OUT OF PLANE STRENGTH OF INFILL PANELS

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ABSTRACT :

This paper presents the results of an analytical investigation on out-of-plane strengths of infill panels. Effects of in-plane damages on the panels' out of plane strengths are studied herein. For the purpose, some infill panels with different numbers of cracks are modeled by finite elements.

It is shown that FEMA formula can accurately predict the out of plane strength of an infill panels, having good connectivity to the surrounding frames. Nevertheless, for infills with a gap between frame and infill, which are practically created in normal earthquakes, infill out of plane strength will be ignorable. In this condition, required strength should be supplied by other elements or devices, such as reinforcements.

Based on experimental results of this study, during in plane loading, interface cracking will be observed in low drifts. For bigger ones, the corners of compression diagonal remain only in contact with the frame; however when the frame returns back to the normal position (zero drift), the gap can be seen all around the infill adjacent to the frame. In this case, infill has minimum out-of-plane strength, which has not been considered yet. Therefore, the out of plane strength of infill panels should be practically less than that proposed by FEMA. Tests on concrete specimens showed that infill may lean outward just for in-plane loading, even in the absence of out of plane acceleration.

KEYWORDS: *Infill, In-plane, Out of plane, FEMA, Strength*

1. INTRODUCTION

Out of plane strength of walls affects structural behavior and earthquake mitigation, therefore, the designers should supply enough out of plane resistance against seismic loads. Furthermore, the out-of-plane strength of walls especially those which are not confined by frames should be checked [1]. Checking for masonry buildings with horizontal and vertical ties, having high stiffness and short period of vibration is more essential. This will lead to high acceleration which may lead to in plane cracking and out of plane instability of walls. X pattern of cracks, resulting from in-plane forces, is similar to the crack pattern for a square panel subjected to out-of-plane forces, implying that the transverse strength can be substantially weakened by in-plane cracking. Therefore, out-of-plane strength, evaluated for a cracked infill, is often surmised to be quite low [2]. In this regard, Mendola et.al, translated the problem into the analysis of a fixed-free ended prismatic column, undergoing static horizontal forces equivalent to the maximum inertia actions [3].

In order to evaluate the perpendicular forces effects on masonry infilled frames behavior, researches have performed a lot of in-plane racking tests. In these tests, specimens were loaded in out of plane direction, and then loaded in plane. The results showed that the specimens, subjected to cyclic out of plane drift displacement within the range a typical infill might experience, are stable and in case of being loaded in plain, only minimal degradation of in-plane stiffness and strength will happen. In other studies, some infill panels were tested using sequential in-plane and out-of-plane pressure. They showed zero to 15% reduction in out-of-plane capacity after being initially loaded by 75% of ultimate in-plane strength. Alternatively, another specimen was simultaneously loaded by in-plane and out-of-plane forces, showing no significant interaction at low to moderate loading levels [4]. A shaking table test, with bidirectional excitation, on two-story, square in plan, concrete frame structure, showed that infill panels with a clear height of 2.5 m and thickness of 11.5 or 8.0 cm, would sustain lateral accelerations of about 1.75g or 1.3g, respectively, showing no out of plane expulsion or significant damage [5].

The arching action, a source of infill out of plane resistance, depends on the infill material, twisting stiffness of frame members and infill to frame connection status. The gaps are developed at the top of the walls soon after being constructed, due to the mortar shrinkage. The walls cannot withstand the out-of-plane forces in the earthquakes and would collapse due to the inadequate binding at the top. However, the walls surrounded by rigid supports, can display very high resistance to out-of-plane forces through the development of arching action in flexure. Therefore, in order to achieve an optimal load-bearing behavior- or rather stability, the remaining gaps at the top of the walls are recommended to be filled with non-shrinkable mortar a few days after their construction [6].

The author believes that out of plane strength of a masonry infill, when it is first loaded in plane, may be practically lower than that calculated by the proposed formula of previous researches, such as Angel [2], or specified by Federal Emergency Management Agency documents [7]. This is because in the worst case, the maximum lateral force may happen during in plane excitation, when zero in-plane drift occurs. In such a condition, the connection between infill and frame is the minimum, specially under the top beam, because of horizontal mortar layers crumbling, caused by in plane movement. Therefore, it is suggested to ignore the arching action and supply the required out of plane resistance by reinforced bars or mesh.

2- PROPOSED FORMULA TO EVALUATE OUT OF PLANE STRENGTH

There are some relations to estimate the out of plane strength of masonry infilled frame. The first method was as empirical relationship developed by Dawe and Seah (1989). In this method the uniform lateral capacity, q (kPa), of an individual infill panel determined from [8]:

$$q = 4.50 \times f'_m{}^{0.75} \times t^2 \times \left(\frac{\alpha}{l^{2.5}} + \frac{\beta}{h^{2.5}}\right) \qquad (2-1)$$

$$\alpha = \frac{1}{h}(E_s I_c h^2 + G_s J_c t h)^{0.25} < 50 \qquad (2-2)$$

$$\beta = \frac{1}{l}(E_s I_b l^2 + G_s J_b t l)^{0.25} < 50 \qquad (2-3)$$

q=Uniform lateral load capacity (kPa)

f'_m=Masonry gross compressive strength (kPa)

t=infill thickness (mm)

h=infill height (mm)

l=infill length (mm)

E_s=Steel frame modulus of elasticity (MPa)

G_s=Steel frame shear modulus (MPa)

I_c=steel column moment of inertia (mm^4)

J_c=Steel column torsional constant (mm^4)

The second analytical method was developed by Angel et al. (1994), which is specified by Federal Emergency Management Agency documents [7]. In this method the out of plane capacity of infill wall is determined as [2]:

$$q = \frac{2 \times f'_m}{(h/t)} R_1 R_2 \lambda \qquad (2-4)$$

where R1 can be determines with table 1 or formual 2-5:

$$R_1 = \left(1.08 + \left(\frac{h}{t}\right)\left\{-0.015 + \left(\frac{h}{t}\right)\left[-0.00049 + 0.000013\left(\frac{h}{t}\right)\right]\right\}\right)^{(\Delta/2\Delta_{cr})} \qquad (2-5)$$

Similarly R2 can be calculated by:

$$R_2 = 0.357 + 2.49 \times 10^{-14} EI \leq 1.0 \qquad (2-6)$$

EI = Flexural stiffness of the smallest member of the confining frame at the panel edge with no continuity ($N.mm^2$)

The value of λ is given in a table as a function of h/t ratio. For values of h/t between 10 and 40, which is the typical range, an exponential function can be fitted to the data as follows:

$$\lambda = 0.154 \times e^{-0.0985 h/t} \qquad (2-7)$$

Table 1- Parameters of Angle formula

h/t	λ	R1	
		Moderate Damage	Sever Damage
5	0.130	1.0	1.0
10	0.060	0.9	0.9
15	0.035	0.9	0.8
20	0.020	0.8	0.7
25	0.015	0.8	0.6
30	0.008	0.7	0.5
35	0.005	0.7	0.5
40	0.003	0.7	0.5

The third analytical method was developed by Cohen and Laing (1956) and extended by Klinger et al. (1996) to two way arching. The uniform lateral load is obtained as [8]:

$$q = \frac{8}{h^2 l}\left\{ M_{yv}\left[(l-h)+h\ln(2)\right] + M_{yh}\left(\frac{x_{yv}}{x_{yh}}\right)\ln\left(\frac{l}{l-h/2}\right) l \right\} \qquad (2\text{-}8)$$

where

$$M_{yv} = \frac{0.85 \times f'_m}{4}(t-x_{yv})^2 \qquad (2\text{-}9)$$

$$x_{yv} = \frac{t \times f'_m}{1000E\left[1-\dfrac{h}{2\sqrt{(h/2)^2+t^2}}\right]} \qquad (2\text{-}10)$$

$$M_{yh} = \frac{0.85 \times f'_m}{4}(t-x_{yh})^2 \qquad (2\text{-}11)$$

$$x_{yh} = \frac{t \times f'_m}{1000E\left[1-\dfrac{l}{2\sqrt{(l/2)^2+t^2}}\right]} \qquad (2\text{-}12)$$

and E is the infill Modulus of elasticity (MPa)

Flanagan et.al. have shown that the best correlation between the experimental results and the predicted results was for the empirical method of Dawe and Seah. Table 2 presents a comparison of the load predicted by the three analytical methods with the observed experimental load [4].

Table 2- Comparison between experimental results and analytical ones for out of plane resistance of infill walls

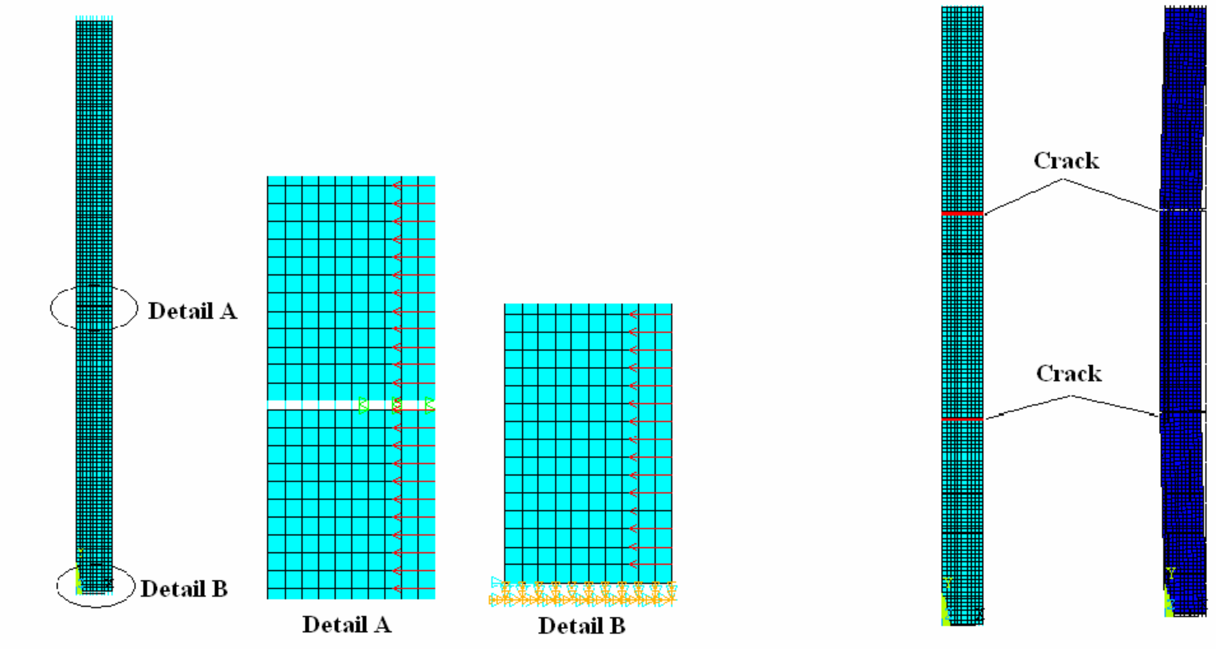
Specimen	Panel Thickness (cm)	Panel length (cm)	Panel height (cm)	Experimental Load (kPa)	Analytical method (kPa)		
					Dawe & Seah	Angel et al.	Klinger et al.
1	33	224	224	39.5	52.4	53.4	57.6
2	20	224	224	26.6	32.6	46.0	43.3
3	10	224	224	8.1	7.42	6.36	5.49

The author of the present study believes that out of plane strengths of a masonry infills should be practically considered lower than those calculated by the proposed formula. Because in certain cases the maximum transversal force may happen when zero in-plane drift occurs. In such a condition, there is the minimum frame to infill contact, because some mortar layers have been crumbled of previous excitation. Therefore, it is suggested to ignore the arching action resistance and supply the required one by reinforced bars, mesh, etc.

3- EXPERIMENTAL AND ANALYTICAL INVESTIGATION

Nonlinear finite element method is applied here to calculate out of plane resistance of infill panels. For which, one strip of the wall is considered, which can be horizontal or vertical, based on the wall aspect ratio. The effects of in plane damage on the out of plane resistance of the wall are regarded as some cracks in the strip, shown in Fig. 1a. In this figure a model of 20 cm thick, 300 cm high wall is shown, having a crack at the middle. As shown in Detail A, the connection of the two segments of a crack is supplied by compression vertical Link elements; however the friction is considered high enough that the segments can be regarded coupled in horizontal direction. In this model, it is assumed that there is not any gap between the wall and frame elements and the wall is in complete contact with the top and bottom frame elements. It is also assumed that sequential in-plane and out-of-plane pressure is applied on the wall; the wall is loaded in-plane, and then at the maximum drift, out of plane load is operated. This analysis leads to high out of plane strengths, very close to one estimated by Klinger formula. For example for a 20 cm thick, 300 cm high infill wall, the strength was calculated as 4500 kg/m^2. Taking into account the above-mentioned assumptions as well as modeling more damages on the wall (by some cracks on the strip), does not affect out of plane strength considerably. In the other words, the out of plane resistance of the wall with one, two (shown in Fig 1b) or 15 cracks are almost the same. This analysis confirms the results of the experimental tests in which infills are loaded transversely, at the maximum drift of being loaded in in-plane direction.

Similar analysis shows that in the presence of top gap, the out of plane strength of the strip is ignorable. Considering the random nature of earthquakes, the infill is probable to suffer from maximum transversal acceleration at frame zero drift, after having been damaged during previous in-plane cycles. Therefore it is highly recommended to ignore out of plane resistance of infills and supply reinforcements or other devices to stabilize walls.



a) A strip of an infill panel, with a crack at the middle

b) A strip of an infill panel, with two cracks, elements and deformation

Fig. 1. Strips of an infill panel, with cracks

From the other point of view, in some cases as observed in the concrete specimens of this research, infills may become transversally unstable, leaning outward, during in-plane loading, even in the lack of out of plane acceleration. In this study some masonry and concrete infill panels were tested. As shown in Fig 2a, each specimen was composed of a IPE-140 frame, with rigid connections, by the length and height of 265 and 200 cm respectively, with a 10 cm thick infill panel inside. The specimen was subjected to seven cycles of loading, with amplitudes of 1, 2, 3, 4, 5, 7.5 and 10 cm, respectively. Similar to previous experimental test results on infill panels, in this study the interface cracking was observed in masonry and concrete specimens in drifts less than 0.01% and 0.1% in average, respectively. Many specimens- including masonry, concrete and multilayer infill panels- were tested in this study, with the same procedure. However in concrete ones (ordinary concrete and fiber concrete infill specimens, in which thickness of the infills and the frames were the same), the out of plane movement of the infill were observed after cycle 3, shown in Fig. 2b. It should be noticed that in these tests, no out of plane loadings were applied and the specimen were loaded only in in-plane direction. Therefore, the author believes that some elements should always be supplied for infill panels to connect it to the frame, in order to avoid such a movement, based on numerical and experimental of this study.

a) A masonry specimen b) Outward movement of a concrete specimen

Fig 2. Loading of specimens and outward movement of a concrete infill specimen

4- CONCLUSION

Based on the results of numerical and experimental studies of the present paper, the following conclusions can be drawn:

Daw & Seah relation results correlates to the experimental results better than the other formula. Since this relation and the other ones ignore the worse case, in which the maximum out of plane acceleration occurs when the minimum contact is between frame and infill, it is believed that all the proposed relations overestimate out of plane strength of infill panels.

Furthermore, based on the experimental observation, infills -especially concrete ones- may become sometimes transversally unstable during just in-plane loading (in the lack of out of plane acceleration), by leaning outward. Therefore some elements should always be supplied to prevent such a movement to stabilize infill panels.

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