Testing and Evaluation of Out-of-Plane Strength of Unreinforced Masonry Infills

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Resumen: *Se llevó a cabo una investigación para examinar la capacidad perpendicular al plano (capacidad trasversal) de muros de relleno de mampostería. En la parte experimental del estudio se construyeron especímenes a escala real de marcos de concreto reforzado que se rellenaron con muros de mampostería, bien fuese de ladrillo, de arcilla o de bloques de concreto. Dichos especímenes se cargan en la dirección perpendicular a su plano mediante la aplicación de una presión uniforme (simulando viento, fuerzas sísmicas, cargas explosivas) perpendicular al muro, hasta que se logra su falla o hasta que la capacidad del marco de prueba sea alcanzada. A medida que la parte experimental se realizaba, se desarrolló un modelo analítico para estimar la capacidad trasversal de estos muros. Con base en este modelo analítico y considerando los resultados experimentales, se propone un método de evaluación para muros de relleno.*

Abstract: *An experimental program was undertaken to determine the out-of-plane or transverse strength of unreinforced masonry infills. Full-scale, single-story, single-bay reinforced concrete frames were constructed, and filled with clay brick or concrete block masonry. Specimens were tested in the transverse direction by applying a uniform pressure (simulating wind, seismic, or explosive loads) to the surface area of the infills until either failure of the infill occurred or the capacity of the testing rig was reached. As the experimental phase of the program progressed, an analytical model to estimate the out-of-plane strength of these infills was developed. Based on this analytical model, calibrated with the experimental results, an evaluation method was developed.*

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1. Introduction

Traditionally masonry infills are not designed as a structural element despite their influence on the structure force resisting system. They are mostly used as environment dividers usually forming the building envelope due to its effectiveness in the insulation of thermal, moisture, and acoustic effects. Although masonry infills are not considered structural elements, they greatly affect the behavior of the structure horizontally in both the parallel (in-plane) and the transverse (out-of-plane) directions with respect to the face of the infill. This paper describes research done in the experimental evaluation and the development of a simplified procedure to estimate the out-of-plane behavior and strength of unreinforced masonry infill panels, and how it is influenced by existing panel damage caused by previously applied in-plane forces.

Infill panels often are subjected to large horizontal forces resulting from earthquakes, detonation of explosives, or high wind speeds. The application of these forces is generally not coincident with the principal axes of the building system. This means that the applied forces have components in both the in-plane and out-of-plane directions of the panels. Now, we are interested in the out-of-plane strength of the panels and the possible influence due to existing in-plane damage. These effects were evaluated experimentally by testing a series of clay brick or concrete block masonry infills confined within a reinforced concrete frame. The specimens were first tested in the in-plane direction under cyclic loading, and once damaged, the panels were tested in the out-of-plane direction by applying a uniform pressure to the entire surface of the panel.

Out-of-plane strength of masonry infills depends on a number of parameters including properties of the panel itself, properties of the confining frame, the boundary conditions along the perimeter of contact between the panel and the frame, and the existing condition of the panel. Based on these parameters and considering a resisting mechanism of arching action, an evaluation procedure was developed to estimate the out-of-plane strength of undamaged and previously damaged infills.

2. Background

Research done on the out-of-plane behavior of masonry infills is far less extensive when compared to the research done on the in-plane direction. Although this is the case, out-of-plane behavior has been a topic of interest since the forties when the concern was purely blast capacity. In 1956 McDowell, McKee and Sevin [1], [2] developed a theory at the Armour Research Foundation (ARF) to predict the out-of-plane strength of masonry infills. The theory was based on arching action for a one-way strip of unreinforced masonry confined within rigid boundaries. The theory considers that the strip of infill is comprised of two equal segments that rotate about their ends until masonry crushes, or the two segments snap through. Later McKee and Sevin [3] published a paper that presented a design method for blast based on their previous work.

In 1958, Monk [4] developed procedures for blast design as part of a blast resistance program sponsored by the Structural Clay Products Research Foundation. During this study Monk tested a series of infills by building them in an octagon shaped test fixtures and detonating a high explosive at the center. The magnitude of the blast was adjusted to reproduce closely the effects of the atomic blast experienced in Operation "Cue" at the 35 kPa (5 psi) overpressure level.

This testing was used for the assessment of damage expected in an atomic blast. For this test, it was determined that the time-pressure effects of the high explosive could be approximately equated to the impulse resulting from an atomic explosion.

During the seventies, Gabrielsen [5] then tested full-scale masonry panels both statically and dynamically. Following, the Defense Civil Preparedness Agency and the Veterans Administration used a shock tunnel to test dynamically a number of full-scale walls by applying an air blast loading to their entire surface of the specimen.

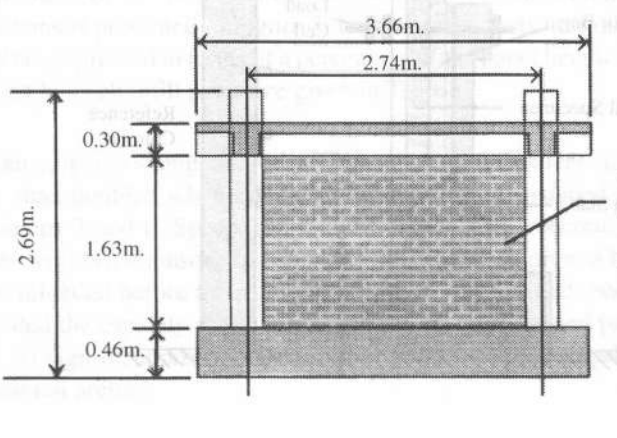
During the last two decades research in this area has increased. Infill behavior has been studied at a number of universities and research institutes in the United States through coordinated programs sponsored by the National Science Foundation (NSF), the U.S. Department of Defense, and the U.S. Department of Energy. During these programs masonry panels of different sizes and scales have been tested statically and dynamically varying most of the infill geometrical and mechanical properties. A summary of efforts in the U.S. is presented in [7]. Along with these experimental experiences, a number of analytical models have been developed to predict the panel behavior and strength under various conditions. These models include more accurate versions of the one-way arching action established initially by McDowell [1], [2], and extend to computerized models that include two-way arching action within flexible frames with solid panels or panels with openings [6].

The interaction between in-plane damage and its influence in out-of-plane behavior and strength presented in this paper comes as a result of an experimental program that took place at the University of Illinois, U.S.

3. Experimental program

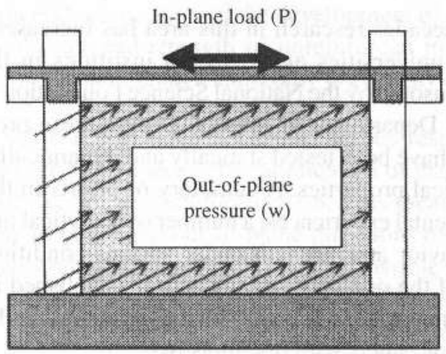
A series of specimens designed to evaluate the influence of damage caused by in-plane forces on the out-of-plane behavior and strength of masonry infill panels were constructed and tested. Full size test specimens consisted of a series of masonry infills placed within single-bay, single-story, reinforced concrete frames (Figure 1). The frame was designed to be both ductile and strong when compared to the masonry infills, so that the frames could be reused for several tests.

Figure 1. Infill-frame test specimens



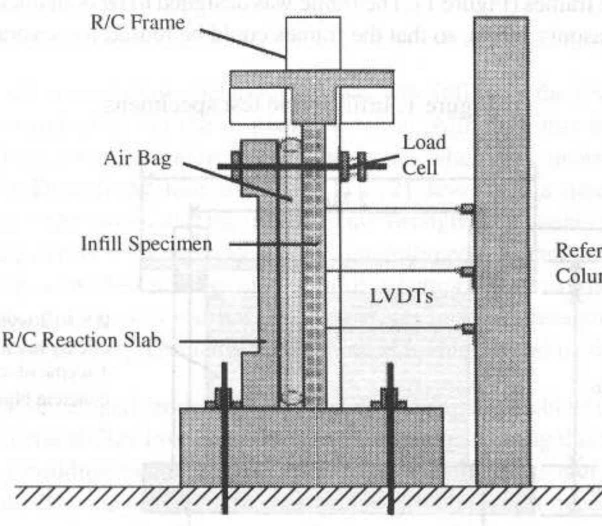
A total of eight specimens were tested. Specimens were first tested in the in-plane direction by applying a series of load cycles to the top beam of the specimen until a fully cracked infill was obtained (Figure 2). To assure a fully cracked infill, the load cycles were applied until lateral deflections were twice that observed for first cracking in the masonry.

Figure 2. Testing sequence



Following the in-plane loading, panels were subjected to uniform pressures applied perpendicular to the face of the infill (out-of-plane direction as shown in Figure 2) using an airbag. The pressures were increased monotonically until ultimate capacities of the specimens were reached. The out-of-plane testing setup is shown in Figure 3. The first of the eight specimens was tested only in the out-of-plane direction allowing us to quantify the out-of-plane strength of an undamaged infill panel.

Figure 3. Test setup for out-of-plane static tests



Properties of the eight tested specimens are presented in Table 1. The parameters studied were the type of unit, the h/t slenderness ratio (infill thickness, t, was varied for a constant height, h) and the mortar type. Infill panels were constructed using both clay brick and ungrouted hollow concrete block laid in running bond. We used low strength reclaimed bricks in half, single, or double wythe running bond. Bricks were cut in half to achieve the larger slenderness ratios used for the first three specimens. Standard 4-inch (10-cm) and 6-inch (15-cm) concrete blocks were used for two of the specimens.

A typical Type N mortar (1:1:6, Portland cement:lime:sand) was used as the control mortar. Type S mortar (1:0.5:4.5) was used for the first specimen. A weaker, low-strength mortar comprised only of lime and sand (1:3) was also used in three of our specimens to represent constructions built during the earlier part of the century. Measured compressive strengths of prisms tested for each infill panel are presented in Table 1.

Table 1. Summary of infill properties and test results

Specimen	Infill Type	h/t	Mortar Type	f'_m (MPa)	In-Plane Drift (%)	Out-of-Plane Pressure (kPa)
1	Brick	34	S	11.51	0.00	8.19
2	Brick	34	N	10.86	0.34	4.02
3	Brick	34	Lime	10.14	0.22	5.99
4	Block	18	N	22.90	0.09	29.78[1]
5	Block	11	N	21.46	0.06	32.22[1]
6	Brick	17	Lime	4.59	0.25	12.40
7	Brick	17	N	11.00	0.25	30.74[1]
8	Brick	9	Lime	3.50	0.39	32.08[1]

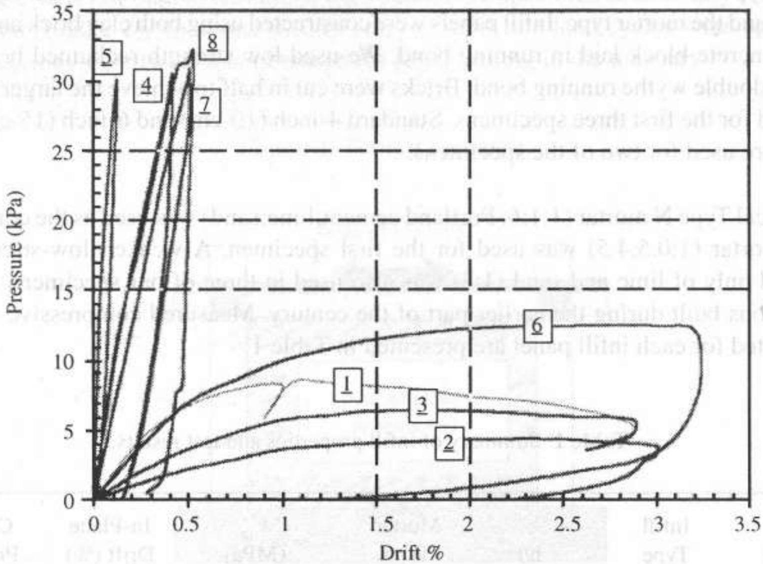
1 maximum pressuer applied to specimen.

4. Experimental Results

A summary of the observed out-of-plane pressure-deflection behavior for the eight tested specimens is presented in Figure 4. Lateral deflections normal to and at the center of an infill panel are expressed in terms of a percentage of the panel height. Maximum transverse pressures resisted by each infill panel are given in Table 1.

Out-of-plane strength of the infill panels were dependent on the h/t ratio. Ultimate pressures more than doubled when the slenderness (h/t) ratio reduced by a factor of 2 is the case for specimens 3 and 6. Specimens 4 and 5 (made with concrete block) and specimens 7 and 8 (made with brick masonry), behaved with high strength and high stiffness. These specimens were unloaded before their ultimate strength was reached, because the capacity of the infills exceeded the capacity of the testing rig. These tests resisted peak pressures exceeding 30 kPa with no sign of approaching their strengths. The large panel strengths were attributable to substantial arching.

Figure 4. Summary of Out-of-Plane Tests



For panels with higher slenderness ratios (specimens 2 and 3) the out-of-plane strength was higher with the weaker lime mortar because cracking with forces in the in-plane direction for the stronger mortar tended to be incident with fracture lines for out-of-plane bending. For panels with a moderate slenderness ratio (specimens 6 and 7) the out-of-plane strength of panels with Type N mortar was more than twice a similar panel with a lime mortar.

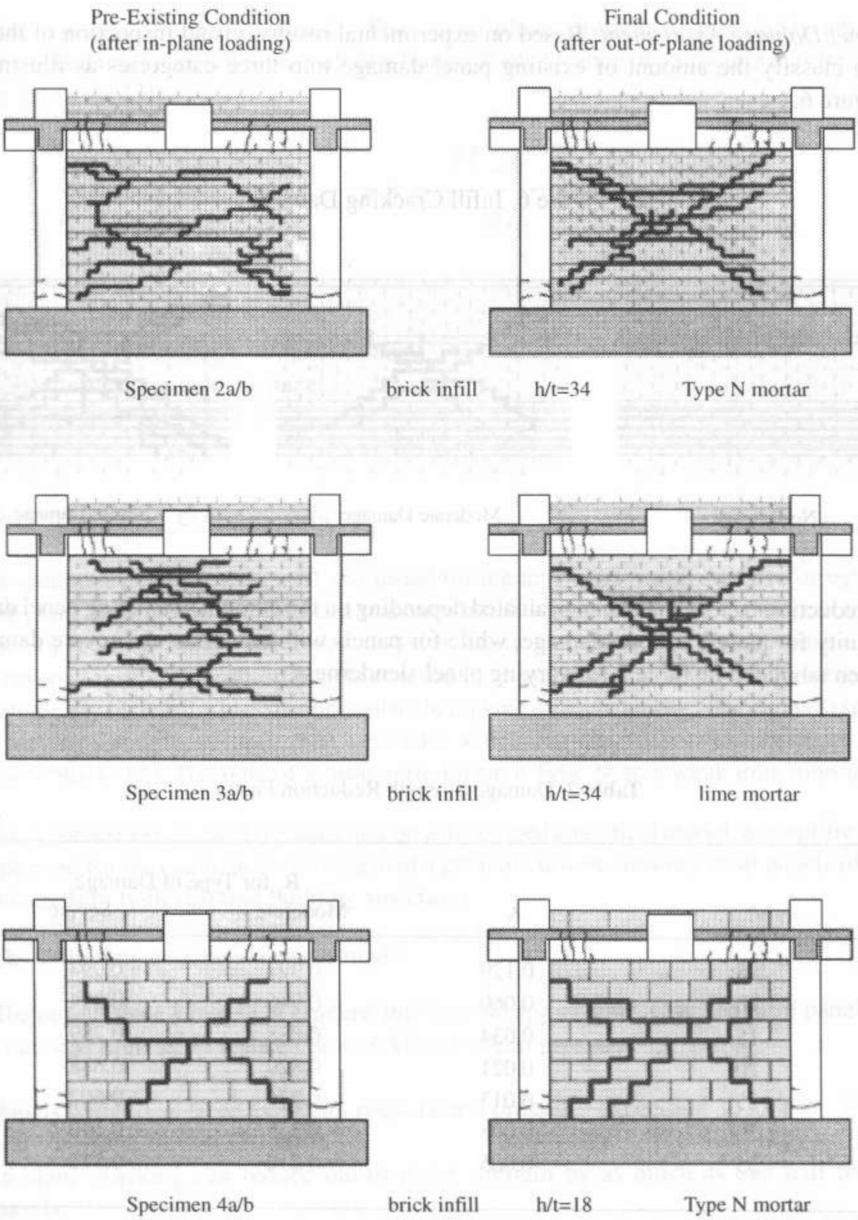
Crack patterns for the pre-existing condition (after in-plane loading) and for the final condition (after out-of-plane loading) are shown in Figure 5 for specimens 2, 3, and 4. Only those cracks that were opened during the loading are designated in the figure. Cracking resulting from out-of-plane loading was generally in an "x" type pattern suggesting that forces were being transferred in both horizontal and vertical directions. Some of the diagonal cracks created during the in-plane testing of the specimen re-opened during the out-of-plane loading. However, new diagonal cracks developed with out-of-plane loading for those specimens that did not cracked in the diagonal direction when subjected to in-plane forces. This is the case for specimen 3. Cracking of infill panels with concrete block units followed primarily head and bed joints, and produced coarser crack patterns and slightly higher strengths, when compared to brick infills (with smaller size units).

5. Analytical Models

Behavior and strength of the tested specimens suggested that arching action was the prevalent mechanism in resisting out-of-plane pressures because considerable out-of-plane strength was developed even after the specimens had cracked. Because the confining frame provided a stiff boundary, triangular and trapezoidal segments of the infill panes were observed to rotate about their base axes while resisting the out-of-plane pressure. This suggested that even cracked unreinforced masonry panels could develop flexural strength as a result of axial compressive stress from internal struts which formed as segments rotate.

An analytical model was developed based on one-way arching action to simplify the analytical derivation, and provide a lower-bound strength. The model then became independent of the panel aspect ration (height/length), and thus applicable to panels of all shapes. Panels were assumed to crack at mid-height, and develop internal thrusts to resist a uniform applied out-of-plane pressure. The development of this model is presented in detailed in [7].

Figure 5. Crack Patterns after In-plane and after Out-of-plane loading

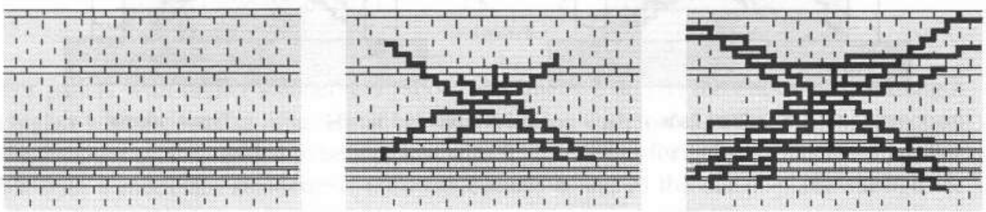


6. Suggested Evaluation Guidelines

Guidelines for the evaluation of out-of-plane strength of infill panels are proposed based on results of the experimental study mentioned in the previous sections, and on an analytical model developed to predict the observed behavior. The analytical model is not presented in this paper for lack of space, but is explained in great detail in [7]. These guidelines consider that the primary resisting mechanism for the out-of-plane strength of the panels is governed by arching of the panel, and that the slenderness ratio (h/t) of the panel limits the type of failure. The following three steps are required to evaluate damaged/undamaged infills:

1. *Panel Damage Assessment:* Based on experimental results, visual inspection of the panel can classify the amount of existing panel damage into three categories as illustrated in Figure 6.

Figure 6. Infill Cracking Damage



A reduction factor (R_1) is then evaluated depending on the amount of existing panel damage. R_1 is unity for panels with no damage, while for panels with moderate and severe damage R_1 has been tabulated in Table 2 for varying panel slenderness ratios.

Table 2. Damage Strength Reduction Factor

h/t	λ	R_1 for Type of Damage Moderate	Severe
5	0.129	0.997	0.994
10	0.060	0.946	0.894
15	0.034	0.888	0.789
20	0.021	0.829	0.688
25	0.013	0.776	0.602
30	0.008	0.735	0.540
35	0.005	0.716	0.512

2. *Flexibility of Confining Frame:* Infill panels within frames with neighboring panels in every direction may assume to have fully restrained boundary conditions ($R_2 = 1$). For panels within frames with at least one neighboring panel missing on any direction, a reduction factor (R_2) for the out-of-plane strength is applied.

(1) $$R_2 = 0.357 + 2.488X10^{-5}EI \quad for\ 5.740E3kN - m^2 < EI < 2.583E4kN - m^2$$

(2) $$R_2 = 1.00 \quad for\ 5.740E3kN - m^2 < EI < 2.583E4kN - m^2$$

3. *Out-of-plane Strength of Panels:* The out-of-plane strength of previously cracked, or uncracked infill panels within confining frames at any location of a structure may be evaluated by Equation [3].

(3) $$w = \frac{2f'_m \lambda}{h/t} R_1 R_2$$

Where:

f'_m = Compressive strength of the masonry
h/t = Slenderness ratio of the panel
λ = Coefficient from Table 2.

7. Summary and conclusions

Eight specimens were constructed and tested during an experimental study to investigate the out-of-plane strength of unreinforced masonry infills within a reinforced concrete frame. All but one of these specimens were first tested in the in-plane direction by applying a series of load reversal until the masonry panels cracked in shear. The panels were then subjected to a monotonically increasing pressure normal to their plane using an air bag. The eight (8) specimens with varying slenderness ratios (h/t) were built with either clay masonry units (6), or concrete masonry blocks (2). The type of mortar varied from a Type N, to a weak lime mortar.

Based on the experimental results and on a developed analytical model, a simplified method is suggested for the evaluation of strength of a general class of masonry infill panels (damaged/ undamaged) in typical frame building structures.

The following conclusions were made:

- The out of plane strength of cracked infill can be appreciable. Cracked infill panels with h/ t ratios as high as 34 resisted up to 6 kPa of lateral pressure.
- Panels with h/t as large as 17 can resist lateral pressures exceeding 30 kPa.
- In-plane cracking can reduce out-of-plane strength by as much as one half for slender panels.

- The developed out-of-plane strength evaluation method provides suitable lower-bound estimates.

References

[1] McDowell, E.L., K.E. McKee and E. Sevin, *Arching action theory of masonry walls*, proceedings of the ASCE, Journal of the Structural Division, Vol. 82, Nº ST2, March 1956, págs. 915-1 to 915-18.

[2] McDowell, E.L., K.E. McKee and E. Sevin, *discussion of arching action theory of* masonry *walls*, proceedings of the ASCE, Journal of the Structural Division, September 1956, págs. 1067-27 to 1067-40.

[3] McKee, K.E. and E. Sevin, *design of masonry walls for blast loading*, ASCE Transactions, Paper Nº 1512, Vol. 124, 1958.

[4] Monk, C.B., *Resistance of structural clay masonry to dynamic forces*, Research Report Nº 7, Structural clay Products Research Foundation, Geneva, IL, November 1958.

[5] Gabrielsen, B.L., and K. Kaplan, *Arching in masonry walls subjected to out-of-plane forces*, Proceeding of National Workshop on Earthquake Resistant Masonry Construction, National Bureau of Standards, NBS Science Series Nº 106, September 1977.

[6] Dawe, J.L., and C.K. Seah, *out-of-plane resistance of concrete masonry infilled panels*, Journal of the Canadian Society of Civil Engineering, January 1990, págs. 854-864.

[7] Angel, R., D. Abrams, *et al.*, *Behavior of reinforced concrete frames with masonry infill*. Structural Research Series Nº 589, Department of Civil Engineering, University of Illinois at Urbana-Champaign, March 1994.