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EXPERIMENTAL STUDY OF MASONRY INFILLED RC FRAMES SUBJECTED TO OUT-OF-PLANE LOADING

Sepasdar, Reza[1] and Liu, Yi[2]

ABSTRACT

This paper presents results of an experimental study focusing on the out-of-plane behaviour and strength of concrete masonry infills bounded by reinforced concrete (RC) frames. A total of four masonry infilled RC frame specimens was tested with different parameters. One was considered as a control specimen; one was built with a window opening in the infill; and the other two had sustained damage caused by either prior in-plane or out-of-plane loading. Of two specimens with prior damage, one was first subjected to in-plane loading until occurrence of a major diagonal crack, and then tested under out-of-plane pressure to failure. The other was first subjected to out-of-plane pressure until occurrence of a major horizontal crack around the mid-height of the infill, and then tested under in-plane loading to failure. All masonry infills were built in tight contact at all boundaries with their bounding frames to enable arching action. All specimens were constructed with the same geometry using half-scale 200 mm standard concrete masonry units laid in running bond. The specimen details, and test setup and procedure are described. The experimental results were presented and discussed in terms of load vs. displacement response, cracking pattern, and failure mode for each specimen. The effect of parameters as well as the effectiveness of MSJC 2013 design method is examined using the results obtained thus far.

KEYWORDS: *masonry infilled RC frame, out-of-plane behaviour, arching action, experimental study, in-plane loading damage*

INTRODUCTION

A masonry infilled frame is either a concrete or steel frame with a masonry wall built within and it is commonly used either as a partition to separate spaces or cladding to complete a building envelope. Previous studies have shown that out-of-plane behaviour and strength of infills is different from ordinary masonry flexural walls without confinement. The out-of-plane strength of

[1] Research Assistant, Department of Civil and Resource Engineering, Dalhousie University, 5248 Morris St., Halifax, NS, Canada, reza.sepasdar@dal.ca
[2] Professor, Department of Civil and Resource Engineering, Dalhousie University, 5248 Morris St., Halifax, NS, Canada, yi.liu@dal.ca

flexural walls relies on the tensile strength of mortar joints while the out-of-plane behaviour of infill walls is characterized by a phenomenon referred to as “arching action”. When an infill is built in tight contact with the bounding frame, the in-plane compressive forces are induced in the wall as it bends under out-of-plane forces, and these compressive forces can delay cracking and increase the out-of-plane capacity of infills ([1], [2]). Arching action was first studied by McDowell et al. [3] for masonry walls with rigid boundaries. Following studies [4-7] confirmed the existence of arching action and a significant increase in the out-of-plane capacity, in some cases 2 to 3 times higher than its flexural capacity, has been reported. More recent research [8-13] focused mostly on the effect of the slenderness ratio of the infill, unit and mortar type, and material properties of the infill and the frame. Results indicated that development of arching action can enhance the stability of infills even after the ultimate capacity has been achieved. However, parameters in previous studies were limited and although the arching phenomenon was well described, no quantitative relationships were established to define the out-of-plane strength in relation to all influential parameters for practical design. The Canadian masonry design standard CSA S304-14 [14] provides no specific design provisions for the out-of-plane strength of infill walls but suggests that first principle mechanics be relied on for analysis. The American masonry design standard MSJC 2013 [15] contains a semi-empirical strength equation for masonry infills subjected to out-of-plane loading, which was largely based on experimental results obtained by three research groups [4-6]. Its efficacy for infilled frames different from those tested in terms of material and geometric properties has not been thoroughly examined.

Also noted is that while considerable research has been conducted in the area of in-plane behaviour of masonry infilled frames, the research on the out-of-plane behaviour of masonry infills in general is limited and research results are scarce in the literature. Furthermore, the in-plane and out-of-plane behaviour may have some level of interaction in an event of earthquake. It is conceivable and also supported by a few studies that the in-plane damage sustained in the infill could affect its out-of-plane strength and vice versa ([5], [12]). However, the potential interaction of in-plane and out-of-plane behaviour of masonry infills has received little research attention.

In view of the above, an experimental investigation was carried out to provide a better understanding of out-of-plane behaviour and strength of masonry infills in general as well as on how the in-plane/out-of-plane damage influences out-of-plane/in-plane strength of infills. This is an ongoing research and this paper presents the results obtained thus far.

EXPERIMENTAL SETUP

Out-of-plane loading

The out-of-plane pressure on the infill panels was applied using an inflatable airbag. A self-equilibrating loading system was designed to apply the transverse load as shown in Figure 1. The airbag was housed between a reaction panel and the masonry infill. The reaction panel was fabricated from a 15 mm thick plywood board stiffened with steel hollow sections (HSS). The panel was connected to the RC frame at its top and base beams using threaded rods through preembedded tubes. The specimens were tightly clamped to the strong floor using two W-section beams on each end of the frame base beam stems.

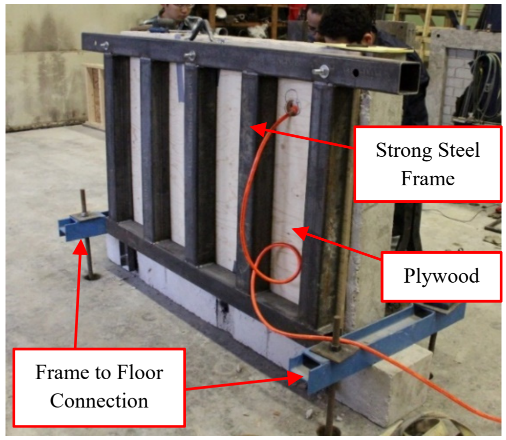


Figure 1: Out-of-plane Test Setup

In-plane loading

The in-plane loading setup is shown in Figure 2. The in-plane loading was applied monotonically using a 250 kN hydraulic jack which was in turn attached to the column of an independent reaction frame. The specimen was tightly clamped to the strong floor in the same way as the out-of-plane test setup. The potential in-plane sliding of the specimen was further restrained using hydraulic rams braced at the frame base beam against the columns of the reaction frame.

Figure 2: In-plane Test Setup

TEST SPECIMENS

A total of four infilled frame specimens was tested in this experimental phase, including one control specimen with no prior damage and opening (IF-ND), one specimen with a central window opening of 17% of the infill area (IF-W-ND), and two specimens (IF-D1 and IF-D2) with prior damage. The 17% opening corresponds to small to medium size opening typical in masonry infill walls. Specimen IF-D1 was first subjected to in-plane loading to the onset of diagonal cracking on the surface of the infill and then the in-plane loading was removed. The specimen was subsequently subjected to the out-of-plane pressure to failure. Specimen IF-D2 was first subjected to the out-of-plane pressure to the onset of horizontal cracking at infill's mid-height and then the out-of-plane loading was removed. The specimen was subsequently tested under in-plane loading to the ultimate capacity of the infilled frame. It was observed during the test that the infill remained largely intact at this point except for some crushing at loaded corners. It was then decided to test the specimen again under out-of-plane loading to complete failure.

All specimens had the same dimensions yielding an aspect ratio of 1.4 as seen in Figure 3. The infills were constructed using half-scale standard 200 mm concrete units (CMUs) laid in running bond. The infills of all specimens were ungrouted except for specimen IF-W-ND, in which the block cells in the course above the opening were grouted. The frame top beam and columns had a 180 mm square section reinforced with four 10M (diameter = 11.2 mm) deformed rebars and 10M stirrups spaced at 100 mm centre-to-centre. The base beam had a 250 mm square cross-section reinforced with four 15M longitudinal rebars and 10M stirrups with a spacing of 100 mm centre-to-centre. In addition, four 300 mm by 300 mm L-shaped made from 10M rebars were used to further reinforce the top beam-column corners. Details of the reinforcement are shown in Figure 3.

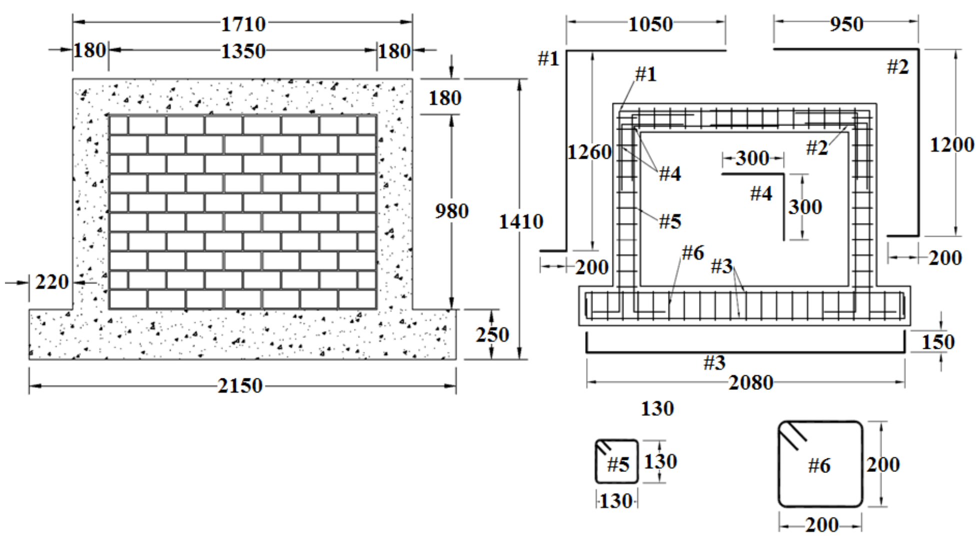


Figure 3: Details of Infilled Frame Specimens

INSTRUMENTATION AND TEST PROCEDURE

In the case of out-of-plane loading, several LVDTs were used to measure the out-of-plane displacement at the infill center and also in its vicinity. A pressure transducer was used to measure the air pressure. The pressure was applied at a slow rate of about 1 kPa per minute until the failure of the infill. In the case of in-plane loading, two LVDTs were used at both the top and base beam locations to measure the in-plane displacement of the infilled frame. The lateral load was applied at a rate of about 6 kN per minute until the failure of the infilled frame. In both cases, the displacement and load readings were recorded at an interval of 0.1 seconds using an electronic data acquisition system. The loading rates were considered slow enough to ensure that the dynamic effect was insignificant. All cracks and their propagation patterns were carefully monitored and occurrence of each crack with its corresponding load was noted.

MATERIAL PROPERTIES

The mechanical properties of each component of the infilled frame specimens were obtained in accordance with the associated ASTM specifications. A summary of results for each specimen is presented in Table 1. Note that differences of material properties between specimens indicate that specimens were constructed with a different batch of materials.

Table 1: Summary of Material Properties

Component	Property	IF-ND	IF-W-ND	IF-D1	IF-D2
CMUs	Strength (MPa)	12.8	12.8	12.8	12.8
Mortar	Strength (MPa)	20.4	20.4	21.6	21.6
Masonry Prism	Strength (MPa)	9.4	9.4	9.7	9.7
	Elastic Modulus (MPa)	7990	7990	8245	8245
Concrete	Strength (MPa)	38.5	38.5	38.5	42.2
	Elastic Modulus (MPa)	16911	16911	16911	20357
Reinforcement	Yield Strength (Ultimate Strength) (MPa)	446 (665)	446 (665)	446 (665)	446 (665)
	Elastic Modulus (MPa)	247357	247357	247357	247357

TEST RESULTS AND DISCUSISON

Ultimate Strength

A summary of the test results is provided in Table 2. For both in-plane and out-of-plane loading cases, the cracking load and ultimate load, and the corresponding displacements are presented. Note that in both cases, cracking load is defined as the load when the first major cracking occurred, and the ultimate load is defined as the maximum load reached. Displacement δ refers to the lateral displacement at ultimate load of the infilled frame whereas Δ represents the out-of-plane displacement at ultimate load of the infill. The values shown in brackets represent those obtained during the prior damage loading stage.

Table 2: Summary of the Test Results

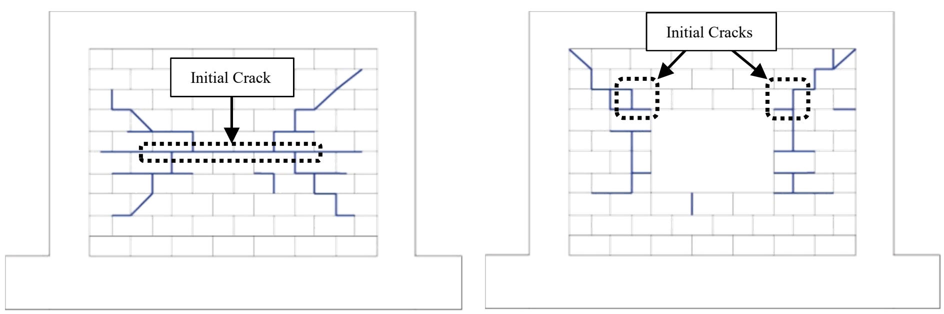
<table>
<tr><th>Loading</th><th>Component</th><th>IF-ND</th><th>IF-W-ND</th><th>IF-D1</th><th colspan="2">IF-D2</th></tr>
<tr><td rowspan="4">In-Plane (Prior)</td><td>F_{cr} (kN)</td><td>-</td><td>-</td><td>(107.4)</td><td colspan="2">113.3</td></tr>
<tr><td>δ_{cr} (mm)</td><td>-</td><td>-</td><td>(7.3)</td><td colspan="2">8.7</td></tr>
<tr><td>F_{ult} (kN)</td><td>-</td><td>-</td><td>-</td><td colspan="2">139.3</td></tr>
<tr><td>δ_{ult} (mm)</td><td>-</td><td>-</td><td>-</td><td colspan="2">16.9</td></tr>
<tr><td rowspan="4">Out-Of-Plane (Prior)</td><td>P_{cr} (kPa)</td><td>26.8</td><td>23.7</td><td>14.6</td><td>(26.0)</td><td>24.8</td></tr>
<tr><td>Δ_{cr} (mm)</td><td>0.5</td><td>0.6</td><td>0.3</td><td>(0.4)</td><td>7.6</td></tr>
<tr><td>P_{ult} (kPa)</td><td>66.3</td><td>43.7</td><td>44.4</td><td>-</td><td>26.4</td></tr>
<tr><td>Δ_{ult} (mm)</td><td>12.5</td><td>4.3</td><td>6.6</td><td>-</td><td>9.9</td></tr>
</table>

Failure Mode

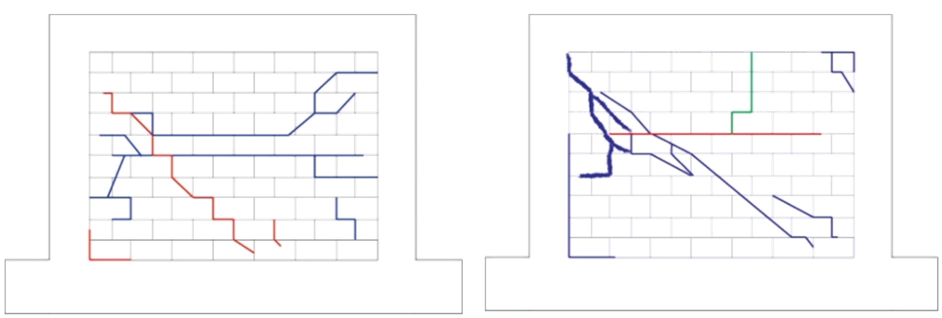
Failure of specimens subjected to out-of-plane loading was sudden and volatile characterized by infill collapse. Figure 4(a) depicts the failure mode of specimen IF-ND showing the remnants after infill collapse. A close examination showed that failure was initiated by web shear failure. In the case of specimen IF-D2 at the in-plane loading portion, the failure was relatively ductile and characterized by corner crushing at the loaded corner as seen in Figure 4(b). Figure 5 illustrates the cracking pattern of all specimens before failure.

(a) (b)

Figure 4: (a) Out-of-Plane Failure Mode of IF-ND, (b) In-plane Failure Mode of IF-D2



(a) IF-ND (b) IF-W-ND



(c) IF-D1 (d) IF-D2

Figure 5: Crack Pattern of Specimens before Failure (Blue Colour: Cracking Pattern; Red Colour: Prior Damage; Green Colour: Second Out-of-Plane Crack of IF-D2)

For specimen IF-ND, the onset of cracking was a horizontal central crack with the length of four blocks as seen in Figure 5(a). With the increase of load, the central crack began to expand horizontally from both sides and diagonal cracking began to develop from each end of the horizontal crack. As load continued to increase, diagonal cracks propagated towards each corner of the infill forming a yield line pattern before failure.

For specimen IF-W-ND the cracking began to develop from both top corners of the opening by formation of two horizontal cracks with the length of a half block at each side (Figure 5(b)). As the pressure increased, those cracks propagated toward the top corners of the infill. A series of small horizontal and vertical cracks also began to develop and expand on both sides of the opening before failure.

The damage of specimen IF-D1 for in-plane loading is illustrated in red on Figure 5(c). After the in-plane loading was removed, the frame returned to its initial position but the developed cracks remained unclosed and visible. Under the subsequent out-of-plane loading, the cracking pattern was similar to IF-ND and the first visible crack occurred at the infill mid-height and propagated towards the corner of the infill. The new cracks on the top-left portion of the infill (at the location of prior in-plane crack) formed later, after the other portions of the infill were cracked. Shortly before failure, another horizontal crack formed above the horizontal central crack.

For specimen IF-D2 under the first out-of-plane loading, a horizontal crack with the length of about five blocks occurred at one course above the centre of the infill (in red, Figure 5(d)). After this point the pressure was removed and the crack remained. Under the subsequent in-plane loading, the diagonal crack developed and the loaded corner (upper left corner) began to crush, and the infilled frame reached its ultimate capacity. Separation of the infill from the bounding frame at unloaded corners and hairline cracks on the left column of the frame near the corners were also observed. Upon removal of the in-plane loading, no new cracks were formed and previous cracks remained open. Under the second out-of-plane loading, the prior cracks on the infill surface gradually widened and only one new crack on the surface of the infill formed which was a vertical crack (in green) above the previous horizontal central crack (from the first out-of-plane loading) shortly before failure.

Effect of Prior Damage

Figure 6 illustrates the in-plane load vs. lateral displacement of specimens IF-D1 and IF-D2. A specimen IFNG from an earlier experimental program conducted by Hu [16] of the same research group was also included for comparison. The specimen IFNG had the same geometry and similar material properties as specimens tested in this program and was tested with the same loading rate (6 kN/min). Note that specimen IF-D2 had sustained a mid-height horizontal crack from the out-of-plane loading. The initial behaviour of specimen IF-D2 up to about 60 kN was almost identical to IFNG. A deviation showing a drop in stiffness in IF-D2 observed after this point might be attributed to the pre-damage of the horizontal crack. However, the ultimate load of IF-D2 was 4% greater than IFNG and was reached at a greater lateral displacement. Referring to Table 2, the prior out-of-plane loading for IF-D2 to generate a horizontal crack was about 40% of its ultimate out-of-plane strength. The above observation suggests that the effect of the prior out-of-plane damage defined by a central crack (40% of the ultimate strength) on the in-plane behaviour was insignificant.

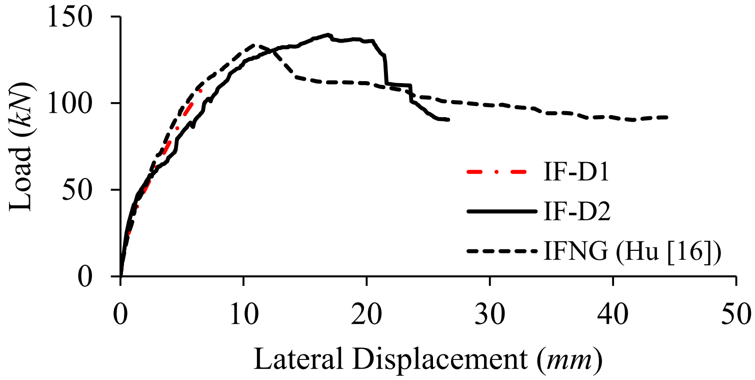


Figure 6: Load vs. Lateral Displacement Curves of IF-D1 (Prior In-Plane Loading), IF-D2 and IFNG (Hu [16])

Figure 7 depicts the pressure vs. out-of-plane displacement of specimens IF-ND, IF-D1, and IF-D2. All displacements were recorded at the center of the infill. Note that in this figure, specimen IF-D1 has sustained prior in-plane damage in the form of diagonal cracking and specimen IF-D2 has reached its in-plane ultimate strength before being subjected to out-of-plane loading. Referring to Figure 6 and Table 2, the prior in-plane loading for IF-D1 was about 75% of its ultimate in-plane capacity. The comparison between IF-ND and IF-D1 showed that the prior in-plane damage in the form of diagonal cracking (75% of the in-plane ultimate strength) resulted in a 33% reduction in the out-of-plane strength of the infill. A further comparison of IF-D2 to IF-ND showed that even when an infilled specimen reached its in-plane capacity, there was still about 40% of out-of-plane strength remaining in the infill.

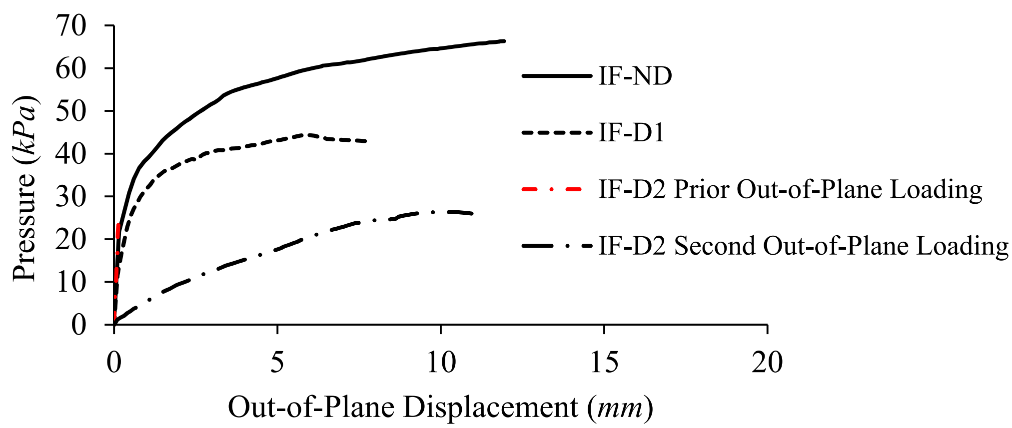


Figure 7: Pressure vs. Out-of-Plane Displacement Curves of IF-ND, IF-D1, and IF-D2

Effect of Window Opening

Figure 8 depicts the pressure vs. out-of-plane displacement of specimens IF-ND and IF-W-ND and displacements used in this case were the maximum displacements recorded. It shows that the presence of the opening (17% of infill area) resulted in a 34% reduction in the ultimate strength. Also noted is that displacement sustained was markedly smaller. It should be pointed out that a plywood panel (485 mm by 660 mm) was used to cover the opening for the application of the pressure from the airbag. It is believed that the plywood panel enabled distribution of air pressure over to the area away from the opening and the infill had essentially less area to resist the pressure, which led to a reduction in the strength.

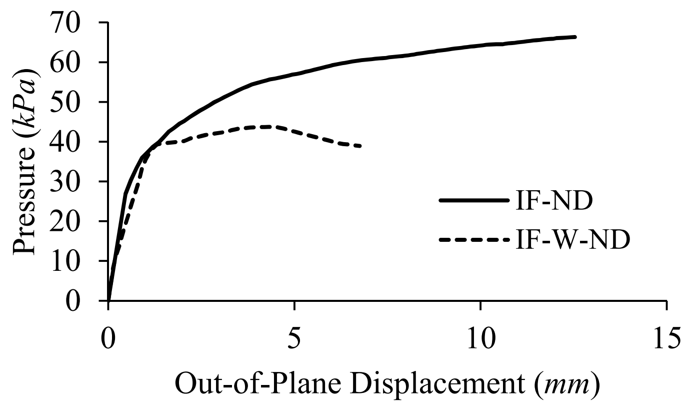


Figure 8: Pressure vs. Out-of-Plane Displacement Curves of IF-ND and IF-W-ND

EVALUATION OF MSJC 2013

In the method proposed by MSJC 2013 [15], the out-of-plane capacity of an infill is dependent on masonry strength, infill geometry, and bounding frame stiffness. The design equation is expressed as:

$$q = 4.1 f_m'^{0.75} t^2 \left(\frac{\alpha}{l^{2.5}} + \frac{\beta}{h^{2.5}} \right) \tag{1}$$

in which f_m' is the masonry compressive strength (kPa), t is the infill gross thickness (mm), h is the infill height (mm), and l is the infill length (mm). The parameters α and β can be determined from:

$$\alpha = \frac{1}{h}(E_c I_c h^2)^{0.25} < 50 \tag{2}$$

$$\beta = \frac{1}{l}(E_b I_b l^2)^{0.25} < 50 \tag{3}$$

where E is the modulus of elasticity of the frame member (MPa), I is the moment of inertia of the frame member in the plane of the infill (mm^2), and subscripts b and c refer to beam and columns respectively.

Using the geometrical and material properties of specimen IF-ND, the design out-of-plane strength is determined to be 48.3 kPa, resulting in a design-to-test ratio of 48.3/66.3=0.73. This suggests that the design method underestimates the strength by 27% of a control specimen. Similar degree of conservatism of MSJC 2013 method was also reported by Flanagan et al. [17]. More experimental work on masonry infilled frames with varying geometric and material properties is being conducted by authors and once the results become available, the method will be further assessed and findings will be reported in follow-up papers.

CONCLUSION

This paper presents results of four masonry infilled RC frame specimens in an on-going study of the out-of-plane behaviour of infills bounded by RC frames. It was found that prior damage sustained from in-plane loading resulted in reduction in the out-of-plane strength, and the more significant the damage, the higher reduction in strength. However, prior damage in the form of a central horizontal crack sustained from out-of-plane loading showed negligible effect on the in-plane strength of the infill. The presence of an infill opening resulted in a reduction in the out-of-plane strength and displacement of the infill. The out-of-plane failure was characterized by web shear failure of masonry units in the infill while the in-plane failure was characterized by corner crushing of infills at loaded corners.

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