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IN-PLANE BEHAVIOUR OF MASONRY INFILLED RC FRAMES SUBJECTED TO QUASI-STATIC CYCLIC LOADING

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Abstract: An experimental study was conducted to study the effect of infill-frame interfacial gap on the in-plane behaviour and strength of concrete masonry infills bounded by reinforced concrete (RC) frames. A total of six specimens, including five masonry infilled frames and one bare RC frame, was tested to failure subjected to quasi-static cyclic loading. Four of the infilled frame specimens had the following design parameters: 1) a gap at the top beam-infill interface of 12 and 25 mm, respectively; 2) a gap at the column-infill interfaces of 12 mm; and 3) a full separation gap of 12 mm at the beam-infill and at column-infill interfaces. Of the two gapped specimens, the infills also had a window opening accounting for 20% of the infill area. All specimens were constructed with the same geometry using half-scale 200 mm standard concrete masonry units laid in the running bond. The quasi-static loading followed the ATC-24 loading protocol to measure specimens' cyclic response. Experimental results showed that compared to the bare frame, a noticeable increase in strength and stiffness was observed with presence of infill regardless of the presence of gaps or infill openings. When compared to a specimen with no gaps, the presence of gaps decreased the initial stiffness and strength of infilled frames and the extent of decrease was dependent on the gap magnitude and location. When both openings and gaps were present, the reduction as a result of gap was not as significant as the reduction due to the opening.

1 INTRODUCTION

A masonry infilled frame is either a concrete or a steel frame with a masonry wall built within and is commonly used in modern construction. It is widely recognized that presence of the masonry wall will increase the strength and stiffness as well as change the dynamic characteristics of the frame structure. To accurately evaluate the contribution of masonry infill to the behaviour of the frame structure, it is crucial to quantify the extent of interaction between the infill and its bounding frame. Much research, which began with experimental studies conducted primarily during 1960s-1990s and followed by numerical studies from 1990s to present, has been dedicated to finding a rational design approach for including the effect of masonry infills. These studies have resulted in several analytical models to evaluate the strength and stiffness of masonry infills. Initially proposed by Polyakov (1960), the equivalent diagonal strut method has been established as the most commonly used method of analysis for infilled frames due to its simplicity and reasonable accuracy. Based on the strut concept, most of later studies by various researchers were conducted to improve the accuracy of the method and verify the method with different geometric and material property combinations of infill and frame (Stafford-Smith and Carter 1969, Liauw and Kwan 1984, Al-Chaar 2002). The diagonal strut method is also adopted in the current Canadian and American masonry design standards (CSA S304-14, MSJC 2013). However, due to the complexity of the frame system whose behaviour is affected by two component materials which could have a wide range of material and geometric properties, the existing analytical methods are only intended for “simple” infills. For example, the effect of gaps at the infill-frame interface has not been addressed in a comprehensive way.

The presence of interfacial gaps is not uncommon, which can be due to the shrinkage and settlement of the infill or defects in workmanship. The total elimination of interfacial gaps is difficult to achieve in practice. The presence of interfacial gaps has been reported to significantly affect the strength and stiffness, and sometimes even alter the failure mode of the infilled frames (Riddington 1984, Richardson 1986, Dawe and Seah 1989, Ng'andu 2006, Nazief 2014, Hu 2015), however, the reported magnitudes of reduction in strength and stiffness due to gaps were very scattered and no definable relationship between the magnitude and location of the gap and stiffness and strength of the infill was generated from those studies. In terms of design practice, the CSA S304-14 does not allow any gaps between the masonry infill and the bounding frame of a participating infill. The MSJC 2013, on the other hand, permits the use of infills with a top beam-to-infill gap of less than 9.5 mm, but in such case, the stiffness and strength of gapped infill shall be reduced by 50%. However, the standard makes no recommendation for stiffness or strength reduction with gaps between the column and the infill or a full gap separating the infill and bounding frame; nor does the standard provide background information on the given size and location of gap. The question as to what gap width on the side, top and all around the infill can be permitted to consider the infill as participating and by what degree of strength or stiffness is affected with gaps remains unanswered.

Quasi-static loading has been established as an effective method for understanding seismic performance of infilled frames. It applies slow cycles of loading in order to study the performance of structures and structural members for crack propagation, strength and stiffness deterioration, energy dissipation, and ductility. None of previous mentioned studies on the effects of predefined interfacial gaps were conducted in a quasi-static loading condition. While monotonic loading condition is simple to apply and does provide fundamental understanding of in-plane behaviour of masonry infilled frames, the hysteresis parameters of infilled frames, such as strength and stiffness degradation, cannot be observed. Those dynamic properties are crucial for seismic design of infilled frames. Quasi-static cyclic loading Quasi-static tests conducted by several researchers (Mehrabi et al. 1996, Mosalam et al. 1997, Stylianidis 2012) showed that the hysteresis in-plane behaviour observed in the quasi-static test are reliable to use for determination of the dynamic features of masonry infilled frames.

This research was then motivated to conduct an experimental program to further investigate the in-plane behaviour and strength of masonry infilled frames under quasi-static cyclic loading with the focus on the effects of interfacial gaps. The test results of this study are intended to augment the existing test database on the in-plane loaded concrete masonry infilled RC frames and facilitate the verification process of numerical simulations. This is an ongoing research and this paper presents the test set-up, specimen details and test results obtained thus far.

2 EXPERIMENTAL SET-UP

Figure 1 shows a schematic view of the test set-up. A hydraulic actuator with a capacity of 150 kN was used to apply the quasi-static lateral load. The actuator was housed in an independent frame which was then attached to the column of a reaction frame. To realize the pulling and pushing action on the specimen, two threaded rods running the full length of the frame beam were used as a simple measure. The actuator head was connected to the specimen through a steel plate and threaded rod assembly. The steel plate was secured to the specimen with two bolt holes for which the two threaded rods of the specimen were bolted through. At the loading point between the steel plate and the RC frame, a rubber pad was used to prevent crushing of the concrete. The base beam of the frame was clamped to the strong floor and braced using hydraulic jacks to prevent potential in-plane movements. Displacement transducers (LVDT) were used

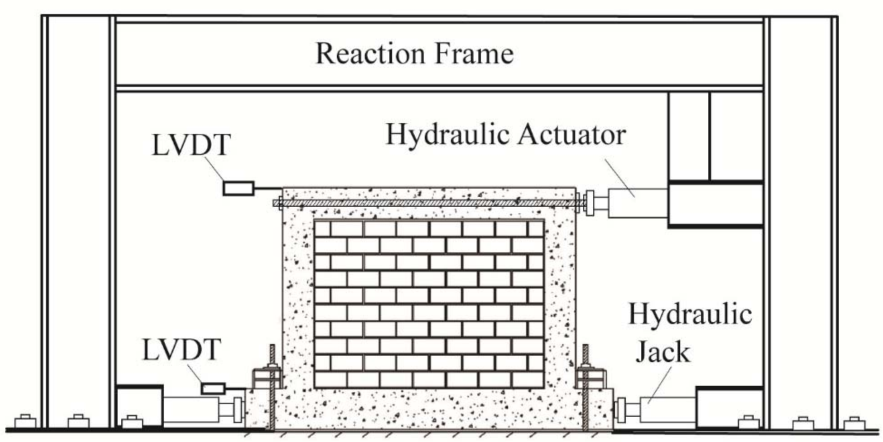

Figure 1: Schematic view of test set-up

to monitor the specimen displacement. As shown in Figure 1, LVDT 1 and LVDT 2 were used to measure the lateral displacement of the top beam and bottom beam of the frame specimen, respectively. Another LVDT was used to measure the potential transverse movement at the frame beam center (not shown).

3 TEST SPECIMEN

Table 1 summarizes the specimens used in this experimental program. Specimen IF-NG was tested as a control specimen. The remaining four infilled specimens incorporated different interfacial gap scenarios, including: 1) at top beam-infill interface (Top Gap), 2) at two column-infill interfaces (Side Gap), 3) at both beam and column-infill interfaces (Full Separation Gap). In addition to the predefined gap, specimens IF-W-SG12 and IF-W-TG12 also had a window opening accounting for 20% of the infill area and with an opening aspect ratio of 1:1.5.

Table 1: Summary of the test specimens

Specimen ID	Gap	Opening/Infill Area Ratio
BF	N.A.	N.A.
IF-NG	N.A.	-
IF-FG12	12 mm Top Gap & 12 mm Side Gap (6 mm each side)	-
IF-W-TG12	12 mm Top Gap	20%
IF-TG25	25 mm Top Gap	
IF-W-SG12	12 mm Side Gap (6 mm each side)	20%

Figure 2 shows the dimensions and reinforcement details used for all specimens. The infill had a height-to-length aspect ratio of 0.73. The half-scale standard 200 mm concrete masonry units (CMUs) were used in a running bond pattern to construct the masonry infill wall. All pre-defined gap magnitudes were achieved by adjusting mortar thickness with the exception of specimen IF-TG25 in which case the height of the top layer of blocks was also trimmed to achieve the desired gap size. The infills of all specimens were ungrouted while for specimens IF-W-TG12 and IF-W-SG12 with openings, the block cells in the course above the opening were grouted as per industry practice. The top beam and columns of the RC frame were 180 mm by 180 mm square sections reinforced with four 10M deformed steel rebars and 10M stirrups spacing at 100 mm center-to-center. The base beam was a 250 mm square section reinforced with four 15M rebars and 10M stirrups spacing at 100 mm center-to-center. In addition, four 300 mm by 300 mm L-shaped made from 10M rebars were used to further reinforce the top beam-column corners.

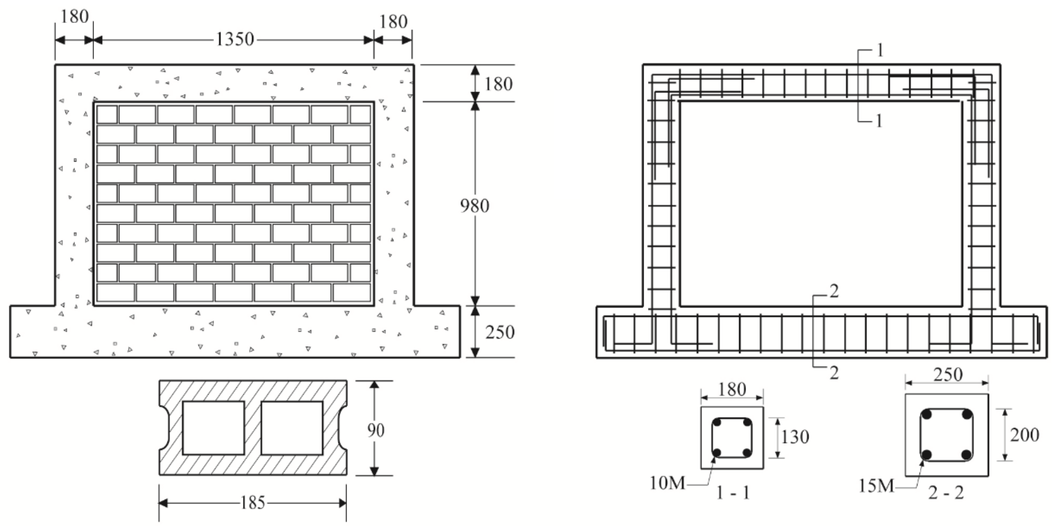

Figure 2: Details of test specimens (unit: mm)

4 LOADING PROTOCOL

The loading protocol is an essential part of a quasi-static test procedure. In the cyclic loading protocol used in this study, a sequential phased displacement technique was used to apply the displacement to the infilled frame based on the procedure specified by the Applied Technology Council (ATC-24 1994) for cyclic load test. Figure 3 shows the lateral quasi-static loading protocol where the peak amplitude for each set of cycles is defined based on the yield deformation. Testing begins with six elastic cycles with at least three of which are performed at 0.75 Δ_y. Following the elastic cycles, three cycles at Δ_y, 2 Δ_y, and 3 Δ_y. respectively are performed. If the specimen has not failed by 3 Δ_y cycles, the loading would continue with sets of two cycles starting at 4 Δ_y increasing by increments of Δ_y until failure. The calculated Δ_y for the RC frame in this study is 7 mm, which occurs at approximately 34 kN of the in-plane lateral force. The displacement amplitudes were applied at a rate of 10 mm per minute to ensure the quasi-static nature of the loading.

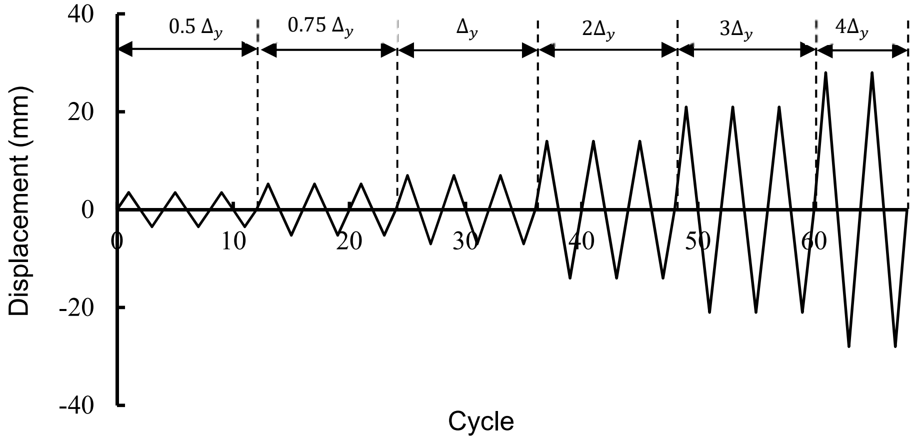

Figure 3: Loading protocol for quasi-static loading

5 MATERIAL PROPERTIES

The mechanical properties of CMUs, mortar, and masonry prisms for the infill and those of concrete and reinforcement of the frame were obtained experimentally in accordance with ASTM specifications. Table 2 presents the average strength and stiffness observed during the material tests. The coefficient of variation of the average for each material was below 15% for masonry components, indicating a relatively consistent level of properties.

Table 2: Material properties of the test specimens

	Strength (MPa)	Stiffness (MPa)
CMUs	17.8	-
Mortar	22.1	-
Masonry Prisms	10.5	-
Concrete	29.2	13203
Reinforcement	446 (665)*	247357

* Yield strength (ultimate strength)

6 TEST RESULTS

6.1 Failure mode

For all specimens, the failure was initiated by diagonal cracking. The cracks began to develop in the approximately diagonal direction for both pushing and pulling actions. As loading increased, the diagonal cracks widened and extended towards the corners of the infill prior to reaching the ultimate. The corner crushing (marked as blue circles) was observed at one or several loaded corners and immediately thereafter, the load began to drop indicating the infill's loss of ability to sustain more load. In the case of infills with openings (specimens IF-W-TG12 and IF-W-SG12), diagonal cracks formed and developed from the corners of the openings towards the infill corners. In the case of interfacial gaps, the diagonal cracking was more intense in the specimens with a top gap than the specimens with a side gap. For the full separation gap, the infill wall had a shear sliding at the early stages of the contact at the base beam location. Then, the diagonal strut was formed in the infilled wall and the wall was subsequently failed due to crushing at the corners. Figure 4 depicts the cracking pattern and the failure observed in all the infilled specimens.

6.2 Hysteresis behaviour

Figures 5a to 5f show the hysteresis lateral load vs. displacement response of all specimens. These curves exhibited pinching characteristics which is typical of masonry infills subjected to cyclic loading. Pinching is believed to be attributed to the opening and closing of the cracks of infills during the cyclic loading. In addition, the loading and unloading stiffness degradation of each successive cycle is also an important indicator of specimen behaviour under cyclic loading. The loading and unloading stiffness can be determined as the secant stiffness averaged over the positive and negative portion of the first cycle in each set of cycles. Figure 6 illustrates the stiffness variation vs. cycle number for each specimen in the loading (6a) and unloading (6b) cases. In the first few cycles, the stiffness of the infilled frame with a full gap (IF-FG12) was almost the same as the stiffness of the bare frame (BF), indicating no engagement of the infill. At the fifth cycle, there was a marked stiffness increase for the infill specimen from the bare frame, indicating engagement of the infill after RC frame developed plastic deformation. Specimens IF-W-TG12 and IF-W-SG12 exhibited similar loading and unloading stiffness degradation trend, and both are close to the variation observed in the bare frame. Although showing relatively high initial stiffness, specimens IF-NG and IF-TG25 had the steepest decrease in stiffness of all infilled specimens. However, close to failure, difference in stiffness of all specimens diminished and they all converged to the level of the bare frame.

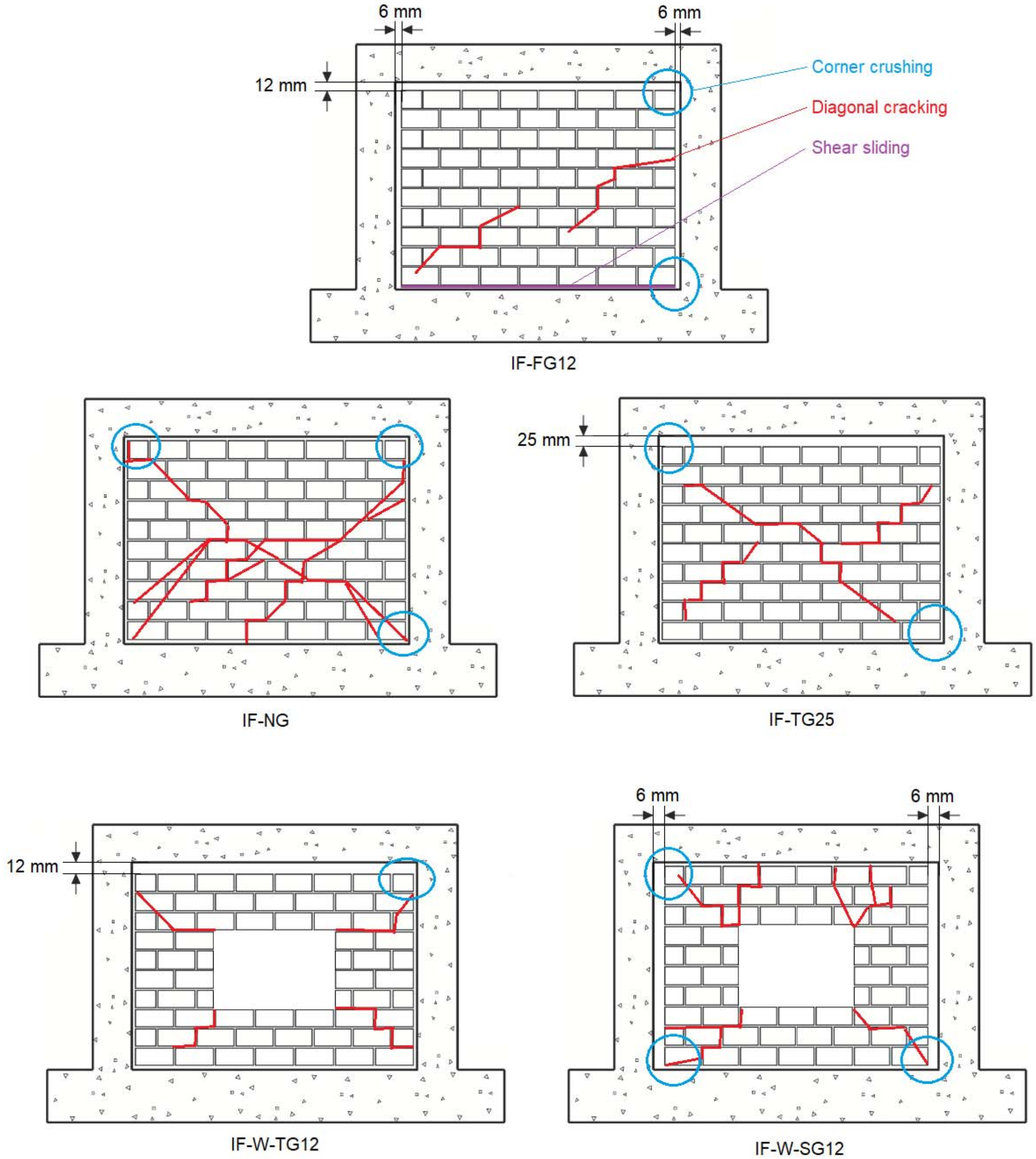

Figure 4: Failure pattern of all infilled specimens

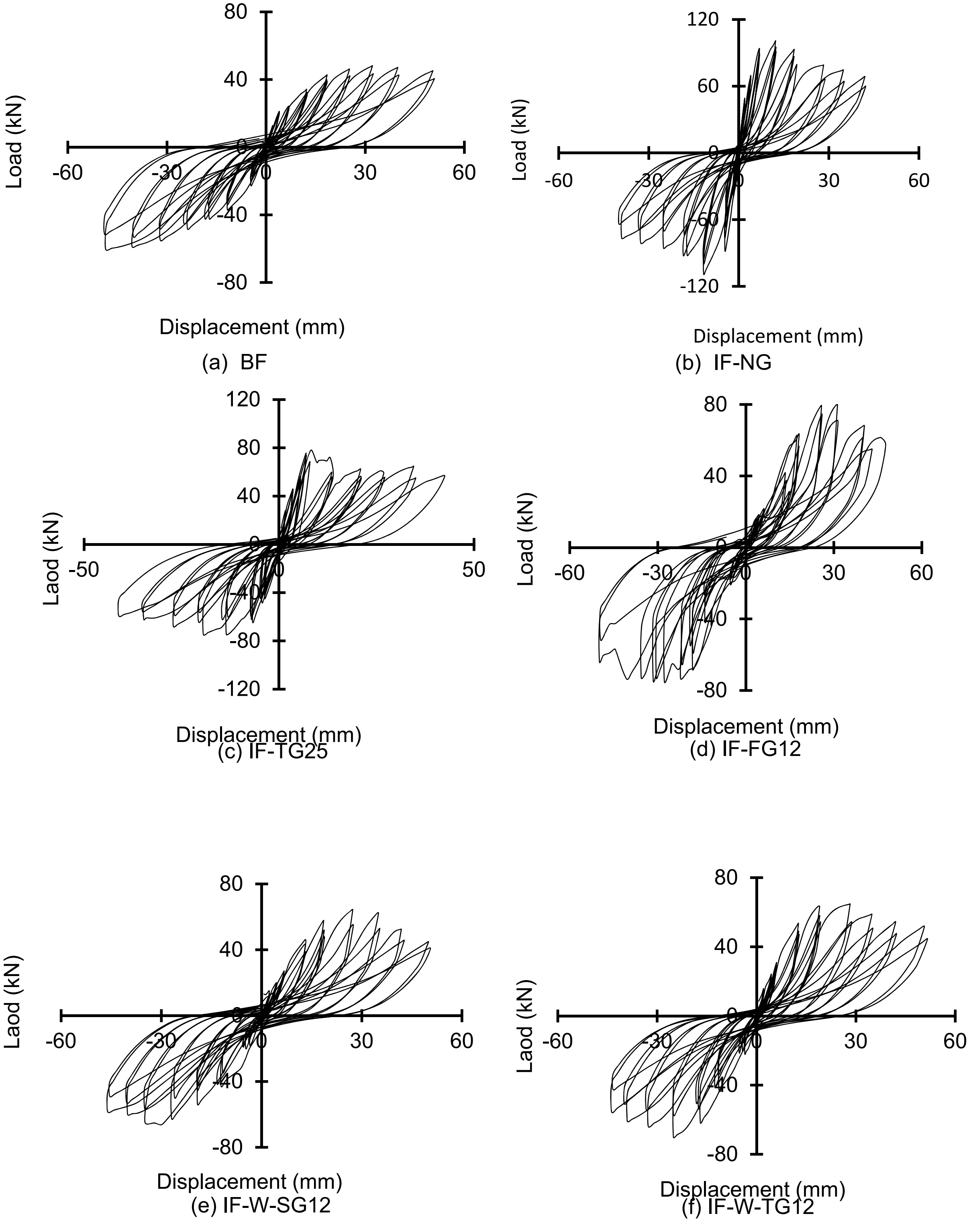

Figure 5: Lateral in-plane hysteresis behaviour observed in the experiment

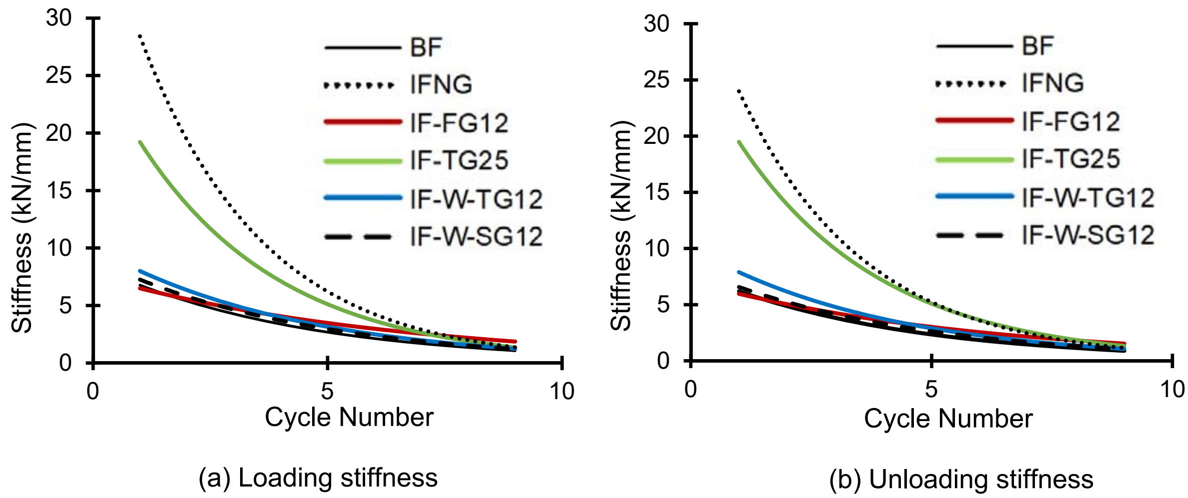

Figure 6: Stiffness variation vs. cycle number for both (a) loading and (b) unloading

6.3 Backbone curves

Figure 7 plots the backbone curves generated from the hysteresis curves for all specimens. A backbone curve is generated by connecting the peak points of each successive cycle of a hysteresis curve. It shows that when compared with the bare frame, the presence of infill, even with openings or interfacial gaps, results in an increase in both the stiffness and strength of infilled frames, albeit to a different extent. Table 3 summarizes the ultimate strength in both pull and push directions, the initial stiffness, as well as calculated strength and stiffness reduction for each specimen. The initial stiffness was determined as the secant stiffness from the origin to the peak load at first half cycle in the positive direction. The effect of interfacial gaps is shown by comparing specimens IF-NG, IF-FG12, and IF-TG25. Overall, the presence of interfacial gap resulted in a reduction in the ultimate strength averaged at about 30% for the gap size considered. The comparison between IF-FG12 and IF-TG25 shows that the former with the full separation gap had a significant lower initial stiffness than the latter with the top gap. This is expected as specimen IF-FG12 behaved more or less like a bare frame before the engagement of the infill. After the infill is engaged in load resisting, specimen IF-FG12 may be considered as a specimen with a top gap of 12 mm, which explains the fact that IF-FG12 attained higher ultimate strength than IF-TG25 but at approximately three times deformation of specimen IF-TG25. As mentioned previously, the infill design provisions in MSJC 2013 permit use of reduction factor of 50% for both stiffness and strength, only for gaps along the top beam-infill interface that are less than or equal to 9.5 mm. Table 3 reveals that both the gap size limit and the reduction factor prescribed in the code are harsh. For a top gap size up to 25 mm, both the strength and stiffness reductions were observed to be around 30%. The gapped specimens with window openings attained markedly higher reduction in ultimate strength than those with only gaps and their stiffness is more or less in line with the bare frame. This indicates that infill openings have more pronounced effect in reduction of stiffness and strength than gaps.

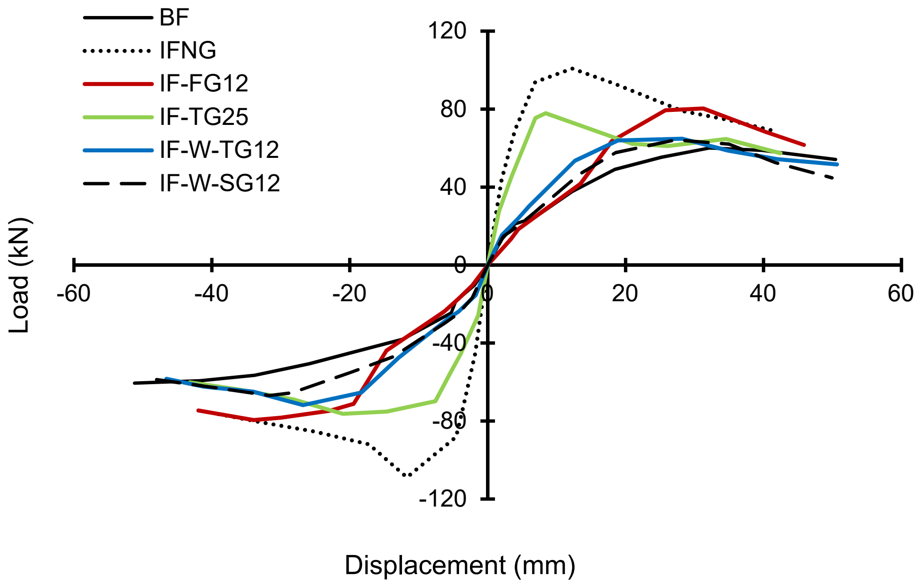

Figure 7: Backbone curve of the load vs. displacement response of infilled frame under quasi-static cyclic loading.

6.4 Ductility

The NBCC 2015 allows for a reduction of seismic loading by a factor from 1 to 5 based on the seismic resisting system implemented. Typical ductility factors for RC frames and unreinforced masonry are 2.5 and 1.0, respectively. In this study, the ductility factor, R, is calculated as the ratio of the displacements occurs at the ultimate load and at the 80% of the ultimate load in the ascending portion of the monotonic backbone curve. Table 3 summarizes the ductility factor R for each specimen in this study. It shows that the ductility of all the masonry infilled RC frames with gaps in this study are greater than 1.0 with an average of 1.6, which is greater than the assigned factor of 1.0 for unreinforced masonry by NBCC 2015, indicating that unreinforced masonry bounded by RC frames has much improved ductility. Although more testing is needed, the results obtained so far suggests that the factor of 1.0 specified in NBCC 2015 is too harsh for masonry infills to be designed in the seismic region.

Table 3: Ultimate strength, initial stiffness and ductility factor of all specimens

Specimen ID	P_{ult}^{+} (kN)	P_{ult}^{-} (kN)	k_{in} (kN/m)	Ductility factor R	Strength reduction %	Stiffness reduction %
BF	60.0	-60.6	7.51	2.3	-	-
IF-NG	100.8	-108.9	25.5	1.6	-	-
IF-FG12	80.3	-79.5	7.60	1.7	27.0	70.2
IF-TG25	77.9	-76.3	18.9	1.4	29.9	25.9
IF-W-TG12	64.8	-71.8	8.9	1.7	34.0	65.1
IF-W-SG12	64.2	-66.9	7.55	1.7	38.5	70.4

6.5 Energy dissipation

Energy dissipation is calculated as the area under the load-displacement hysteric loop of a single cycle. The sum of the energy dissipated over the entire test duration is known as the cumulative energy dissipation (CED). Figure 8 plots the cumulative energy dissipated (kN·m) for each cycle of the frame specimens.

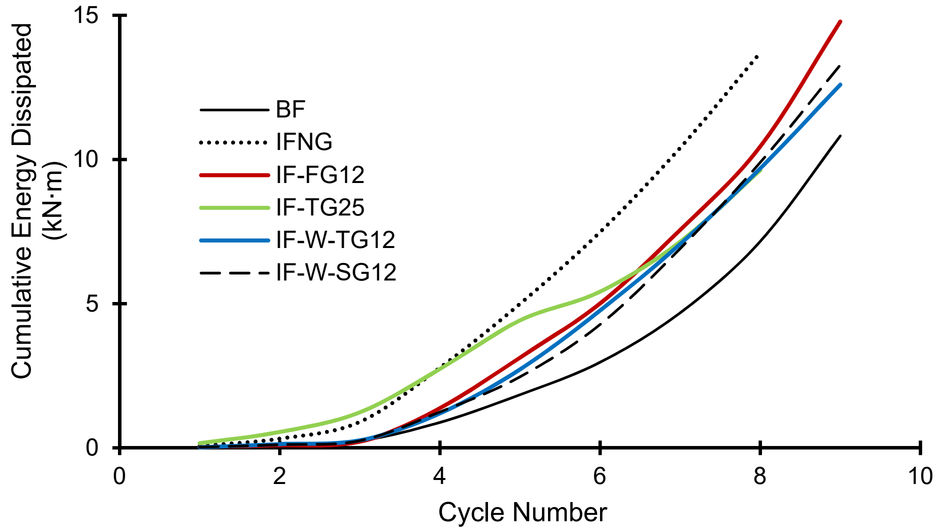

Figure 8: Cumulative energy dissipated vs. cycle number

It shows that all infilled specimens dissipated more cumulative energy than the bare frame specimen. Overall, specimen IF-NG showed most cumulative energy dissipation. In early cycles, the energy dissipation of specimen IF-TG25 is similar to IF-NG. All other specimens dissipated energy at roughly the same rate as the bare frame. Beginning at the fourth set of cycles, a marked deviation from the bare frame was observed as cracks in the infill began to develop and propagate further. At the seventh set of cycles, the cumulative energy dissipated by specimen IF-FG12 and specimens IF-W-TG12 and IF-W-SG12 increased at a greater rate than specimen IF-TG25 and at failure, specimen IF-FG12 attained the most energy dissipation next to IF-NG.

7 CONCLUSION

This research was conducted to investigate the effect of interfacial gaps on the in-plane cyclic behaviour of masonry infilled RC frames. Six specimens, including one bare frame, one infilled frame with full contact and four gapped infilled frame specimens were subjected to quasi-static cyclic loading to failure. In all infilled specimens, failure was initiated by diagonal cracking in the infill and corner crushing was observed as the final failure mode. It was found that the presence of gaps decreased the initial stiffness and strength of infilled frames. The degree of decrease was dependent on the gap magnitude and location. When both openings and gaps were present, the reduction as a result of gap was not as significant as the reduction due to the opening. The gap size limit and reduction factor specified in MAJC 2013 was found to be conservative. The infilled frame specimens with interfacial gaps/openings showed higher ductility than that prescribed in NBCC 2015. More specimens covering a wide range of gap magnitudes and locations are needed to further verify the findings of this study.

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