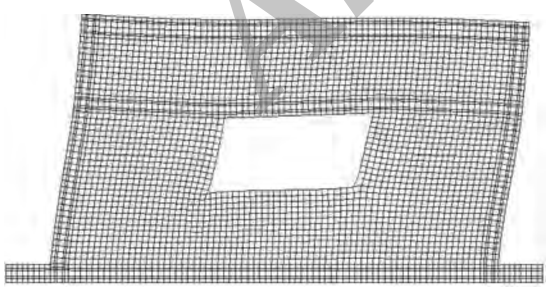


Figure 14. Deformed shape of wall CMWO-4.

the theory of elasticity, which takes account of the flexural and shear deformations of the wall [21,15]:

$$K_e = \left(\frac{h^3}{\beta E I_W} + \frac{\kappa h}{G A_W}\right)^{-1}, \qquad (1)$$

$$K = K_e(1 - \sqrt{1.281 I_d - 0.320}), \qquad (2)$$

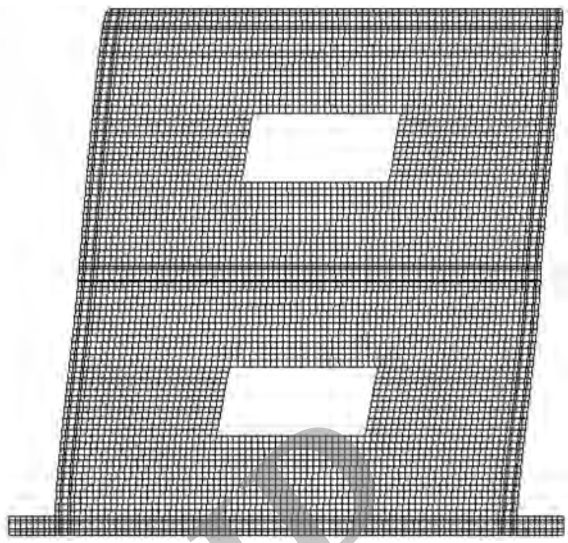


Figure 15. Deformed shape of wall CMWO-5.

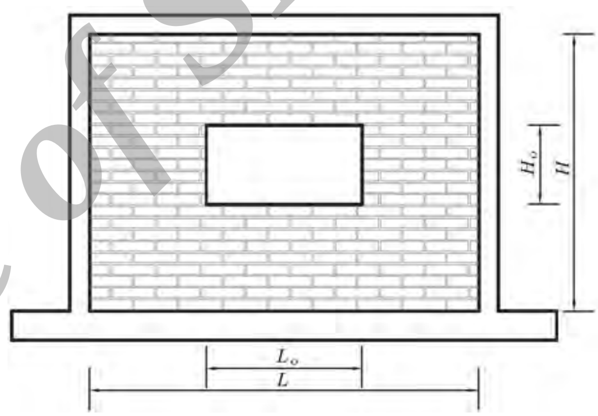


Figure 16. Parameters considered in the parametric study.

where I_w is the moment of inertia of the horizontal cross-section of the wall, β is the coefficient depending on boundary restraints ($\beta = 12$ in the case of fixed-ended and $\beta = 3$ in the case of cantilever wall), and κ is the shear coefficient of the section.

Since the dimensions of RC confining elements are relatively small, their contribution to lateral stiffness is not taken into account in Eq. (1). Eq. (2) estimates the stiffness of the wall at maximum resistance (damage index $I_d = 0.5$) and ultimate state (damage index $I_d = 1$). Considering parameters reported for the model [13], Eq. (1) gives the amount of stiffness equal to 72.6 KN/mm. This is approximately 15% greater than the initial stiffness obtained from the test result, which is an acceptable error in case of initial stiffness.

4.2. Parametric study

Dimensions of central openings, L_o and H_o, as shown in Figure 16, are taken as variable parameters. A set of analyses for varying opening width ratio (L/L_o)

and opening height ratio (H/H_o) are performed. The initial lateral stiffness of each analysis is calculated and normalized with the initial stiffness of the full panel CM wall (K_o).

4.2.1. Stiffness reduction factor for one-story fully grouted CM wall (CMWO-1)

Most codes recommend filling head joints during the construction of masonry walls. Walls constructed in this manner are called fully grouted walls. A set of analyses for opening width ratio (L/L_o) of 0.12, 0.35, 0.59, 0.82 and 1, and opening height ratio (H/H_o) of 0.2, 0.3, 0.5, 0.7 and 1 for each width are performed on fully grouted walls. Figure 17 shows the effect of central opening dimensions on the initial stiffness of a CM wall normalized with an initial stiffness of the CM full panel wall (K_o). We distinguish between two parts of CM wall stiffness (tie frame stiffness and masonry panel stiffness) to better formulate the reduction factor. Thus, we subtract the bare tie frame stiffness (K_t) from the CM wall stiffness (K), which results in masonry panel stiffness (K_m).

$$K = K_m + K_t, \tag{3}$$

$$K_o = K_{mo} + K_t. \tag{4}$$

The stiffness reduction factor, the ratio between the stiffness of panels with central openings (K_m) and a full panel (K_{mo}) are calculated for all analyses. This ratio is drawn versus the opening area (A) over the masonry panel area (A_o) in Figure 18. It is seen that a second-order polynomial curve with a very simple equation follows the data reasonably well, with a coefficient of correlation (R value) of 0.97. The equation is as follows:

$$\frac{K_m}{K_{mo}} = \left(1 - \frac{A}{A_o}\right)^2. \tag{5}$$

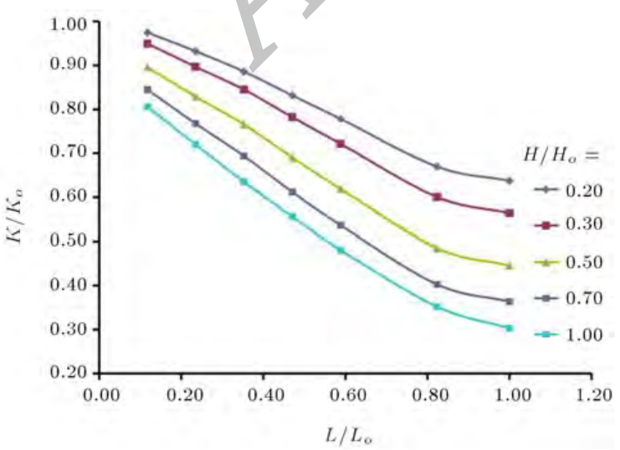


Figure 17. The effect of opening size on initial lateral stiffness of one-story fully grouted CM wall (CMWO-1) calculated by FE analysis.

4.2.2. Stiffness reduction factor for one story CM walls with unfilled head joints (CMWO-2)

In common construction, filling head joints are sometimes omitted to make the construction easier and faster, although it is not permitted in most codes. Some FE analyses are performed on CM walls with unfilled head joints, with an opening width ratio (L/L_o) of 0.12, 0.35, 0.59, 0.82 and 1, and an opening height ratio (H/H_o) of 0.2, 0.3, 0.5, 0.7 and 1 for each width. Figure 19 shows the effect of central opening dimensions on the initial stiffness of the CM wall normalized with the initial stiffness of the same CM wall without an opening (K_o). Stiffness reduction factors of analyzed walls are drawn versus the opening area ratio in Figure 20. It is observed that a third-order polynomial curve with a very simple equation follows the data reasonably well with a coefficient of correlation (R value) of 0.96. The equation is as follows:

$$\frac{K_m}{K_{mo}} = \left(1 - \frac{A}{A_o}\right)^3. \tag{6}$$

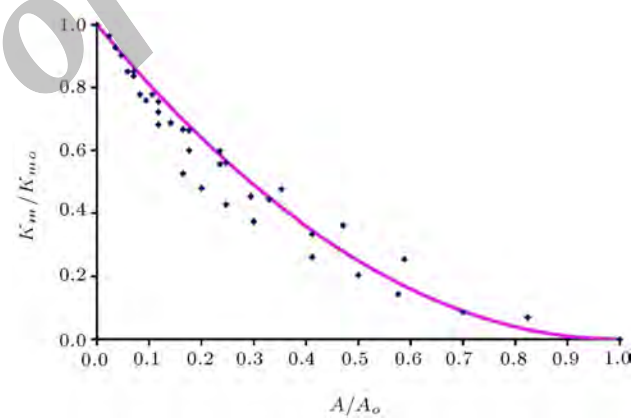


Figure 18. Fit curve of analytical results to stiffness reduction factor of one-story fully grouted wall (CMWO-1).

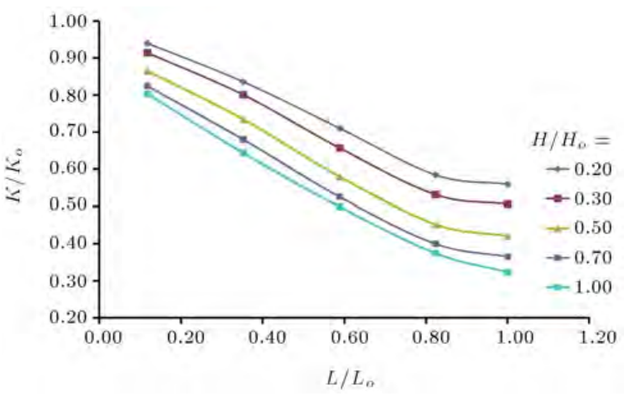


Figure 19. The effect of opening size on initial lateral stiffness of one-story CM wall with unfilled head joints (CMWO-2) calculated by FE analysis.

4.2.3. Stiffness reduction factor for CM wall with vertical opening ties (CMWO-3)

In some codes and standards, it is compulsory to add vertical ties on both sides of the opening. We considered a CM wall with added vertical ties on both sides of the central opening to investigate the effect of added ties on the lateral stiffness of walls with a central opening. Specifications of the added ties are similar to the vertical confining ties. Dimensions of the wall and the openings in the half-scale model are: $H = 1500$ mm, $L = 2760$ mm, $H_o = 500$ mm, 1000 mm and 1500 mm, and $L_o = 0$, 300 mm, 450 mm, 750 mm and 1050 mm. Stiffness reduction factors of the analyzed walls are drawn in Figure 21 versus opening area ratio. It is seen that a polynomial curve with a very simple equation follows the results reasonably well with a coefficient of correlation (R value) of 0.95. The equation is as follows:

$$\frac{K_m}{K_{mo}} = \left(1 - \frac{A}{A_o}\right)^{2.5}. \quad (7)$$

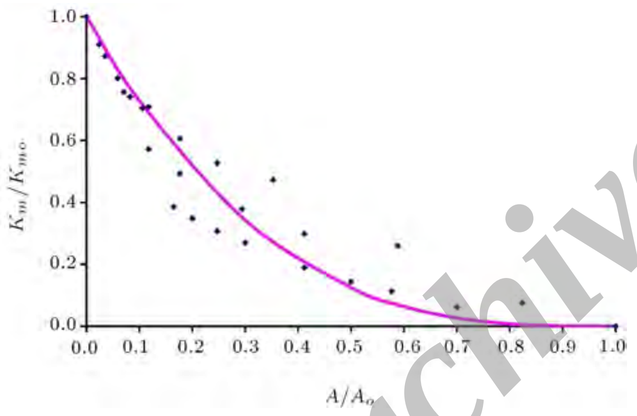


Figure 20. Fit curve of analytical results to stiffness reduction factor of one-story CM wall with unfilled head joints (CMWO-2).

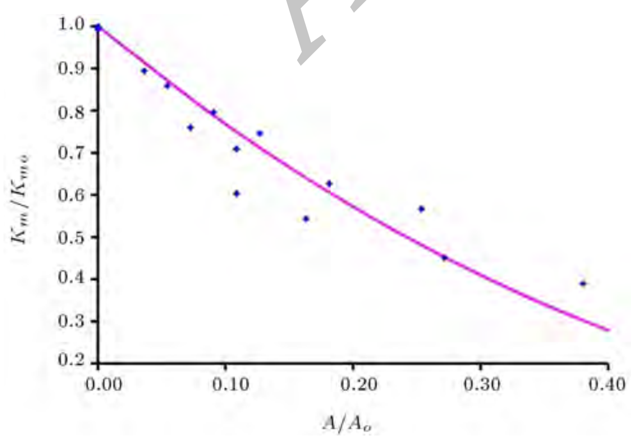


Figure 21. Fit curve of analytical results to stiffness reduction factor of CM wall with vertical opening ties (CMWO-3).

4.2.4. Stiffness reduction factor for CM wall with lintel band (CMWO-4)

Some codes and standards, such as Indian standards [22], recommend using a lintel band, which is a band provided at lintel level in all load-bearing walls. To investigate the effect of the bands on the lateral stiffness of CM walls, a set of analyses is performed on a one-story one-bay CM wall with the same modeling parameters as in the previous analysis. We consider a one-meter-height window in the center of the panel with different widths. In the half-scale model, dimensions are taken to be: $H = 1500$ mm, $L = 2760$ mm, $H_o = 500$ mm and $L_o = 0$, 250 mm, 500 mm, 750 mm, 1000 mm, 1250 mm, 1500 mm, 1750 mm and 2000 mm. The stiffness reduction factors of analyzed walls are drawn versus the opening area ratio in Figure 22. It is seen that a third-order polynomial curve with a very simple equation follows the results reasonably well with a coefficient of correlation (R value) of 0.98. The equation is as follows:

$$\frac{K_m}{K_{mo}} = \left(1 - \frac{A}{A_o}\right)^{3}. \quad (8)$$

4.2.5. Stiffness reduction factor for two-story CM walls (CMWO-5)

A two-story one-bay CM wall with similar central openings in both stories is considered. The FE model of the wall is analyzed with opening width ratio (L/L_o) of 0.12, 0.35, 0.59, 0.82 and 1, and opening height ratio (H/H_o) of 0.2, 0.3, 0.5, 0.7 and 1, for each width. Figure 23 shows the effect of the opening dimension on the initial stiffness of the CM wall with a central $H_o \times L_o$ opening. Stiffness reduction factors, which are the ratio between the stiffness of panels with central opening (K_m) and a full panel (K_{mo}), are drawn versus the opening area (A) over the masonry panel area (A_o) in Figure 24. It is observed that a third-order polynomial curve with a very simple equation follows the data reasonably well with a coefficient of correlation

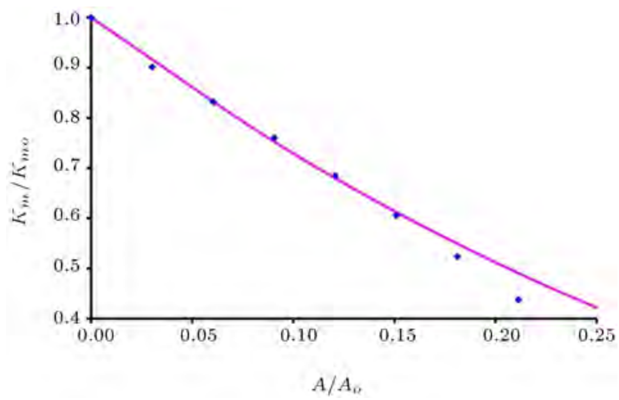


Figure 22. Fit curve of analytical results to stiffness reduction factor of CM wall with lintel band (CMWO-4).

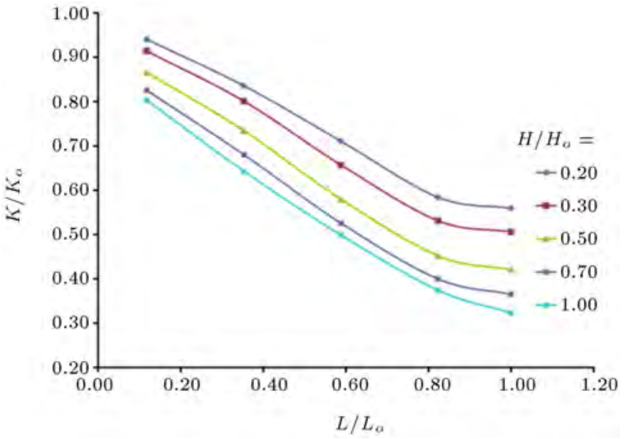


Figure 23. Effect of opening size on initial lateral stiffness of two-story fully grouted CM wall (CMWO-5) calculated by FE analysis.

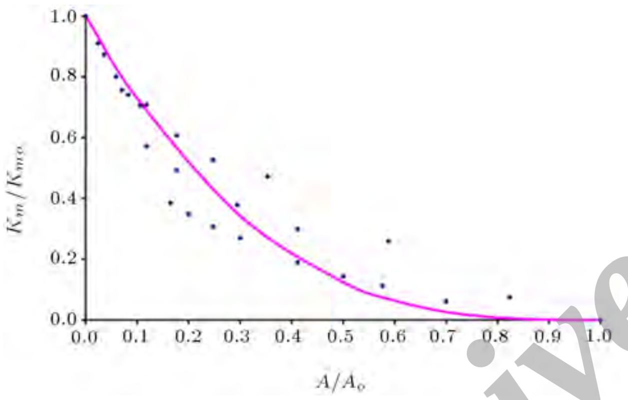


Figure 24. Fit curve of analytical results to stiffness reduction factor of two-story CM wall (CMWO-5).

(R value) of 0.96. The equation is as follows:

$$\frac{K_m}{K_{mo}} = \left(1 - \frac{A}{A_o}\right)^3. \qquad (9)$$

5. Cracking shear strength of CM walls with central openings

The effect of openings on the lateral strength of CM walls is studied with the same methodology adopted in the previous sections. The study focuses on the walls with filled head joints (CMOW-1). The cracking shear strength of walls is derived from the FE model using the micro modeling scheme, as introduced before. The size of openings, H and L, as shown in Figure 16, are taken as the only varying parameters. In walls with central openings, cracks normally start from the edges of the opening, easily in the early steps of loading. Therefore, the cracking strength level in such walls is considerably lower than that of walls without openings. Apparently, the cracking shear strength differs from the ultimate strength of the wall.

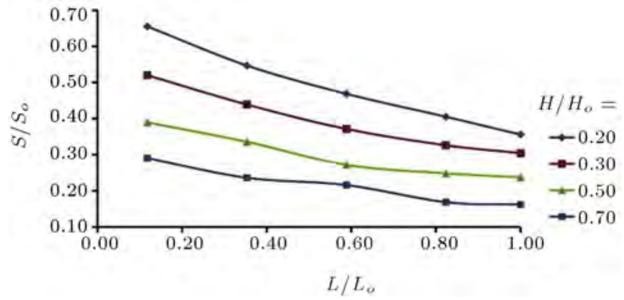


Figure 25. Effect of opening size on strength of fully grouted CM wall calculated by FE analysis.

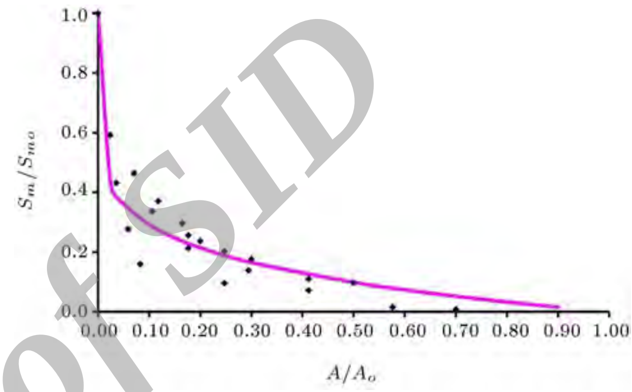


Figure 26. Fit curve of strength reduction factor of fully grouted CM wall.

A set of analyses with opening width ratio (L/L_o) of 0.12, 0.35, 0.59, 0.82 and 1, and opening height ratio (H/H_o) of 0.2, 0.3, 0.5 and 0.7, for each width, is performed. The cracking strengths of the analyzed walls are drawn versus the opening length in Figure 25. The cracking strength is normalized, with respect to the ultimate strength of a full panel CM wall (S_o), and the length of the opening is normalized with respect to the wall length (L_o). We subtract the bare tie frame lateral strength (S_t) from the CM wall strength (S) and the result is the masonry panel strength (S_m):

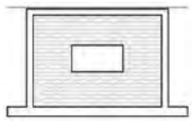
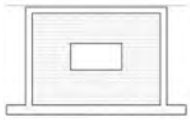
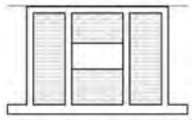
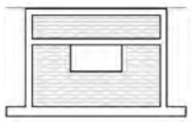
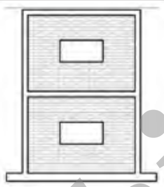
$$S = S_m + S_t. \qquad (10)$$

Also, it is subtracted from the lateral strength of the full panel CM wall (S_o) and the result is the masonry full panel strength (S_{mo}):

$$S_o = S_{mo} + S_t. \qquad (11)$$

The strength reduction factor, the ratio between the strength of panels with central openings (S_m) and a full panel (S_{mo}), is calculated for all models. This ratio is drawn versus opening area over the masonry panel area (A/A_o) in Figure 26. It is seen that a polynomial curve with a simple equation follows the data reasonably well with the coefficient of correlation (R value) of 0.98. The equation is as follows:

Table 3. Schematics of studied CM walls

Name	Figure	Description
CMWO-1		Confined masonry wall with central opening One-story Solid clay bricks/fully grouted
CMWO-2		Confined masonry wall with central opening One-story Solid clay bricks with unfilled head joints
CMWO-3		Confined masonry wall with central opening One-story Solid clay bricks/fully grouted with two added vertical ties
CMWO-4		Confined masonry wall with central opening One-story Solid clay bricks/fully grouted With one added horizontal tie (lintel band)
CMWO-5		Confined masonry wall with central opening in both stories two-story Solid clay bricks/fully grouted

$$\frac{S_m}{S_{mo}} = 1 - \left(\frac{A}{A_o}\right)^{0.15}. \tag{12}$$

6. Results

Results indicate that a central opening reduces the initial lateral stiffness of CM walls significantly. It is shown that, as a rough estimate, the lateral stiffness of the masonry panel in CM walls decreases as a function of the opening area ratio with the following equation:

$$\frac{K_m}{K_{mo}} = \left(1 - \frac{A}{A_o}\right)^{a}, \tag{13}$$

where K_m is the stiffness of the panel with a central opening, K_{mo} is the stiffness of the full panel, A is the opening area and A_o is the masonry panel area without an opening. Note that to estimate the stiffness of the CM wall, the stiffness of the bare tie frame (K_t) should be added to the calculated stiffness, according to Eqs. (14) and (15).

$$K = K_m + K_t, \tag{14}$$

$$K_o = K_{mo} + K_t. \tag{15}$$

The schematics of studied CM walls are shown in Table 3, and the amount of the 'a' parameter is presented in Table 4.

A parametric study on the lateral strength of fully grouted CM walls with a central opening (CMWO-1 type) is also performed. With respect to Eqs. (10) and (11), the strength of these walls can be estimated using the following equation:

$$\frac{S_m}{S_{mo}} = 1 - \left(\frac{A}{A_o}\right)^{0.15}, \tag{16}$$

Table 4. 'a' values to estimate initial stiffness of CM walls with central opening.

Name	Type of CM wall	a
CMWO-1	One-story	2
CMWO-2	One-story with unfilled head joint	3
CMWO-3	One-story with added vertical ties	2.5
CMWO-4	One-story with lintel band	3
CMWO-5	Two-story	3

where S_m is the strength of panels with a central opening, S_{mo} is the strength of a full masonry panel, A is the opening area and A_o is the masonry panel area.

Hence, in a one-story, fully grouted wall, when a central opening occupies about 30% of the masonry panel area, the initial lateral stiffness of the masonry panel is reduced by about 50%, according to Eq. (13). This result indicates the importance of considering openings when finding the center of stiffness of CM buildings. The existence of even small openings in a CM wall may result in distortion in the stiffness symmetry and torsion effects in the buildings and should be considered in the design.

To see the effect of wall openings on the general behavior of CM buildings, consider a simple plan, as shown in Figure 27; a one-story building with three structural walls in the Y direction and six structural walls in the X direction. The walls are fully grouted and confined with vertical and horizontal ties. The building has four central openings two for windows on axis B and two for doors on axes B and 3. Assume that openings decrease 30% of the panel area, which is allowed according to the Iranian seismic code (Standard No. 2800-05) [19]. Then, the stiffness of these panels is reduced by 50%, according to Eq. (13), for one-story fully grouted walls. Taking the stiffness of the ties as 5% of the full masonry panel (K) is a good estimate according to the analysis results. Eccentricity between the center of stiffness and the center of mass in the Y direction is calculated as follows:

$$e_y = 2 - \frac{4 \times (3 \times 0.5K + 3 \times 0.05K)}{3 \times K + 3 \times 0.5K + 6 \times 0.05K} = 0.625\text{m},$$

$$\frac{e_y}{L} = \frac{0.625}{4} = \%15,$$

in which K is the stiffness of one full panel CM wall. It results in 15% eccentricity in the Y direction and shows the importance of considering the effect of openings in the general behavior of CM buildings. Such buildings are usually designed ignoring this important effect.

7. Conclusion

The authors carried out a series of FE analyses on one-story one-bay, and two-story one-bay CM walls to investigate the effect of central openings on their initial stiffness. An FE program, DIANA BV (version 9.2), is used to perform the analyses. The FE models are verified through two experimental test results. The first test was conducted on two CM walls under monotonic lateral load, and the second test was conducted on a two-story half-scale CM building with door and window openings. Iranian seismic code provisions were used for constructing test specimens. After validating the FE models, we analyzed CM walls with different sizes of openings in a fully grouted CM wall (CMWO-1), a CM wall with unfilled head joints (CMWO-2), a CM wall with two added vertical ties on opening sides (CMWO-3), a CM wall with one added horizontal tie, called a lintel band (CMWO-4), and a two-story CM wall (CMWO-5). Schematics of the models are summarized in Table 3. We found that, as a rough estimate, the lateral stiffness of the masonry panel decreases as a function of the opening area ratio (see Eq. (13)). Also, a simple equation is proposed to estimate the effect of a central opening on the cracking strength of fully grouted CM walls (CMWO-1).

It can also be concluded that the effect of central openings, with dimensions less than 10% of the width and height of the masonry panel, on the lateral stiffness of CM walls, can be neglected. This opening area is less than 1% of the masonry panel's area and its effect on the lateral stiffness of the CM wall is less than 3%.

The proposed equations can be used by structural designers to take into account the effect of central openings in the design of CM buildings. The present study is limited to CM walls with central openings. Future work can be performed to estimate the effect of changing the location of openings in the stiffness and strength of CM walls. More research studies and experimental tests are required to develop efficient provisions in future codes.

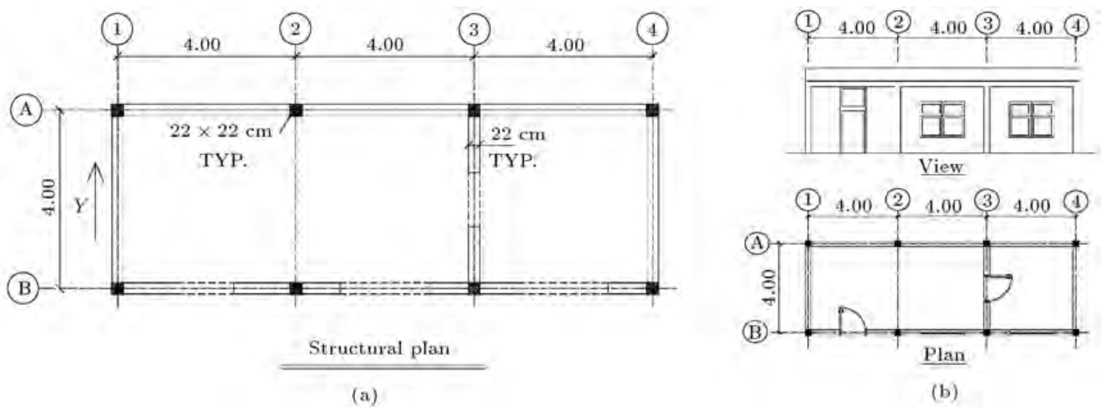


Figure 27. Simple CM building: (a) Structural plan; and (b) architectural view and plan.

References

1. Brzev, S., *Earthquake-Resistant Confined Masonry Construction*, Kanpr: NICEE (2007)
2. NTCM-2004, *Complementary Technical Norms for the Design and Construction of Masonry Structures*, Gaceta Oficial del Distrito Federal, Mexico (2004).
3. Eurocode 6 "Design of masonry structures. Part 1-1: General rules for buildings", *Rules for reinforced and unreinforced masonry*, ENV (1995).
4. Moroni, M.O., Astroza, M. and Acevedo, C. "Performance and seismic vulnerability of masonry housing types used in Chile", *Journal of Performance of Constructed Facilities*, **18**(3), pp. 173-179 (2004).
5. Aschheim, M., Flanagan, S., Harlander, J., Pitt, C., Alfaro, A., Rivas, C. and Rodriguez, M.E. "Improving the earthquake resistance and sustainability of confined masonry (Mixto) dwellings in El Salvador", *Proceedings of the 8th US National Conference on Earthquake Engineering* (2006).
6. Klingner, R.E. "Behavior of masonry in the Northridge (US) and Tecoman-Colima (Mexico) earthquakes: Lessons learned, and changes in US design provision", *Construction and Building Materials*, **20**, pp. 209-219 (2006).
7. Nasrollahzadeh Neshele, K. "Structural damage to buildings due to Bam earthquake of December 29, 2003, Iran", Institue of Industrial Science, The University of Tokyo, Newsletter, **3**(4), pp. 1-3 (2004).
8. Eshghi, S. and Naserasadi, K. "Performance of essential buildings in the 2003 Bam, Iran, earthquake", *Earthquake Spectra*, **21**(S1), S375-S393 (2005).
9. Chiou, Y.J., Tzeng, J.C. and Liou, Y.W. "Experimental and analytical study of masonry infilled frames", *J. of Structural Engineering*, **125**(10), pp. 1109-1117 (1999).
10. Schneider, S.P., Zagerz, B.R. and Abrams, D.P. "Lateral strength of steel frames with masonry infills having large openings", *J. of Structural Engineering*, **124**(8), pp. 896-904 (1998).
11. Yanez, F., Astroza, M., Holmberg, A. and Ogaz, O. "Behavior of confined masonry shear walls with large openings", *Proceedings of the 13th World Conference on Earthquake Engineering* (2004).
12. Balasubramanian, S.R., Balaji Rao, K., Dhiman Basu, Anoop, M.B. and Vaidyanathan, C.V. "An improved method for estimation of elastic lateral stiffness of brick masonry shear walls with openings", *KSCE Journal of Civil Engineering*, **15**(2), pp. 281-293 (2011).
13. Eshghi, S. and Pourazin, K. "In-plane behavior of confined masonry walls - with and without opening", *International Journal of Civil Engineering*, **7**(1), pp. 49-60 (2009).
14. Asinari, M., Penna, A. and Magenes, G. "Comparison of existing strength criteria for confined masonry walls", *XX JAIE Conference* (Buenos Aires, Argentina) (2008).
15. Tomasevic, M. and Klemenc, I. "Seismic behaviour of confined masonry walls", *Earthquake Eng. Struct*, Dynamics, **26**, pp. 1059-1071 (1997).
16. Bourzam, A., Ikemoto, T. and Miyajima, M. "Lateral resistance of confined brick wall under cyclic quasi-static lateral loading", *14 th World Conference on Earthquake Engineering* (2008).
17. Pourazin, K. and Eshghi, S. "In-plane behavior of a confined masonry wall", *TMS Journal*, **27**(1), pp. 21-34 (2009).
18. Tasnimi, A.A., *Behaviour of Confined and Non-Confined Masonry Brick Buildings* (in Persian), Natural Disaster Research Institute of Iran (2005).
19. Building & Housing Research Center., *Iranian Code of Practice for Seismic Resistant Design of Buildings*, Standard No. 2800-05, 3rd Ed., Tehran, Iran, BHRC publication (2005).
20. TNO Building and Construction Research, *DIANA Finite Element Analysis*, User's Manual - Element Library, Delft (2005).
21. Turnsek, V. and Cacovic, F., *Some Experimental Results on the Strength of Brick Masonry Walls, Proc. 2nd Int. Brick Masonry Conf.*, PP. 149-156 (1971).
22. IS 4326, *Indian Standard Code of Practice for Earthquake Resistant Design and Construction of Buildings*, Bureau of Indian Standards, New Delhi (1993).

Biographies

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