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Code 729 the First Iranian Guideline for Strength-based Design of Non-Structural Masonry Walls: A Verification Report

Seyyed Amin Mousavi [1*]

[1*] *Ph.D., Behsazan Larzeh Davam Co., The Science and Technology Park of University of Tehran, Tehran, Iran (s.a.mousavi@ut.ac.ir)*

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ABSTRACT

In 2017, the first Iranian guideline for strength-based seismic design of non-structural masonry walls, Code 729, published by The Plan and Budget Organization of Iran. Code 729 uses strength-based procedure and the yield-line theory to design unreinforced and reinforced non-structural masonry walls with or without openings. In this paper, first a brief overview of Code 729 is presented and then using a comprehensive experimental database of 72 full-scale masonry walls, accuracy of the code is demonstrated. It is seen that Code 729 can estimate out-of-plane capacity of different masonry walls with good accuracy. According to the results, average, median, and median plus one standard deviation of errors of the Code 729 in estimating out-of-plane capacity of masonry walls, respectively, are 20%, 18%, and 33.2% and with a probability of 85% the error would be less than 34%. Considering the complicated two-way orthotropic behaviour of non-structural masonry walls and their highly uncertain properties, such level of error is deemed to be acceptable for practical applications. In addition to experimental results, Finite Element simulations are also carried out in this study to shed more light on out-of-plane behaviour of walls with different opening details.

Keywords:

Nonstructural Elements, Nonstructural Masonry Wall, Out-of-plane Behavior.

1. Introduction

It is well recognized that non-structural elements and contents represent most of the monetary investments in almost all buildings. During a seismic or windstorm event, failure of heavy non-structural elements can impose significant life threat. Surprisingly, current national and international codes of practice do not provide a straightforward design procedure for non-structural elements. Partition walls and claddings are among the most important non-structural components and in many countries, including Iran, these components are commonly made from masonry units. These walls, if properly isolated from the main structure along their in-plane direction, are acceleration-sensitive elements which would be subjected to out-of-plane bending. Note that non-structural masonry walls are orthotropic and most of them are constrained along three or four edges. Subsequently, the wall would experience a two-way bending which further complicates the problem (Figure 1(a)). During the last decades, substantial efforts have been made to explore out-of-plane capacity of reinforced and unreinforced masonry walls. The most simplified technique is to use small wall panels to experimentally determine out-of-plane flexural capacity of brickworks parallel and perpendicular to the bed joints (Ryder 1963, Willis 2004) [1, 2]. However, materials and construction techniques used for small masonry panels may not represent actual masonry practice. As a result many of the previous researches were devoted to large-scale or full-scale masonry specimens. West el al. (1977) [3], Lawrence (1983) [4], Drysdale and Essawy (1988) [5], Chong (1993) [6] and Griffith et al. (2007) [7] are among the researchers who experimentally investigated behavior of full-scale non-structural masonry walls under out-of-plane two-way bending. The main findings from the earlier researches and case histories are gathered in the current masonry codes, such as ACI 530 (2013) [8], Eurocode 6 (2005) [9], AS 3700 (2001) [10] and Code 729 (2017) [11]. In 2017, a strong earthquake with magnitude of 7.3 occurred in Kermanshah, western Iran. This quake resulted in significant damages to structural and non-structural components, as shown in Figure 1(b). Non-structural damages have also been observed during earlier earthquakes in Iran as depicted in Figure 1 (b). Considering the time gap between the Manjil and Kermanshah earthquakes, it can be concluded that after about three decades, literally no improvement has been made in design and construction of non-structural masonry walls. This is also the case in many other countries, as shown in Figure 1 (c). Several months before Kermanshah Earthquake, the first Iranian guideline for strength-based design of non-structural masonry walls, Code 729 (2017), published by The Plan and Budget Organization of Iran. Code 729 uses the yield line theory to estimate vertical and horizontal flexural moments imposed to the wall during a seismic or wind storm event. Then the demand would be compared with the related capacity of the wall. Code 729 accounts for two-way orthotropic behaviours of masonry walls and considers many parameters including, different edge boundary conditions (BCs), mortar mixtures, presence or absence of openings, masonry unit types, bed joint reinforcements, among others.

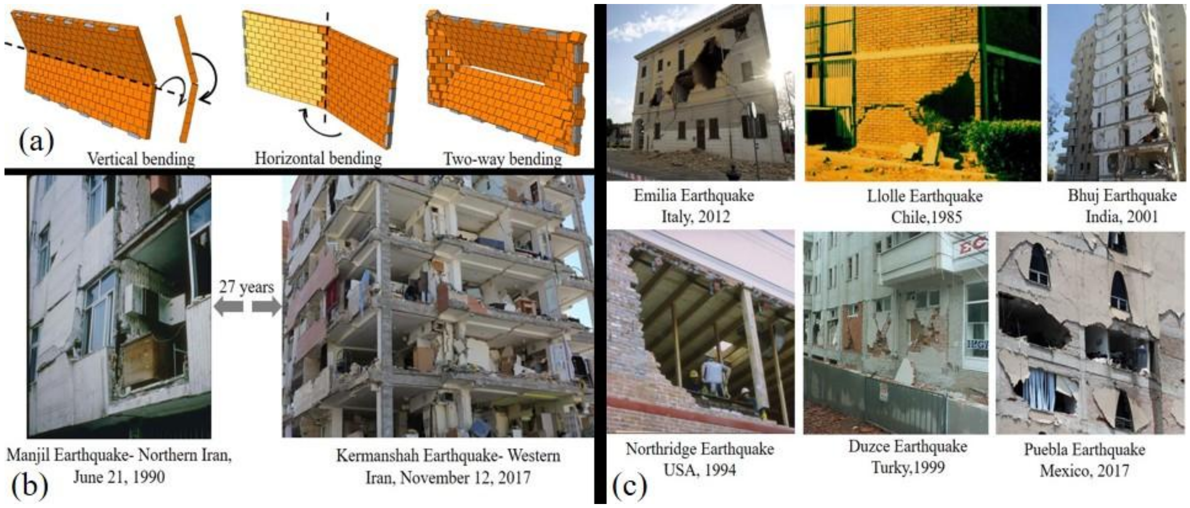

Figure 1. (a) Vertical bending, horizontal bending, and two-way bending in masonry walls. Seismic-induced damages of non-structural masonry walls in (b) Iran and (c) other countries.

2. Code 729

Full description of Code 729 is not possible here due to page number limitations. As a result as very brief overview is presented in this section. According to Code 729 vertical or horizontal flexure capacity of unreinforced masonry walls per unit length (or height) can be estimated as (in N-mm units),

$$M_n = \frac{1000 f_r t_s (h - t_s)^2}{h} \ (N.\frac{mm}{m}) \tag{1}$$

Where h and ts are thickness of the wall and shell thickness of the hollow block, respectively, as shown in Figure 2 (a). The parameter fr is rupture modulus of the wall which depends on direction of the bending, either vertical or horizontal, masonry unit, and the used mortar mixture. Rupture modulus are presented in Code 729 for different cases. Vertical or horizontal flexure capacity of walls per unit length (or height) with bed joint reinforcements are (in N-mm units),

$$M_n = \frac{1000\ A_s f_y}{B}\left(d - \frac{A_s f_y}{2\beta f'_m B}\right)(N.\frac{mm}{m}) \tag{2}$$

Where *B* is distance between different bed joint reinforcements along height of the wall which would be a multiplier of the masonry unit height. As shown in Figure 2(b), A_s is the cross section of each longitudinal chord of the bed joint reinforcement. Yield strength of the bed joint reinforcement is f_y and the parameter β is 0.8 for clay and cement masonry units and 0.85 for AAC blocks. Distance between the tensile chord of the bed joint reinforcement and the compression face of the wall is also denoted by *d* as depicted in Figure 2(b). Finally reduction strength factors of 0.6 and 0.9 are used to estimate design moment capacity of unreinforced and reinforced walls, respectively. According to Code 729, bed joint reinforcements should be implemented in all non-

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structural masonry walls, expect those constructed with AAC blocks which may or may not need bed joint reinforcements.

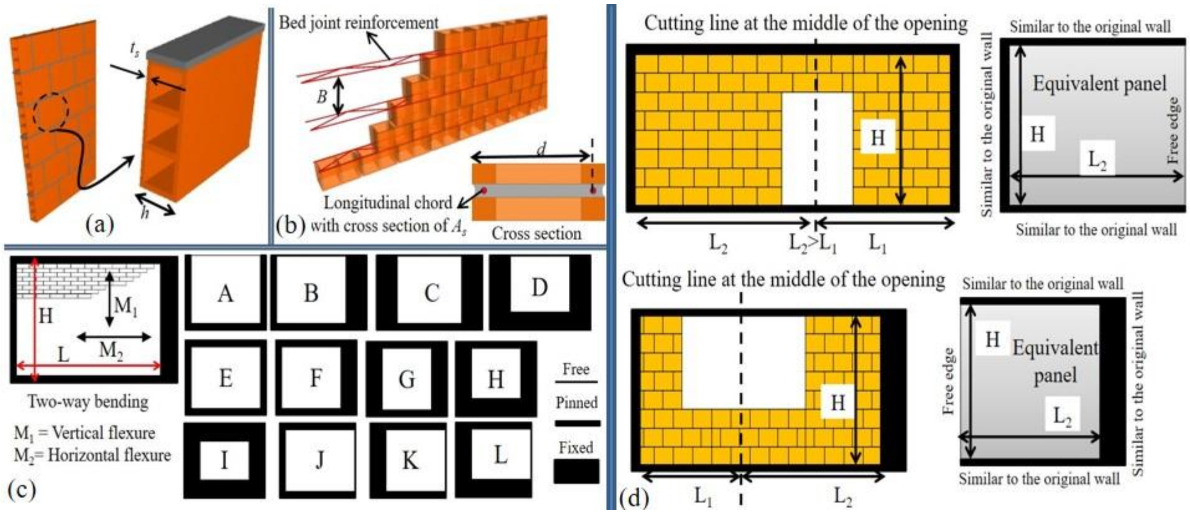


Figure 2. (a) Geometric parameters of a typical hollow masonry block. (b) Placement of bed joint reinforcements. (c) Two-way bending of walls with different boundary conditions. (d) Equivalent panel technique for walls with opening.

After estimating vertical and horizontal moment capacities of the wall, imposed demands need to be calculated. Ultimate seismic and wind storm out-of-plane pressures, wu, can be estimated using the applicable code. Having the ultimate out-of-plane pressure, horizontal and vertical flexural demands of the wall can be estimated as,

$$M_{u2} = \alpha_2 w_u L^2 \tag{3}$$
$$M_{u1} = \mu M_{u2} \tag{4}$$

As shown in Figure 2(c), Mu2 and Mu1 are horizontal and vertical flexures of the wall. Orthogonal ratio, μ, is the ratio of vertical design flexure capacity of the wall to its horizontal design flexure capacity. Horizontal bending moment coefficient, α2, depends on the aspect ratio of the wall, its boundary condition (BC), and its orthogonal ratio. This parameter for different walls can be found in Code 729. For walls with opening, Code 729 proposed an equivalent panel technique which is illustrated in Figure 2(d). Instead the original wall, demand/capacity ratio would be checked for the equivalent panel.

3. Verification with Test Results

In this section, using a database of 72 full-scale specimens, accuracy of Code 729 in estimating out-of-plane capacity of non-structural masonry walls with different details is assessed. No strength reduction factor is considered in the carried out verifications of this study.

3.1. Griffith et al. (2007) test results

Using quasi-static air-bag cyclic tests, Griffith et al. (2007) have reported out-of-plane behavior of unreinforce med masonry walls with and without openings. Note that the selected specimens had no axial load. Details of the tested specimens are illustrated in Figure 3 (a). All specimens had thickness of 110 mm. Experimental results with those estimated by Code 729 are compared in Figures 3(b-e). To achieve a better understanding, Finite Element (FE) simulations are also carried out in this study, as illustrated in Figure 3. It can be seen that the measured results during the tests and those estimated by Code 729 and FE analyses are in general agreement with average error of 14%.

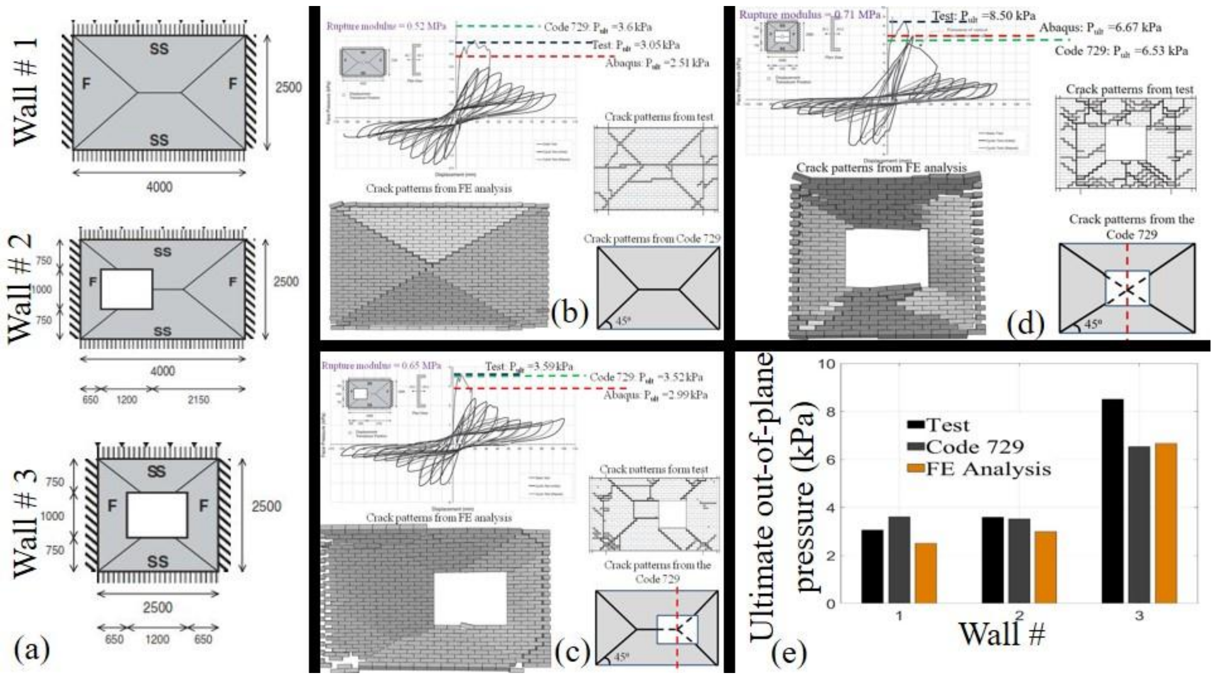


Figure 3. (a) Details of the tested specimens by Griffith et al. (2007). Verifications for (b) Wall #1, (c) Wall#2 and (d) Wall#3. (e) Summary of the obtained results.

3.2. West et al. (1977) test results

West et al. (1977) tested 18 full-scale unreinforced solid masonry walls. Height and thickness of all specimens were 2.6 m and 103 mm, respectively. Rupture modulus of the specimens varied from 0.71 MPa to 0.73 MPa. In this verification report, a constant value of 0.72 MPa is assumed for the rupture modulus of all specimens. For all specimens, the lower edge was pinned, the upper edge was free, and the vertical edges had a semi-rigid connection. As a result, BC of the specimens were between BCs A and C per Code 729 (Figure 2(c)). Estimated capacities are calculated by interpolating between BCs A and C. Length of each walls and the corresponding out-of-plane capacities are presented in Table 1. For comparison purposes, estimated capacities from the Australian code (AS 3700), reported by Willis (2004), are also presented in Table 1. Note that AS 3700 uses virtual work theory to estimate out-of-plane capacity of masonry walls. It is clear that both Code 729 and AS 3700 estimated out-of-plane capacity of the walls with enough accuracy. Graphical presentation of the carried out comparisons are shown in Figure 4. It seems that for walls with longer lengths and smaller aspect ratios (H/L), both Code 729 and AS 3700 resulted in conservative estimations (positive errors). The same conclusion has been made earlier by Chong (1993). It would be shown later that this is not necessarily the case for other walls.

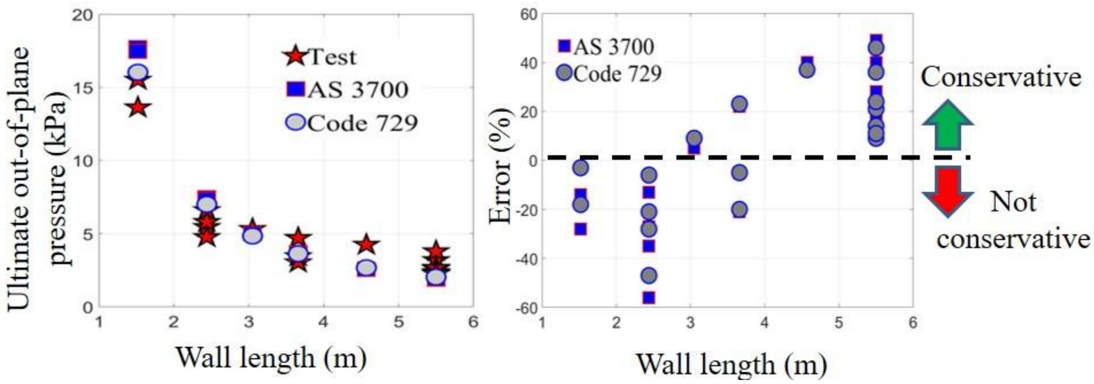


Figure 4. Verification of Code 729 with experimental results by West et al. (1977).

Table 1. Verification of Code 729 with experimental results by West et al. (1977).

Wall #	Length (m)	Ultimate out-of-plane capacity (kPa)			Error (%)	
		Test	Code 729	AS 3700	Code 729	AS3700
1	5.5	3.18	2.03	1.92	36	40
2	5.5	3.79	2.03	1.92	46	49
3	4.57	4.24	2.67	2.56	37	40
4	3.66	4.7	3.63	3.68	23	22
5	3.05	5.31	4.84	5.02	9	5
6	2.44	6.6	7	7.44	6	13
7	1.52	15.51	16.03	17.71	3	14
8	5.5	2.37	2.03	1.89	14	20
9	2.44	5.45	7	7.34	28	35
10	1.52	13.62	16.03	17.47	18	28
11	5.5	2.59	2.03	1.92	21	26
12	3.66	3.03	3.63	3.68	20	21
13	2.44	4.76	7	7.44	47	56
14	5.5	2.24	2.03	1.89	9	16
15	3.66	3.45	3.63	3.63	5	5
16	2.44	5.79	7	7.34	21	27
17	5.5	2.66	2.03	1.92	24	28
18	5.5	2.28	2.03	1.92	11	16
Average					21%	26%

3.3. Lawrence (1983) test results

In a comprehensive experimental program, Lawrence (1983) tested 32 solid masonry walls with thickness of 110 mm and different lengths, heights and BCs. Based on four point tests on small panels, Lawrence (1983) reported significantly high values for the rupture modulus of the walls. The author believes that the reported values cannot be representative for the rupture modulus of the tested full-scale specimens. As a result, in this study, the highest value of the rupture modulus per Code 729 (0.92 MPa under vertical bending) is considered as the rupture modulus of the walls.

Details of the tested walls and obtained results are summarized in Table 2. Average error of the Code 729 from Table 2 is 21%. Obtained results from this verification indicate that Code 729 may not necessarily be conservative for walls with large aspect ratios.

Table 2. Verification of Code 729 with Lawrence (1983) experimental results.

Wall #	Length (m)	Height (m)	BC*	Out-of-plane capacity (kPa)		Wall #	Length (m)	Height (m)	BC*	Out-of-plane capacity (kPa)	
				Test	Code 729					Test	Code 729
1	6	3	I	8	7.4	17	5	2.5	I	9.9	10.6
2	6	3	I	8.1	7.4	18	5	2.5	G	6.4	7.1
3	6	3	E	3.2	3.7	19	5	2.5	C	3.9	4.2
4	6	3	G	5.5	4.9	20	5	2.5	A	2.7	2.7
5	6	3	A	1.7	1.8	21	6	2.5	E	3.1	4.8
6	2.5	2.5	E	8.6	10.4	22	6	2.5	A	2.3	2.1
7	2.5	2.5	I	12.1	21.2	23	6	2.5	C	3.5	3.4
8	2.5	2.5	G	20	16.5	24	6	2.5	G	4.7	6.3
9	2.5	2.5	A	7.8	7.2	25	6	2.5	I	6.9	9.5
10	2.5	2.5	C	14	12.6	26	6	3	E	3.5	3.7
11	3.75	2.5	A	3.4	4	27	6	3	I	4.7	7.4
12	3.75	2.5	E	4.9	6.9	28	6	3	G	3.9	4.9
13	3.75	2.5	G	6.7	9.9	29	6	3	C	2.5	3
14	3.75	2.5	I	11.6	13.8	30	6	3	A	1.9	1.8
15	3.75	2.5	C	4	6.6	31	2.5	2.5	I	24	21.2
16	5	2.5	E	4.7	5.3	32	2.5	2.5	G	18.8	16.5

* *According to Code 729 BCs*

3.4. Chong (1993) test results

Out-of-plane capacity of unreinforced masonry walls with and without openings have been experimentally investigated by Chong (1993). Rupture modulus of the walls reported to be 0.96 MPa which is more than the maximum value per Code 729 (0.92 MPa). Accordingly, value of 0.92 MPa is considered in the following calculations. Table 3 compares experimental results with those estimated by Code 729. Crack pattern and pressure-deformation of the tested walls are illustrated in Figure 5.

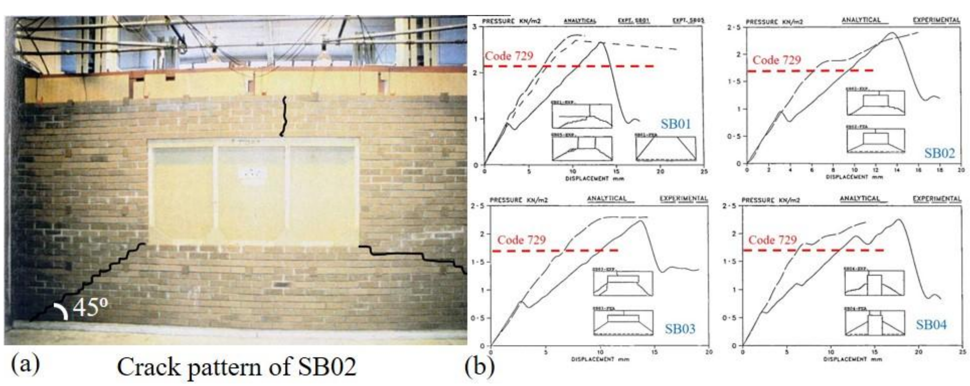
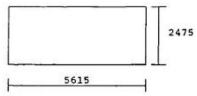
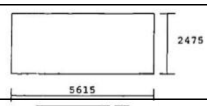
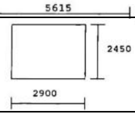
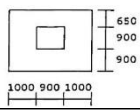
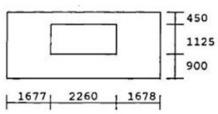
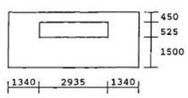
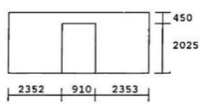


Figure 5. (a) Crack pattern of SB02 and (b) pressure-deformation of some of the specimens tested by Chong (1993) and the corresponding capacities per Code 729.

Table 3. Verification of Code 729 with Chong (1993) experimental results.

Specimen name	Wall dimensions (mm)	BC			Out-of-plane capacity (kPa)		Error (%)
		Vertical edges	Lower edge	Upper edge	Test	Code 729	
SB01		Pinned	Fixed	Free	2.8	2.1	25
SB05		Pinned	Pinned	Free	2.7	2.1	22
SB06		Pinned	Fixed	Pinned	7.5	7.9	5
SB07		Pinned	Fixed	Pinned	5.5	6.8	24
SB02		Pinned	Fixed	Free	2.4	1.7	29
SB03		Pinned	Fixed	Free	2.3	1.7	26
SB04		Pinned	Fixed	Free	2.2	1.7	23
Average							22%

3.5. Drysdale and Essawy (1988) test results

Previous tests have been carried out on unreinforced masonry walls. However, masonry walls with bed joint reinforcements have been also experimentally investigated earlier. Out-of-plane behavior of full-scale walls with hollow concrete masonry units and thickness of 190 mm were investigated by Drysdale and Essawy (1988). The walls had truss-like bed joint reinforcements at alternate rows. Adopted mortar was also mortar type S with Portland cement and lime with the mix proportion of 1Cement + 0.21 Lime + 4.24 Sand + 0.9 Water (by volume). Details of the walls and obtained results are presented Figure 6 and Table 4.

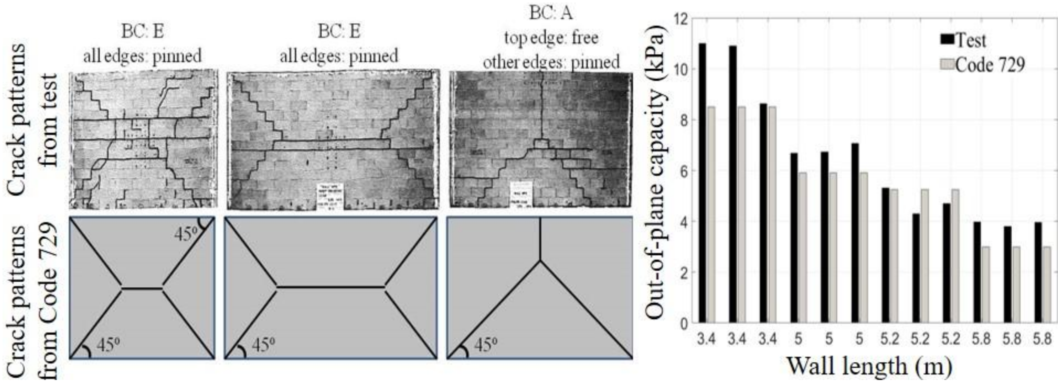


Figure 6. Verification of Code 729 with Drysdale and Essawy (1988) experimental results in terms of crack patterns and out-of-plane capacity- height of all walls is 2.8 m.

Table 4. Verification of Code 729 with Drysdale and Essawy (1988) experimental results.

Wall #	BC	Height (m)	Length (m)	Ultimate out-of-plane capacity (kPa)		Error (%)
				Test	Code 729	
1	E	2.8	3.4	11.00	8.50	23
2	E	2.8	3.4	10.90	8.50	22
3	E	2.8	3.4	8.63	8.50	2
4	E	2.8	5.0	6.67	5.90	12
5	E	2.8	5.0	6.73	5.90	12
6	E	2.8	5.0	7.06	5.90	16
7	E	2.8	5.8	5.30	5.25	1
8	E	2.8	5.8	4.30	5.25	22
9	E	2.8	5.8	4.70	5.25	12
10	A	2.8	5.2	3.97	2.98	25
11	A	2.8	5.2	3.79	2.98	21
12	A	2.8	5.2	3.95	2.98	24
Average						16%

It is seen that Code 729 can estimate out-of-plane capacity of different masonry walls with enough accuracy. The estimation is not exact, of course. Errors of Code 729 according to the carried out comparisons are illustrated in Figure 7. Reported errors are partly because of the highly uncertain characteristics of masonry walls, but mostly due to the simplifications made by Code 729. This simplification is inevitable as the code should be simple enough to be used in practical applications.

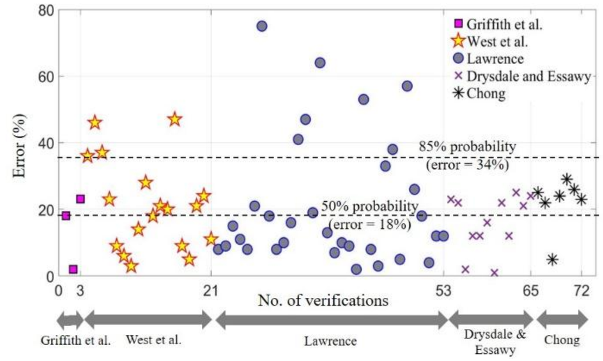


Figure7. Error of Code 729 in estimating ultimate out-of-plane capacity of non-structural masonry walls according to the carried out verifications

4. Verification with Finite Element Results

In addition to experimental results, FE simulations are also carried out in this study to shed more light on out-of-plane behaviour of walls with different opening details. According to Code 729, unreinforced non-structural masonry walls are not allowed in seismic prone regions. Figure 8 not only shows accuracy of Code 729 compared with FE results, but also illustrates contribution of bed joint reinforcements to out-of-plane capacity of a non-structural masonry walls.

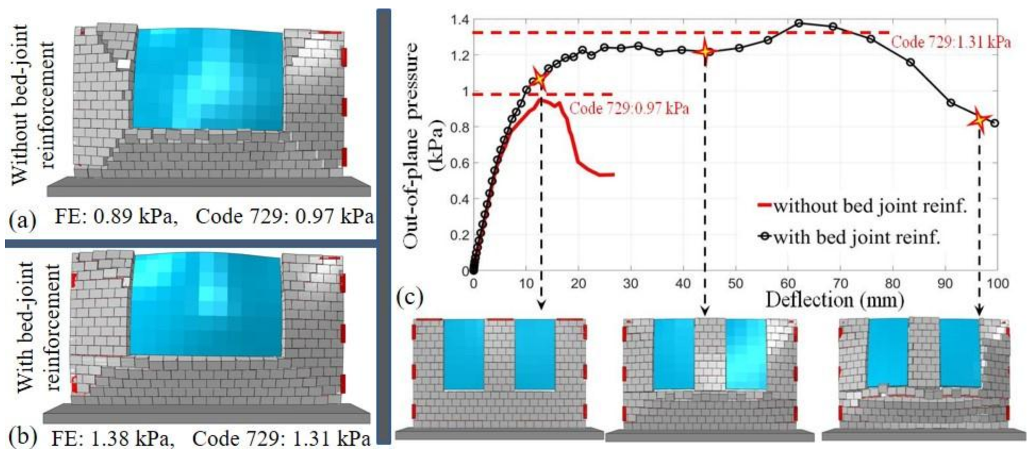


Figure 8. Verification of Code 729 with FE simulations. For all walls length=6 m, height =3m, thickness=150 mm, height of opening=2m, total length of opening=3m, masonry unit=concrete hollow units, mortar: type N with masonry cement.

5. Conclusion

In 2017, the first Iranian strength-based guideline for seismic design of non-structural masonry walls have been published by The Plan and Budget Organization of Iran. Code 729, should be able to reliably estimate ultimate out-of-plane capacity of non-structural masonry walls considering their anisotropic two-way behaviors. In this paper, using a comprehensive experimental database of 72 full-scale masonry walls, as well as some FE simulations, accuracy of Code 729 is demonstrated. Obtained results of this study indicated that Code 729 is a reliable guideline to design non-structural masonry walls with different boundary conditions, different masonry units and different types of opening. It is concluded that with 50% certainty, error of Code 729 would be less than 18% and with probability of 85% this value would be less than 34%. This level of accuracy is comparable or even better than other masonry codes, such as AS 3700, and deemed to be enough for most practical applications.

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