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COMPARISON OF EXPERIMENTAL AND ANALYTICALLY PREDICTED OUT-OF-PLANE BEHAVIOR OF FRAMED-MASONRY WALLS CONTAINING OPENINGS

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Abstract. *During an earthquake, structures are loaded in both in-plane and out-of-plane direction. This paper investigates the behaviour of load-bearing frames with infill walls that contain openings. As when they are subjected to out-of-plane, inertial loads. In the experimental campaigns of like structures, it was found that even with openings, the beneficial arching-action was able to develop. However, its effectiveness was limited. Namely, the deformation capabilities in all cases were significantly lowered. Same can not be stated for the load-bearing capacities, as some researches found no reduction while others did. Additionally, this paper analyses the existing equations that can calculate the load-bearing capacity of such structures. Low correlations were found between the experimental and analytical capacities. Hence, further research endeavours should be addressed in order to gain a reliable analytical model*

1 Introduction

Various countries around the world are located on seismically active areas. Globally, common structural systems of multi-storey buildings are assembled of load-bearing frames with masonry infill walls. Generally, hollow clay masonry blocks are used as infill unit, and reinforced-concrete (RC) or structural steel (SS) frames. During an earthquake, ground motions excite such structures in both in-plane (IP) and out-of-plane (OoP) direction. Thus, the field of seismic engineering specialised in the analysis of those general and their combined direction.

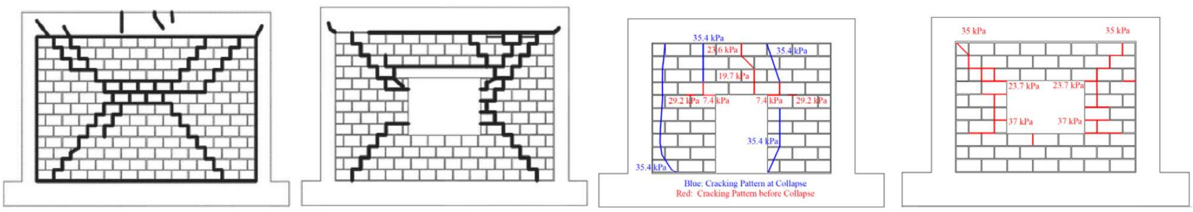
During ground motions, frames in such structures interact with infills. This however, is a topic greatly researched, as a way of implementing the interaction is still not provided within the European seismic codes [5].

Various conditions affect the interaction, and with it, the overall behaviour of the structure. Those conditions include the influence of: infill type, slenderness, openings, frame stiffness, gravity load, boundary conditions and etc.

This paper investigates the OoP relation between experimental and analytical models of frames with infills that contain openings. The field of IP loading was researched in greater extend when compared to the OoP field [3]. This is especially true in the case of openings. Namely, in the IP studies openings had a profound effect on the overall behaviour [15, 14]. However, the same is not clear in the case of OoP behaviour.

2 Experimental endeavours

When structures are excited by earthquakes ground motions, the inter-storey drift and inertial forces act upon them. The majority of research done in the field of OoP loading was conducted with the inertial methods. Namely, with the use of air-bags. In like manner, all OoP experiments that included openings were done using inertial methods with air-bags. Prior to loading, the openings were covered with plywood and frames were restrained from translation. Hence, such test procedures damage the infill while frames are more or less intact (Fig. 1). When tested with inertial methods, infills had transverse bearing capacity substantially higher than what would be expected from flexural theory. This is however, due to the effects of arching-action. Arching-action is well observed phenomena of developing additional compressive that resist transversal forces. In detail, when infill is loaded it bends as a beam would. With an increase of load, infill cracks and separates in two parts. Those parts, on one end clamp and on the other open. Points that clamp make the compression arch. If the infill is fully bounded by all sides, the horizontal and vertical arching forms a characteristic “X” like failure pattern (Fig. 1a).



(a) Plain infill [1] (b) Window opening [1] (c) Door opening [17] (d) Window opening [13]

Figure 1: Various inertial failures

From Figure 1, it is evident that, even with the presence of openings, arching-action was able to develop. The only difference can be found with door opening, as it has cracks nearly all vertical. This can be attributed to the fact that due the door opening, boundary conditions developed such as having only horizontal arching-action. As it is case with columns-infill gaps [7, 17]. Furthermore, all authors that studies the effects of openings [1, 6, 17, 13, 16] observed a significant reduction of deformation capabilities (Fig. 2). The same can not be stated for the case of load-bearing capabilities, as different authors had different outcomes. For instance, [6, 1] (Fig. 2b) found no decrease with window, while, [17, 13, 16] (Fig. 2a) found a significant drop in bearing capacity of window, door and full height opening.

Likewise, in the case of initial stiffness, openings in some cases did lower it (Fig. 2a) and in others did not (Fig. 2b).

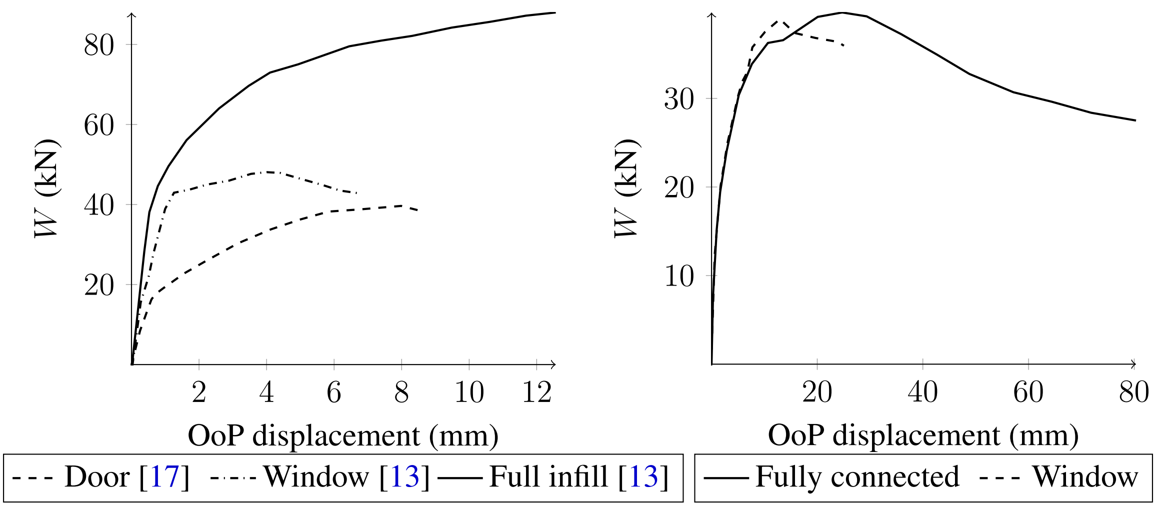
In Table 1, the geometrical and mechanical properties of specimens with openings are shown. It is to be noted that [9, 16] tested a specimen with full wall height opening. However, data provided from authors is scarce.

Table 1: Geometrical and mechanical characteristics of specimens with openings

# Author	Specimen	t (mm)	l (mm)	h (mm)	Frame type	Opening	Lintel
1 Wang (2017) [17]	IF-RC-DO	90	1350	980	RC	Door	No
2 Sepasdar (2017) [13]	IF-W	90	1350	980	RC	Window	No
3 Dawe & Seah (1989) [6]	WE9	190	3600	2800	SS	Window	n/a
4 Akhoundi et al. (2015) [1]	SIF-B	110	2415	1635	RC	Window	Yes

#	Column size (mm×mm)	Beam size (mm×mm)	f_m (MPa)	E_m (MPa)	E_F (MPa)	A_o/A_i (%)	Capacity w (kPa)	Displacement @ w (mm)
1	180×180	180×180	9.0	7650	16911	17	36.2	7.9
2	180×180	180×180	9.0	7650	16911	17	43.7	4.3
3	W250 × 58	W200 × 46	24.3	17575	210000	19	22.3	n/a
4	160×160	270×160	1.0	1000*	32000*	20	9.9	25.0

** Estimated*



(a) Window and door, no lintel (b) Window with lintel [1]

Figure 2: Force vs. displacement graph of infilled frames with openings

3 Analytical models

All developed analytical models are based on inertial failures and with it, arching-action. There are no specific equations developed for infilled frames with the implementation of openings. However, Mays et al. (1998) [11] developed an equation (Eq. 6) that can be used to modify an arbitrary equation of infilled frame as to address the effects of openings. Hence, one can use equations made for infilled frames, and modify it with the equation of Mays et al. (1998) [11]. Note that the equation was developed for RC walls with openings (no frame).

Equation by Angel et al. (1994) [2] Authors developed an equation to answer the problem of OoP capacity due to previous IP damage. Ways of calculating both R_1 and R_2 were omitted as all specimens with openings did not contain previous IP damage nor did infill had any connection gap with the frame.

$$w = R_1 R_2 \frac{2 f_{\mathrm{m}} \lambda}{h/t} \tag{1}$$

No previous IP damage $R_1 = 1$, full frame and infill contact $R_2 = 1$, λ see Tab. 2

Table 2: Values of λ

h/t	5	10	15	20	25	30	35
λ	0.129	0.060	0.034	0.021	0.013	0.008	0.005

Equation by Dawe & Seah (1989) [6] Authors also developed an equation to evaluate the one-way (gapped) arching action. However, as all specimens with openings have their infill restrained by all sides; hence, the equation was omitted from this paper.

$$w = 0.8 f_{\mathrm{m}}^{0.75} t^2 \left(\frac{\alpha}{l^{2.5}} + \frac{\beta}{h^{2.5}} \right) \tag{2}$$

Where: $\alpha = \frac{1}{h} \left(E_{\mathrm{f}} I_{\mathrm{c}} h^2 + G_{\mathrm{f}} J_{\mathrm{c}} t h \right)^{0.25}$; $\beta = \frac{1}{l} \left(E_{\mathrm{f}} I_{\mathrm{b}} l^2 + G_{\mathrm{f}} J_{\mathrm{b}} t l \right)^{0.25} \leq 50$

Equation by Flanagan & Bennett (1999) [8] Authors here modified Eq. 2, by changing the front constant and by eliminating torsional effects from parameters α and β

$$w = 0.73 f_{\mathrm{m}}^{0.75} t^2 \left(\frac{a}{l^{2.5}} + \frac{\beta}{h^{2.5}} \right) \tag{3}$$

Where: if $h/t < 8 \rightarrow t = h/8$; $\alpha = \frac{1}{h} \left(E_{\mathrm{f}} I_{\mathrm{c}} h^2 \right)^{0.25} \leq 50$; $\beta = \frac{1}{l} \left(E_{\mathrm{f}} I_{\mathrm{b}} l^2 \right)^{0.25} \leq 50$

Equation by Moghaddam & Goudarzi (2010) [12] Authors differentiated failure of slender and thick infills. Thick infill's suffered crushing at supports (frame); while slender ones had transverse instability failure, due to large deflections. The transverse instability failure is withal, a favourable one due to magnification of arching-action effects.

$$w = \min \begin{Bmatrix} w_{\text{cr}} = \dfrac{0.85 f_{\text{m}}}{(h/t)^2} - \left(0.12 + \dfrac{0.45}{\alpha}\right) \dfrac{f_{\text{m}}^2}{E_{\text{m}}} \\ w_{\max} = \dfrac{0.18 E_{\text{m}}}{(0.12 + 0.045/\alpha)(h/t)^4} \end{Bmatrix} \tag{4}$$

Where: w_{cr} crushing failure, $w_{\max}$ transverse instability failure, $\alpha = \dfrac{384 E_{\text{f}} I_{\text{b}} h}{E_{\text{m}} t l^4}$

Equation by Klingner et al. (1996) [10] Authors here developed their equation based on the work by [4].

$$w = 8\frac{M_{\text{yv}}}{h}(l-h) + 8\frac{M_{\text{yh}}}{h} \ln(2) \left(\frac{x_{\text{yv}}}{x_{\text{yh}}}\right) \ln\left(\frac{l}{l-h/2}\right) l \tag{5}$$

Where: for calculation of x_{yh} replace h with l, and for calculation of M_{yh} replace x_{yv} with x_{yh}, $x_{\text{yv}} = \dfrac{t f_{\text{m}}}{1000 E_{\text{m}} \left(1 - \dfrac{h}{2\sqrt{(h/2)^2 + t^2}}\right)}$

Equation by Mays et al. [11]

$$w_{\text{o}} = w + w F_{\text{r}} \left(\frac{A_{\text{o}}}{A_{\text{i}}}\right) \tag{6}$$

Where F_{r} is obtained by using Tab. 3

Table 3: Modification factor F_{r} for panels with openings [11]

Panel type	Opening location	F_{r}
One window	Central and offset	-1.00
One door	Central	$+1.36$
One door	Offset	-0.13
Two windows	Evenly distributed	-0.05
One window + one door	Evenly distributed	-0.41

For the analysis of equations a mixture of Eq. 6 and others (Eq. 1 - 5) was used. In detail, plain masonry's load-bearing capacity w was calculated by Eq's. 1 - 5. Than it was modified in order to address the openings w_{o} by the use of Eq. 6. Data that was used for the calculations was obtained from Tab. 1.

4 Results

By the use of Eq. 6, the reductions of each openings are shown on Tab. 4. The reductions were calculated with an excerpt from Eq. 6: $F_{\text{r}}(A_{\text{o}}/A_{\text{i}})$.

The differences between experimentally and analytically obtained bearing capacities are presented in Tab. 5 and Fig. 3.

Table 4: Reduction of bearing capacity due to openings

Specimen	IF-RC-DO	IF-W	WE9	PIF-A
Opening	Door	Window	Window	Window
Reduction (%)	24	-17	-19	-20

Table 5: Difference by equation

Author	Specimen	Difference (%) Eq. 1	Eq. 2	Eq. 3	Eq. 4	Eq. 5	Opening
[17]	IF-RC-DO	213.26	77.00	60.23	49.61	127.33	Door
[13]	IF-W	73.79	-1.81	-17.00	-17.00	26.11	Window
[6]	WE9	440.00	54.55	40.59	-1.20	361.79	Window
[1]	PIF-A	-61.93	-71.65	-74.08	-82.18	-67.60	Window
Absolute average		197.25	51.25	47.97	37.50	145.71	

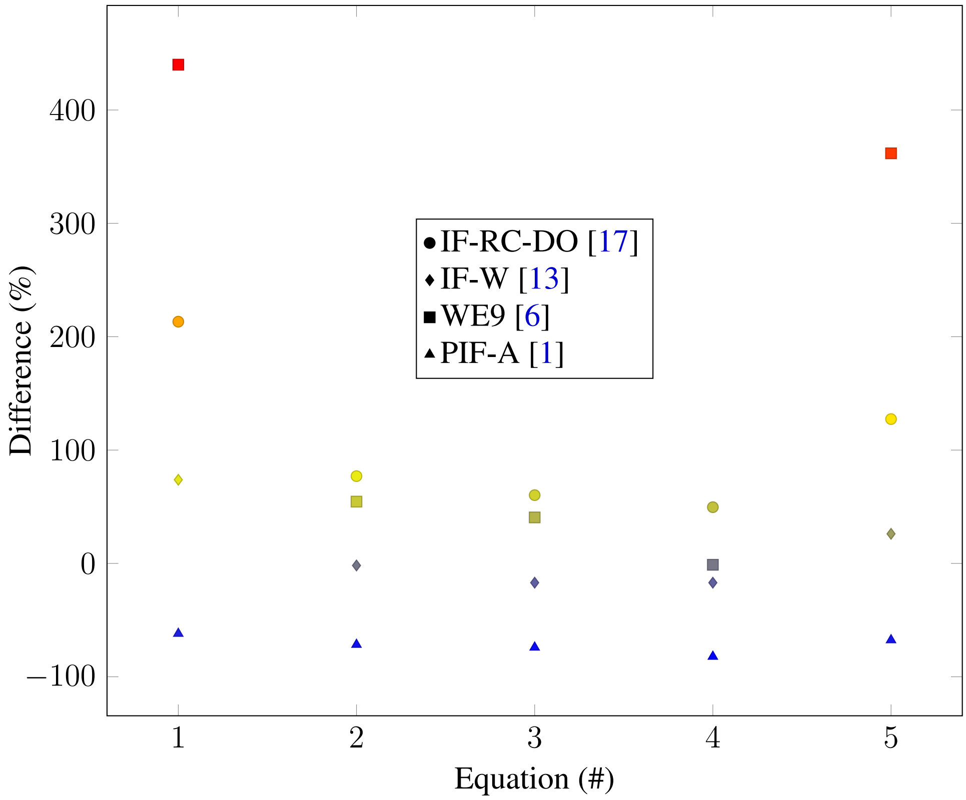


Figure 3: Differences of various analytical models

5 Discussion and conclusion

From Tab. 4 it is clear that there was an obvious mismatch between the analytical and experimental outputs. For instance, specimens WE9 and PIF-A from [6, 1] analytically had a 20 % reduction of bearing capacity. Both authors observed no reduction in their experimental investigations. Furthermore, with the door opening IF-RC-DO specimen [17], equation resulted in an increased capacity of 24 %. This was also inconsistent with data obtained experimentally, as there was also a drastic decrees in the bearing capacity.

From Tab. 5 and Fig. 3 it is clear that the best experimental to analytical correlation was with Eq's. 2 - 4. Certainly, the best fitting was with Eq. 4. Furthermore, IF-W model had the greatest correlation with all equations.

From the literature review and results analysis the following points can be drawn:

1. Openings do not prevent the development of arching-action; rather, they limit its effectiveness. In all cases the deformation capabilities were significantly lowered. However, load-bearing capacities and initial stiffness's in some instances were lowered and in others staid the same;

2. Window openings tend to develop characteristic "X" shaped yield lines as plain masonry infills do. However, door opening developed more or less vertical yield lines. This can be attributed to type of opening in that it changes the boundary conditions;

3. Analytical models showed great aberration between experimental data and between other models. Hence, they could be rendered non-reliable;

4. The Eq. 4 by Moghaddam & Goudarzi (2010) [12] had the best correlation with all the specimens, followed by Eq's. 3, 2, 5 & 1. Furthermore, window specimen IF-W [13] had the best overall correlation with analytical models.

In summation, more research effort should be made to address the effects of openings in structural systems of infilled frames. Also, there is a need to address the effects of out-of-plane, inter-storey drift forces on plain infilled frames and those with openings.

Annotation

h	Height	E_f	Frames elastic modulus	G_f	Frames shear modulus
l	Length	I_c	Columns moment of inertia	R_1	Previous IP damage coeff.
t	Thickness	I_b	Beams moment of inertia	R_2	Boundary condition coeff.
f_m	Masonry compressive strength	J_c	Columns torsional constant	A_o	Area of opening
E_m	Masonry elastic modulus	J_b	Beams torsional constant	A_i	Area of infill

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