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ESTIMATING OUT-OF-PLANE STRENGTH OF CRACKED MASONRY INFILLS

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16. Abstract (Limit: 200 words)

The primary objective of the research project was to determine the transverse (out-of-plane) seismic strength of unreinforced masonry infill panels that have been cracked with in-plane lateral forces. The goal of the research was to develop a simple method that practicing engineers could use for evaluating strength of infill panels that have been damaged in earthquakes. In addition, the feasibility of using a low-cost repair or rehabilitation technique for improving transverse strength was examined.

A total of 22 tests were run on eight large-scale masonry infill panels that were constructed in a single bay, single story reinforced concrete frame. Test panels were first subjected to in-plane load reversals to create a pre-existing cracked, damaged state for the subsequent out-of-plane tests which were done with an air bag. Following this test sequence, selected damaged panels were repaired and retested.

Previous in-plane cracking was found to reduce out-of-plane strength by as much as a factor of two. However, transverse strength of a cracked masonry infill was found to be appreciable because of arching action. A simple equation was developed for out-of-plane strength based on the masonry compressive strength, the h/t ratio, the amount of in-plane damage and the stiffness of the bounding frame. An evaluation procedure was developed based on this procedure.

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1 Introduction

Background

Unreinforced masonry infill construction can be found in many buildings. This construction typically consists of steel or concrete boundary frames infilled with unreinforced masonry. The frames function to resist gravity loads and the infills serve as non-bearing walls or partitions. Typical infill materials are clay brick, hollow clay tile, and hollow concrete block.

Unreinforced masonry infills are generally not designed to resist lateral loads. Yet these infills can often be a large contribution to a building's overall ability to resist seismic forces. Due to the brittle nature of this type of construction, buildings consisting primarily of unreinforced masonry infills may experience damage after being subjected to strong earthquake ground motions. However, the behavior of infilled frames is not well understood. For example:

- How does the frame and the infill interact? How does their relative stiffness affect the interaction?
- What are the effects of frame aspect ratio, boundary conditions, materials, openings, and infill slenderness ratio?
- How does existing in-plane seismic cracking of the infill affect the out-of-plane strength of the panel when subjected to future earthquakes?
- How do repair or rehabilitation techniques strengthen an infill?

Many infills have collapsed from strong earthquake shaking in what appears to be an out-of-plane failure mode. Analytical tools that are readily available, and simple enough for routine use by the practicing structural engineer, are needed for predicting the behavior of unreinforced masonry infills in existing buildings.

Purpose

This summary presents an easy-to-use procedure for estimating the out-of-plane behavior of unreinforced masonry infills previously cracked by in-plane loads. The

procedure is applicable for infills of clay brick or concrete masonry. The procedure has been calibrated with test panels with a height-to-length aspect ratio of 1.5. For longer panels, estimated strength should be reduced by perhaps 20% to account for loss of two-way action. Its application is limited to solid panels until further research is done on infills with openings.

The paper is based on a research project funded by the National Science Foundation. The research was performed at the University of Illinois at Champaign-Urbana with the collaboration of SOH & Associates, Structural Engineers, of San Francisco, CA. For a complete account of the research project see Angel et al.[1]

2 Previous Experimental Research

Although a number of research programs have been concerned with the out-of-plane behavior of infilled frames, previous experimental research has been primarily directed at in-plane behavior. Parameters studied include type of confining frame, type of masonry, relative frame/infill strength and stiffness, aspect ratio, infill slenderness ratio, and boundary conditions.

Although there is a body of research data on the loading of infilled frames in one direction only, there is little available research on the interaction between in-plane and out-of-plane loading of infills. This is believed to be the first research project to specifically address the out-of-plane behavior of unreinforced clay brick and hollow concrete block infills which have been previously cracked by in-plane forces.

3 Description of Experimental Program

Eight full-scale specimens were tested. A one-story, single-bay ductile reinforced concrete frame was infilled with varying thicknesses of brick and concrete block masonry

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[1] Angel, R.E., Abrams, D.P., Shapiro, D., Uzarski, J., and Webster, M., "Behavior of Reinforced Concrete Frames with Masonry Infill Walls," Structural Research Series Report, University of Illinois at Urbana-Champaign, March 1994, 184 pp.

(Figure 1). Vertical compressive loads were applied to the specimen columns to simulate gravity loads during testing. In-plane tests were conducted by applying a cyclic horizontal load to a loading stub at the center of the concrete beam. The specimens were loaded in-plane to twice the deflection which caused initial cracking in the infill. The specimens were then tested monotonically out-of-plane by applying a uniform load over the entire surface of the infill with an airbag. Some of the specimens were then repaired and re-tested out-of-plane. The infill repair method consisted of applying a half-inch thick ferrocement coating to one or both faces of the infill panel (Figure 2). A summary of the experimental test program is shown in Table 2.

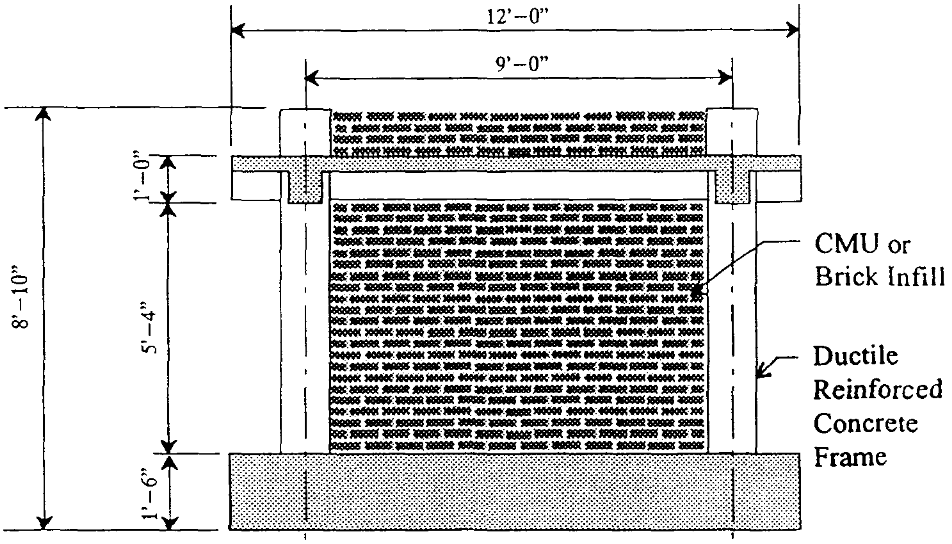


Figure 1: Elevation of Typical Test Specimen

4 Results of In-Plane Testing

In-plane test results are summarized in Table 1. A typical load-displacement hysteresis loop is presented in Figure 3.

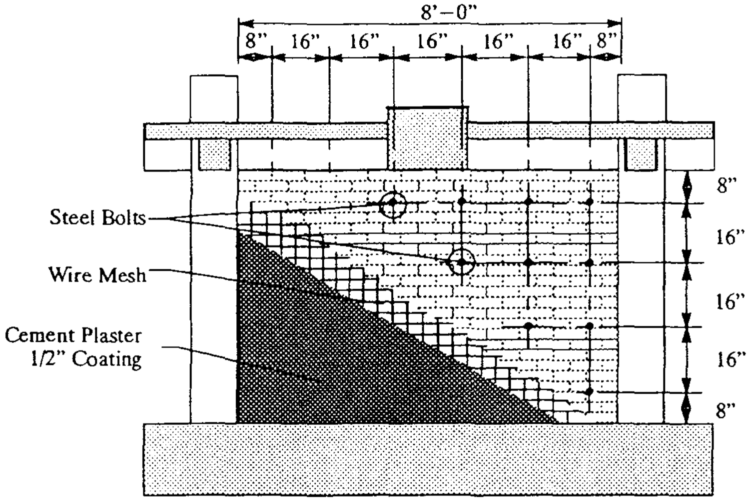


Figure 2: Repair Method

Specimen	Δ_{cr} (in)	Δ_{cr}/h (%)	f_v at Δ_{cr} (psi)	f_v at $2\Delta_{cr}$ (psi)
2a	0.11	0.172	189	271
3a	0.07	0.109	122	189
4a	0.03	0.047	75	135
5a	0.02	0.031	161	196
6a	0.08	0.125	117	169
7a	0.08	0.125	117	169
8a	0.12	0.195	47	71

Δ_{cr} = in-plane lateral displacement of the specimen required at first cracking of the infill
h = height of masonry infill panel
f_v = masonry shear stress

Table 1: In-Plane Test Results

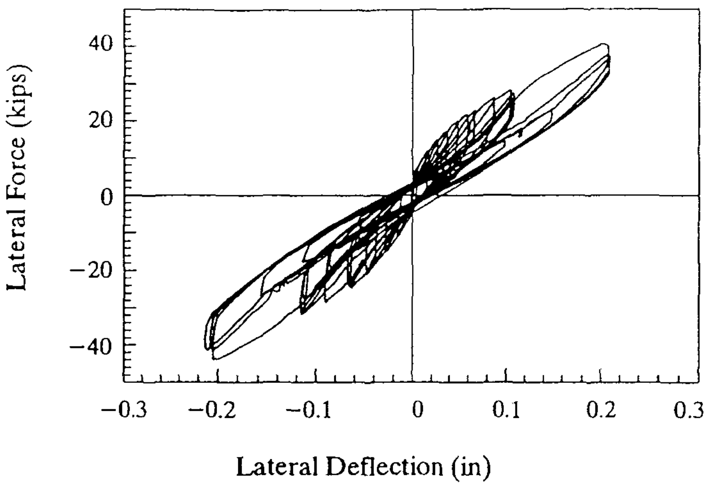


Figure 3: Typical Load-Displacement History

5 Results of Out-of-Plane Testing

Table 2 summarizes the results of the out-of-plane tests. Specimens were tested to a deformation corresponding to 3% drift ($\Delta / h = 0.03$) except where their strength exceeded the capacity of the test set-up. Figure 4 shows several typical force-deflection curves.

Results show that previous in-plane cracking reduces out-of-plane strength, as expected. Infill panels with large slenderness ratios are particularly affected. Out-of-plane strength was observed to be reduced by as much as a factor of two.

Vertical compressive stresses due to simulated gravity loads increased the initial out-of-plane stiffness, but had little influence on behavior once the vertical stress was overcome by the out-of-plane forces. There was no observed strength increase due to vertical loads.

Test Number[4]	Infill Type	Infill h/t	Mortar Type	f'_m (psi)	Maximum Previous In-Plane Deflection $2\Delta_{cr}$ (in)	Out-of-Plane Tests		
						Lateral Pressure (psf)		
						Unrepaired (psf)	Repaired (psf)	Bidirectional Loading (psf)[3]
1	half-wythe brick	34	S	1670		171[1]		
2a	half-wythe brick	34	N	1575	0.22			
2b						84		
2c							417	
3a	half-wythe brick	34	lime	1470	0.14			
3b						125		
3c							437	
4a	4" CMU	18	N	3321	0.06			
4b						622[2]		
5a	6" CMU	11	N	3113	0.04			
5b						673[2]		
5d								675[2]
6a	one wythe brick	17	lime	665	0.16			
6b						259		
6b2						221		
6c							644[2]	
6d								194
6t								637[2]
7a	one wythe brick	17	N	1596	0.16			
7b						642[2]		
8a	two wythes brick	9	lime	507	0.25			
8b						670[2]		

[1] no previous in-plane damage.

[2] maximum applied pressure (strength of specimen exceeded capacity of test mechanism).

[3] maximum applied out-of-plane pressure with simultaneous in-plane force; in-plane force is that force which caused deflection of $2\Delta_{cr}$ during in-plane testing.

[4] the letter in the test number describes the type of test: a = in-plane; b = unrepaired out-of-plane; b2 = repeated unrepaired out-of-plane; c = repaired out-of-plane; d = bidirectional loading; t = no vertical load.

Table 2: Out-of-Plane Results

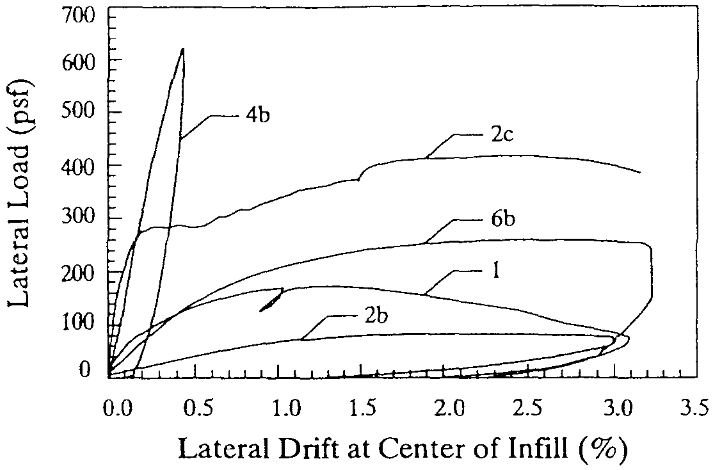


Figure 4: Typical Out-of-Plane Force-Deflection Curves

The simultaneous application of in-plane stress also slightly increased the initial out-of-plane stiffness, but had little effect on out-of-plane strength.

The repair method used in the testing program proved quite effective. Repaired specimens typically had five times the out-of-plane strength of unrepaired specimens. The out-of-plane strength of the repaired panels was not affected by the amount of initial damage in the panel. The repaired specimens which were tested to 3% drift showed good strength retention up to their final deflection.

6 Analytical Model

Existing analytical models for out-of-plane behavior of masonry infills fall into two categories: plate theories and arching theories. Both theories suggest that strength is proportional to the inverse of the square of the *h/t* ratio. Neither has been used to take into account the effects of previous in-plane cracking.

A new analytical arching model has been developed which may be used to determine the transverse uniform pressure that cracked or uncracked masonry infill panels can resist. The model does not account for two-way action.

The new analytical model idealizes the infill panel as a strip of unit width that spans between two supports fully restrained against translation and rotation. A uniformly distributed lateral load is applied normal to the plane of the panel. Precracking is modeled in the "worst case" condition: a crack at midspan (Figure 5). The cracking separates the strip into two segments that rotate as rigid bodies about their supported ends. Arching action is developed by internal "struts." Statics and material mechanics are used to develop equations which describe the behavior of the idealized model. Equation parameters include the infill height-to-thickness ratio, infill masonry strength, and infill masonry crushing strain.

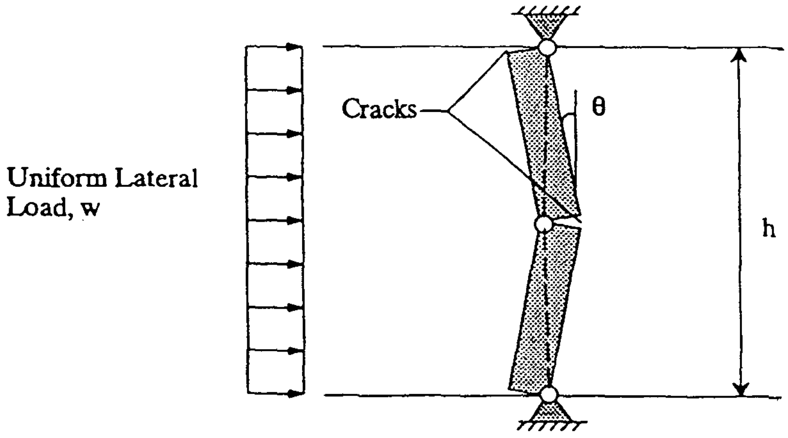


Figure 5: Idealized Loading and Behavior of Unit Strip of Infill Panel

The new analytical model shows that the out-of-plane strength of the infill is highly dependent upon the panel's slenderness ratio.

Comparison with Test Results

Test specimens with high slenderness ratios were about twice as strong and stiff as the analytical model's predictions, indicating that there is more arching action available than the model predicts.

Behavior of repaired specimens was well modeled up to their ultimate strength. However, the test specimens sustained this strength at higher deflections to a much greater degree than predicted by the analytical model. Apparently the steel mesh in the plaster repair effectively carried the load once the ultimate strength was reached.

Specimens with a slenderness ratio of 18 had mixed results. The strength and stiffness of specimen 6b were quite close to the predicted strength and stiffness. It was expected that specimen 7b would behave similarly, except that the lateral strength would increase in proportion to the higher masonry compressive strength. However, the strength was much greater than expected, exceeding the capacity of the testing equipment.

The stiffness of specimens which exceeded the strength of the test equipment generally nearly matched the initial stiffness predicted by the analytical model.

A sample comparison between predicted and measured behavior is shown in Figure 6.

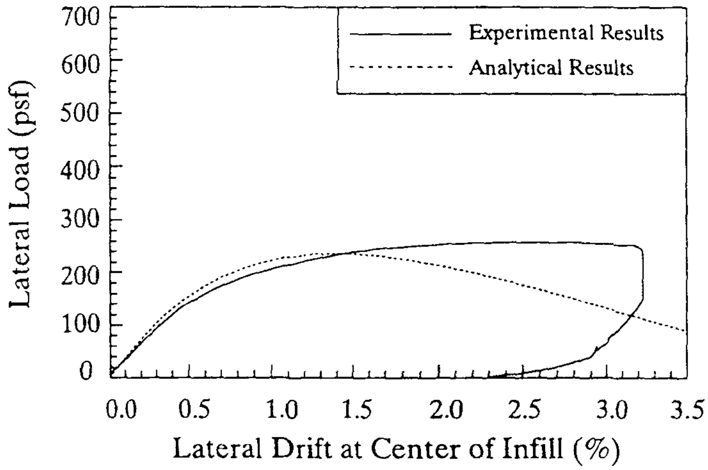


Figure 6: Results for Test 6b

7 Proposed Evaluation Procedure

Modifications and simplifications may be made to the analytical model to adapt it for the purpose of infill evaluation by practicing engineers. Three primary parameters must be accounted for in the evaluation procedure: previous in-plane damage, confining frame stiffness, and infill slenderness ratio.

An empirical factor was developed for the analytical model to account for previous in-plane damage. Although no testing was done for infill panels with previous in-plane deflections greater than twice the cracking deflection, the empirical factor may be extrapolated to account for such cases. The factor for previous in-plane damage is:

$$R_1 = 1 \qquad \text{for } \frac{\Delta}{\Delta_{cr}} < 1.0$$

$$R_1 = \left[1.08 + \left(\frac{h}{t}\right)\left(-0.015 + \left(\frac{h}{t}\right)\left(-0.00049 + 0.000013\left(\frac{h}{t}\right)\right)\right)\right]^{\frac{\Delta}{2\Delta_{cr}}} \qquad \text{for } \frac{\Delta}{\Delta_{cr}} \geq 1.0 \qquad (1)$$

Some values for R_1 are tabulated in Table 3.

Another factor must be used to account for the stiffness of the surrounding frame. Infill panels which are continuous with adjacent infill panels may be assumed to be fixed at their edges. Panels with one or more discontinuous sides are dependent upon the stiffness of the surrounding frame. The following factor is used to account for these cases:

$$R_2 = 0.5 + 7.14 \times 10^{-8}\, EI \qquad \text{for } 2.0 \times 10^{6} \text{ k-in} \leq EI \leq 9.0 \times 10^{6} \text{ k-in}$$

$$(2)$$

$$R_2 = 1 \qquad \text{for } EI > 9.0 \times 10^{6} \text{ k-in}$$

where:

E = the modulus of elasticity of the surrounding frame

I = the moment of inertia of the beam or column in the surrounding frame which is under consideration

The flexural stiffness used in these equations should correspond to the most flexible member of the confining frame at panel edges with no continuity.

The simplified analytical equation governing out-of-plane strength follows:

$$w = \frac{2 f'_m}{\left(\frac{h}{t}\right)} R_1 \, R_2 \, \lambda \tag{3}$$

where:

w = uniform lateral load

f'_m = compressive strength of masonry

h/t = slenderness ratio of the panel

R_1 = out-of-plane strength reduction factor to account for existing in-plane damage

R_2 = out-of-plane strength reduction factor to account for confining frame flexibility

λ = strength factor dependent upon the h/t ratio

λ and R_1 have been evaluated for a number of h/t ratios and the results are presented in Table 3.

A recommended evaluation procedure is:

1. Inspect the infill. The interface between the infill and the surrounding frame should be sound on all four sides. If the infill is cracked as a result of exposure to seismic forces, estimate the ratio of the maximum previous in-plane seismic deflection to the in-plane cracking deflection. Two procedures are suggested:

h/t	λ	R_1 for corresponding ratio of Δ / Δ_{cr}	
		$\Delta / \Delta_{cr} = 1$	$\Delta / \Delta_{cr} = 2$
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
40	0.003	0.727	0.528

Table 3: λ and R_1 for Various Values of h/t

a. Method 1: Calculation

The in-plane cracking deflection may be estimated by calculating the uncracked stiffness of the wall and the cracking force of the wall. Non-destructive testing may be used to determine lower-bound estimates of the cracking strength. The maximum in-plane deflection may be estimated using a dynamic analysis of the building or other rational means.

b. Method 2: Visual Inspection

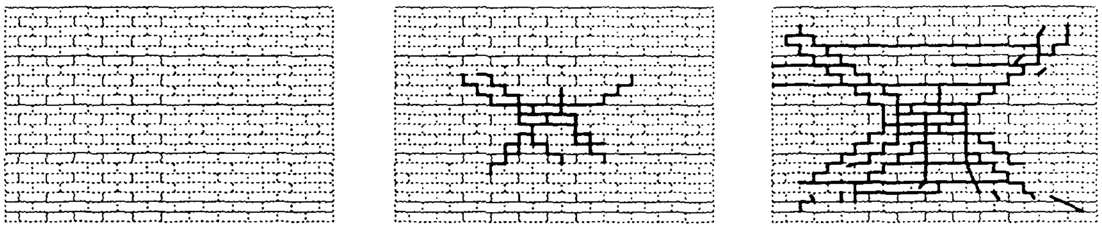
Figure 7 shows the damage expected in an infill panel as a result of two levels of in-plane deflection ($\Delta / \Delta_{cr} = 1$ and $\Delta / \Delta_{cr} = 2$). Compare the level of cracking in the wall under investigation to the cracking shown in Figure 7 to estimate the appropriate value of Δ / Δ_{cr} to use in the evaluation.

2. Determine h/t, λ, and R_1. The values for λ and R_1 may be taken from Table 3.

3. Determine whether the infill panel is surrounded by other infill panels on all sides. If not, calculate R_2 using equation 2. Use the EI of the most flexible frame member at a discontinuous edge.

4. Solve for w using equation 3.

Engineering judgment must be used to determine the appropriate factor of safety. If the compressive strength of the masonry has been tested and the condition of the mortar and the interface between the infill and the surrounding frame have been inspected and determined to be sound, a factor of safety of three may be appropriate. If the condition of the panel infill and surrounding frame or the strength of the infill is unknown or uncertain, a more conservative factor of safety such as five may be appropriate.



$\frac{\Delta}{\Delta_{cr}} = 0$ No Damage

$\frac{\Delta}{\Delta_{cr}} = 1$ Moderate Damage

$\frac{\Delta}{\Delta_{cr}} = 2$ Significant Damage

Figure 7: Infill Cracking Damage

Example

A reinforced concrete building with infilled frames has been damaged by an earthquake (Figure 8). It has been determined that the concrete frame did not sustain serious damage; however, the masonry infills are badly cracked and must be evaluated for out-of-plane stability in the event of a future earthquake.

An infill panel to be investigated is 20′ long x 15′ high x 7 3/8" thick and has no openings. The interface between the infill and the surrounding frame is determined to be sound. The infill material is brick, constructed in two wythes with a medium strength Type N mortar. A series of masonry compression tests and shove tests are carried out to determine the mechanical properties of the infill brick. The compression tests, carried out

in accordance with ACI 530.1-92/ASCE 6-92/TMS 602-92, provide values for the masonry compressive strength (f'_m). Values for the modulus of elasticity (E_m) can be found in ACI 530-92/ASCE 5-92/TMS 402-92 knowing the mortar type and unit strength. The shove test provides a value for the masonry shear strength (f_v). E_m and f_v are required if Δ / Δ_{cr} is to be determined using Method 1 (calculation). Results are presented in Table 4.

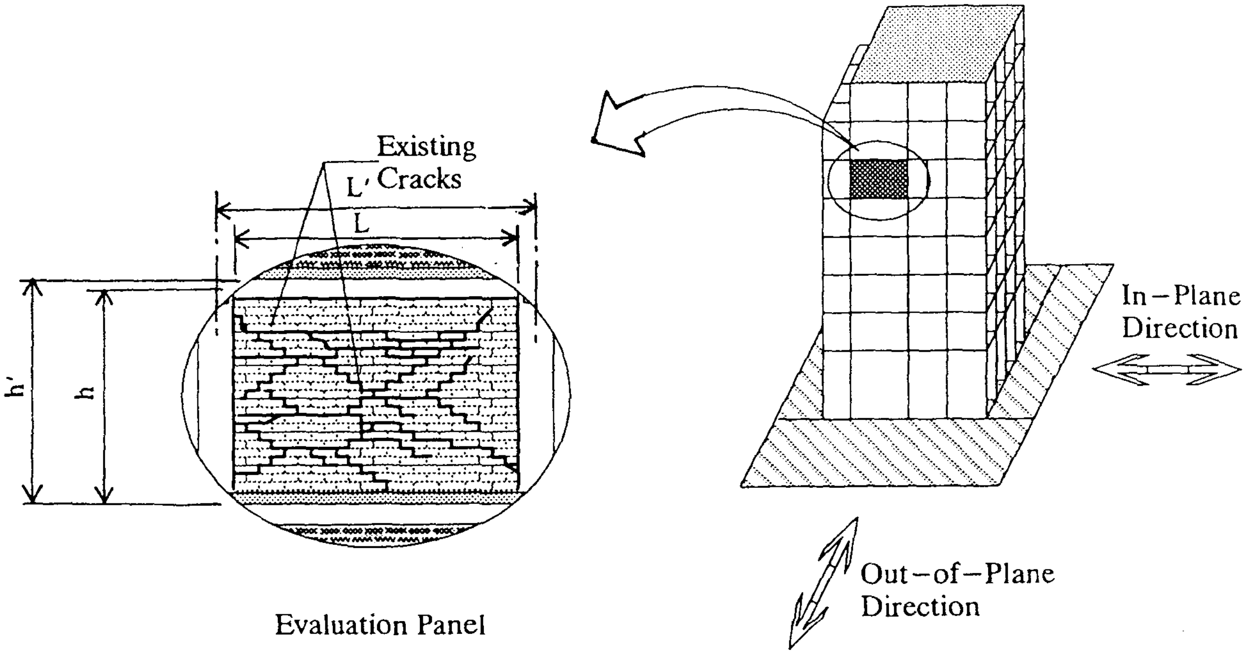


Figure 8: Example Problem

Frame		Infill	
Physical Properties	Mechanical Properties	Physical Properties	Mechanical Properties
I_c = 13800 in^4	E_c = 3600 ksi	t = 7 3/8 in	f'_m = 1000 psi
I_b = 15600 in^4		h = 180 in	E_m = 750 ksi
h' = 205 in		L = 240 in	f_a = 40 psi
L' = 264 in		(h/t) = 25	f_v = 200 psi

Table 4: Frame-Infill Properties

The visual method (Method 2) is selected to estimate the damage ratio (Δ / Δ_{cr}) of the wall. A comparison of the subject wall to Figure 7 indicates that the wall is "significantly" damaged ($\Delta / \Delta_{cr} = 2$). Table 3 shows that R_1 is 0.60 for (h/t) = 25 and $\Delta / \Delta_{cr} = 2$.

The frame under consideration is surrounded on all four sides by adjacent infilled frames. R_2 is therefore taken as 1.

Substituting into Equation 3 it is found that the out-of-plane strength of the infill is 90 psf.

$$w = \frac{2 f'_m}{\left(\frac{h}{t}\right)} R_1 \, R_2 \, \lambda = \frac{2 \, (1000 \, psi)}{(25)} (0.602)(1)(0.013) = 0.626 \, psi = 90 \, psf$$

The design lateral force is assumed to be 75 psf. The resulting factor of safety for the existing wall is only 1.2. Therefore this panel should be retrofitted. The proposed retrofit is to apply a half-inch thick ferrocement coating reinforced with wire mesh to each side of the wall. The new panel thickness is 8 3/8" (h/t = 21). Plaster compressive strength as determined from cylinder tests is greater than the masonry compressive strength (f'_m), so the masonry strength of 1000 psi is used for calculating the strength of the repaired wall. The results of the testing program suggested that infills repaired using this method have at least the out-of-plane strength of an undamaged wall, so a damage reduction factor of 1.0 is selected.

The out-of-plane strength of the repaired wall as determined using Equation 3 is 266 psf. The resulting factor of safety for the retrofit scheme is 3.5, which is deemed adequate for this application.

$$w = \frac{2 f'_m}{\left(\frac{h}{t}\right)} R_2 \, \lambda = \frac{2 \, (1000 \, psi)}{(21)} (1)(0.0194) = 1.85 \, psi = 266 \, psf$$

8 Conclusion

A procedure has been developed for the out-of-plane analysis and evaluation of clay brick and hollow concrete masonry unit infilled frames. For the procedure to be applicable the boundary between the infill and the surrounding frame should be sound on all sides. The effect of previous in-plane cracking has been considered.

The results suggest that for most infills with h/t of approximately 10 or less no retrofit is required. This conclusion arises from the application of Equation (3) to a hypothetical infill with conservatively assumed properties. If an infill is assumed to have a compressive strength (f'_m) of 500 psi, significant in-plane damage, and a confinement reduction factor (R_2) of 0.5, Equation (3) predicts that such an infill can resist lateral forces of at least 2g's provided h/t is 10 or less. This force level has been selected because seismic forces of 2g's have been recorded by strong motion instruments in the upper stories of multi-story buildings.

The described procedure is a start; further research should be conducted to expand the applicability of the procedure. Configuration variables could include the type of confining frame, the flexibility of the frame, the type of boundary conditions between the frame and the infill panel, the type of masonry unit in the infill, the number and size of openings in the infill, the aspect ratio of the infill, and the amount of existing in-plane damage in the infill. Further research should also be conducted to investigate alternate repair and rehabilitation techniques for infilled frames.