EFFECTS OF INTERFACIAL GAPS ON THE IN-PLANE BEHAVIOUR OF MASONRY INFILLED RC FRAMES

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Abstract: Four scaled specimens, including three concrete masonry infilled reinforced concrete (RC) frames and a bare RC frame were tested to investigate the effect of interfacial gaps on the in-plane behaviour and strength of masonry infilled RC frames. The specimens were subjected to an in-plane lateral load applied at the frame top beam level to failure. The interfacial gap between the beam and the top of the infill was considered with two magnitudes, 7 and 12 mm. The load vs. lateral displacement behaviour and failure mode for each specimen were presented and discussed. Results showed that in general, the ultimate stiffness, first crack strength and ultimate strength decreased as the top gap size increased while the deflection at the ultimate load increased as the gap size increased. Compared with the specimen with no gaps, a top gap of 7 mm resulted in 3% reduction in the lateral strength and 40% reduction in the lateral stiffness of the infilled system whereas a top gap of 12 mm resulted in 22% and 72% reductions in the lateral strength and the lateral stiffness of the infilled system, respectively.

Key words: concrete masonry infills, RC frames, in-plane behaviour, stiffness, strength, gaps

1 INTRODUCTION

Masonry walls are often used in the modern construction to infill either concrete or steel frames. They fulfil the function of either partitions to separate spaces or claddings to complete the building envelope. Although they have inherently large stiffness and strength, they are often treated as non-structural elements in practice and the lateral and gravity load is designed to be resisted by the surrounding frame. However, if they are built tight against the bounding frame, ignoring their contribution to the stiffness and strength of the infilled system will not necessarily result in a safe and economical design. Instead, the presence of infills will attract large forces to the frame region and thus skew the lateral load distribution of the structure. If not designed properly, they may compromise the stability of the frame system. Hence, an accurate evaluation of the infill contribution to the stiffness and strength of the infilled system is critical. During the last 50 years, both experimental studies (Holmes 1961; Angel 1994; Al-Chaar 2002; Liu and Soon 2012) and finite element analysis (Papia 1988; Seah 1998; Chiou et al. 1999) have been conducted in an effort to develop a rational method for the determination of infill effects on the stiffness and strength of the infilled frame. These studies have contributed to the development of the "equivalent diagonal strut method". First proposed by Polyakov (1956) and Holmes (1961), this method considers the effect of the entire infill using a single diagonal strut connecting the loaded corners. Once the width of the strut is known, the stiffness of the infilled system can be determined through a simple frame analysis. The strength of the infill can also be related to the width of the strut in compression. Previous studies have shown that the diagonal strut width is dependent on the interaction between the frame and the infill which is in turn dependent on the geometric and material properties of the infill and the frame. A comprehensive review of infill-to-frame interactions as affected by some factors can be found in Soon (2011).

This paper is focused on the investigation of the effect of the interfacial gap between the frame top beam and the infill. The initial interfacial gap between the infill and the surrounding frame commonly exists due to the shrinkage and settlement of the infill or defects in workmanship. Previous research has shown that the presence of interfacial gaps can affect the stiffness and strength, and sometimes alter the failure mode of infilled frames. Abdul-Kadir (1974) tested two small scale brickwork infilled steel frames with a 1.6 mm top gap and found that the ultimate load was the same as that of an infilled frame without gaps. Riddington (1984) tested one infilled steel frame with a 3 mm top gap and one with a 3 mm top gap plus a 1.5 mm side gap at each column side. He found that the frame with only top gap showed 50% reduction in stiffness and 7% decrease in peak load; while the frame with both top and side gaps showed 70% reduction in stiffness and 15% decrease in peak load. Yong (1984) tested a steel frame with a concrete block masonry infill having a 10 mm top gap and found that the specimen continued to gain strength once the gap had closed at the loaded corner as if the gap had not existed. Dawe and Seah (1989) tested an infilled steel frame with a 20 mm top gap and found that the frame showed 50% reduction in stiffness and 60% reduction in strength. Seah (1998) inspected a 25 mm gap between the infill panel and the roof beam in a numerical study. Results showed when the gap was closed due to the deformation of the infill and the frame beam, an abrupt growth in the stiffness was observed and the system behaviour was to some extent similar to that of a fully bounded infill-frame system. Ng'andu (2006) tested a calcium silicate element wall infilled steel frame with a 12 mm top gap. Results showed that the initial gap caused a noticeable reduction in infilled frame stiffness during the early stage of loading but with no significant decrease in the cracking load of the infill wall. However, the majority of the existing research on the gap effect was focused on infilled steel frames and results on reinforced concrete (RC) bounding frames are limited. No definable relationship between the magnitude of the gap and stiffness and strength of the infilled frame was generated from these studies.

To better the understanding of the behaviour and strength of infilled RC frames with interfacial gaps, an experimental program was carried out to investigate the effect of interfacial gaps on the in-plane behaviour of masonry infilled RC frames. While the study is still on-going, only results of infilled frames with top gaps are reported in this paper.

2 EXPERIMENTAL SET-UP

A schematic view of the test set-up is illustrated in Figure 1. A hydraulic actuator with a capacity of 250 kN was used to apply the lateral load. The actuator was fastened to the column of the reaction frame and a load cell was attached to the actuator to measure the load. A steel plate was placed between the load cell and the frame beam to ensure a uniform distribution of the applied load. The reaction frame consisted of a skewed A-frame including two steel W columns welded to a stiffened W beam which was connected to the strong floor through high strength bolts. The frame bottom beam was clamped to the strong floor using two W-shape steel beams at its two side stems. An additional brace support was used at one end of the frame stem to further restrain the potential in-plane sliding of the frame specimen.

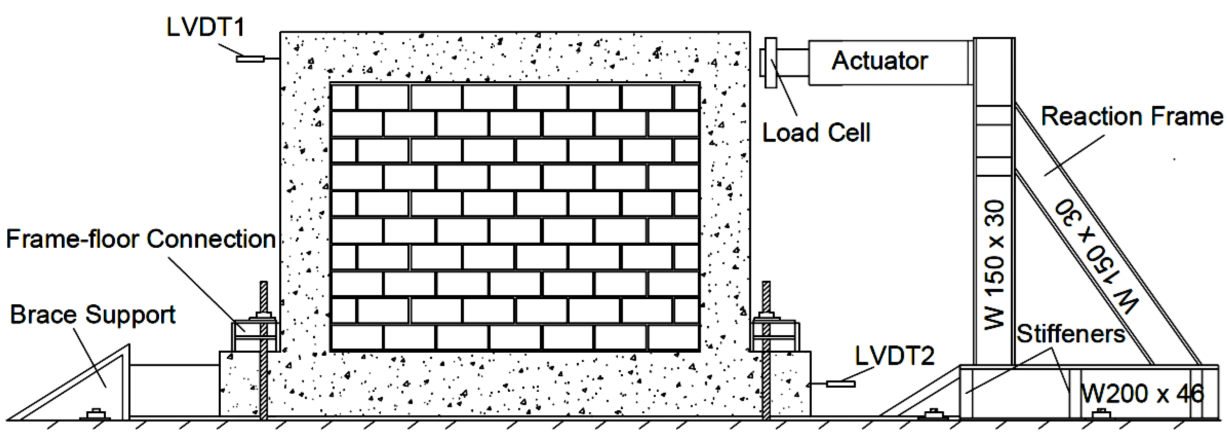


Figure 1 Test set-up

Two linear variable differential transformers (LVDTs) (LVDT 1 and 2) were mounted at the centreline of the top and bottom beam respectively to measure the in-plane lateral displacements as shown.

3 TEST SPECIMENS

A total of four frame specimens were tested, including one bare frame (BF) specimen without infill, one specimen with the infill built tight against the frame members and thus considered as specimen without gaps (IFNG), and two specimens with infills having a gap of 7 mm and 12 mm respectively between the infill and the frame top beam (labelled as IFTG7 and IFTG12, respectively). All frame specimens had the same dimensions as shown in Figure 2. The required gap magnitudes were achieved by slightly adjusting the thickness of mortar. The geometry of the infill yielded a height-to-length aspect ratio of 0.73. The infills were constructed using custom-made half scale standard 200 mm concrete masonry units (CMUs) laying in the running bond. The infills were unreinforced and ungrouted.

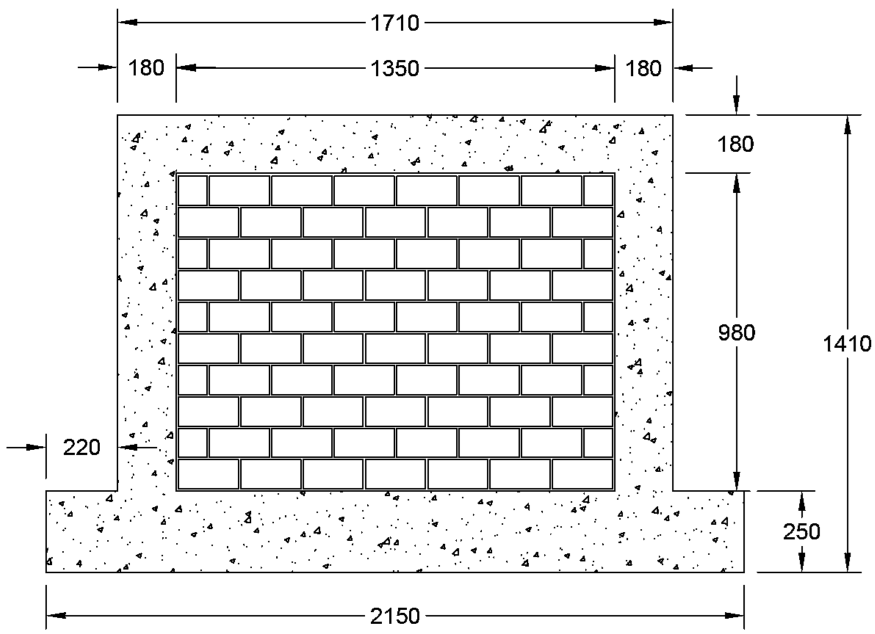


Figure 2 Geometric properties of infilled frame specimens

The frame top beam and columns had a 180 mm square section and 4-10M deformed rebars, with 10M 130×130 mm 135° bent stirrups spacing at 100 mm center-to-center. The base beam had a 250 mm square section and 4-15M longitudinal rebars, with 10M 200×200 mm 135° bent stirrups spacing at 100 mm center-to-center. Four 300×300 mm L-shape 10M bars were positioned at each top beam-column corner for strengthening. The clear concrete coverage for the frame is 25 mm. Details of the reinforcement are shown in Figure 3.

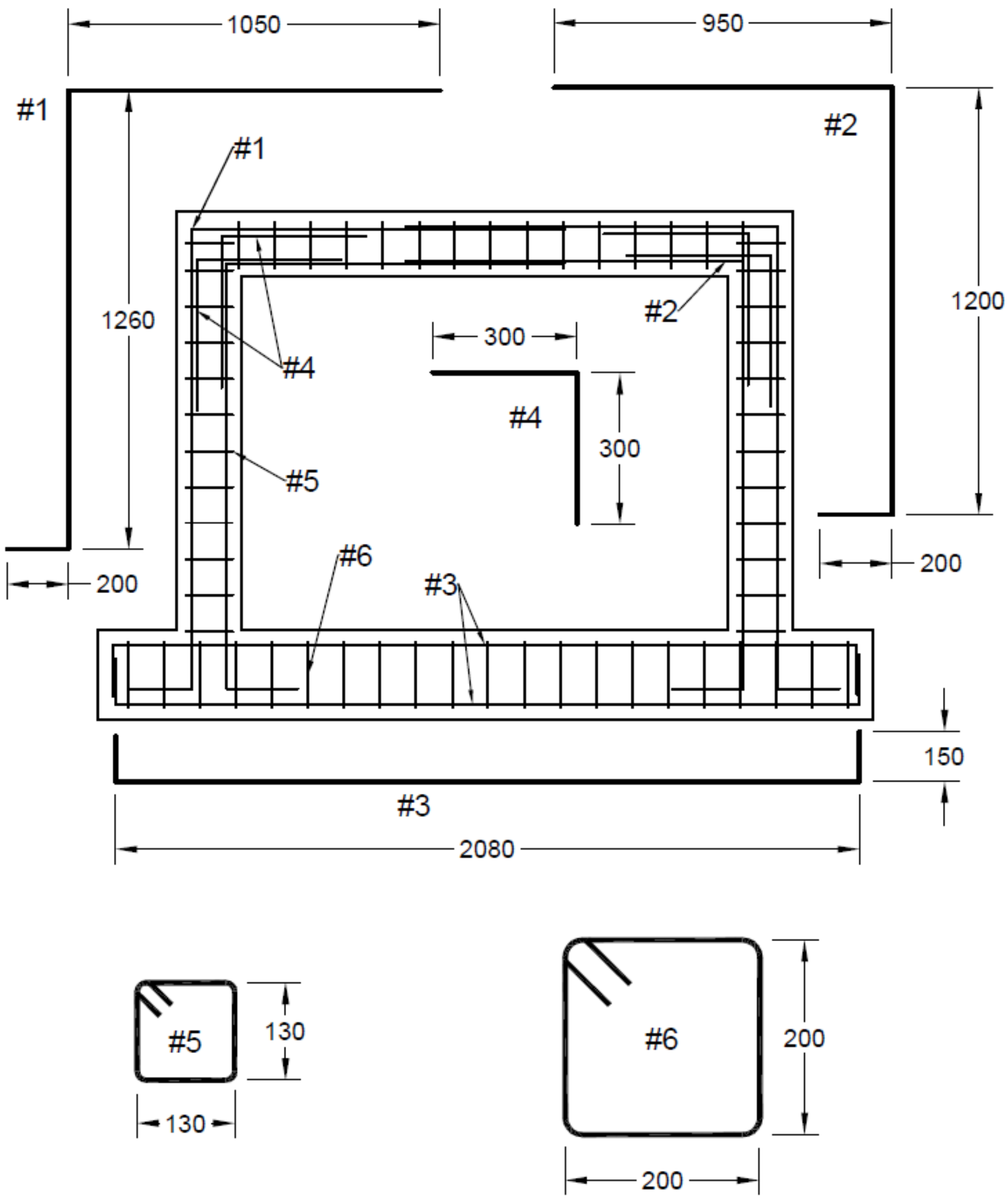


Figure 3 Details of reinforcement of RC frames

4 FABRICATION OF INFILL SPECIMENS

The construction of RC frames consists of fabricating formworks, placing and tying reinforcement steel in position, and casting concrete. The form was placed in a laying down position for concrete pouring. The ready-mix concrete was used with a specified compressive strength of 35 MPa and a maximum coarse aggregate size of 12 mm. The concrete was poured into the formwork as quickly as possible and vibrated thoroughly with a concrete vibrator to minimize air pockets. The construction of masonry infills was conducted approximately five weeks after the concrete frame casting and by an experienced mason to the standard of practice of masonry construction. A level and plumb were used throughout the construction process to ensure the wall being straight and levelled. The mortar was applied on the block face shell only for the bed joints and for the head joints. Masonry prisms and mortar cubes were built along the frame specimens and cured under the same conditions as the frame specimens until the day of testing. The ambient temperature variation of the laboratory ranged from 10 to 25°C while the humidity varied from 60% to 80%.

5 TEST PROCEDURES

Prior to testing, the infilled frame specimen was positioned in place and was aligned carefully in both in-plane and out-of-plane direction. The load cell and all the LVDTs were then checked to ensure that they functioned properly. The lateral load was applied gradually at a rate of 6 kN per minute until the failure of the specimen. The load and LVDT readings were monitored and recorded with an interval of 0.2 seconds throughout the test using an electronic data acquisition system. For each test, the cracking load, ultimate load, cracking pattern and failure mode were noted and photographed.

6 MATERIAL PROPERTIES

Auxiliary tests were conducted in accordance with corresponding standards to determine relevant material properties for this study. The results are presented in Table 1. While the modulus of elasticity for the concrete frame and steel reinforcement were obtained experimentally, the modulus of elasticity of masonry prisms was determined as $850f'_m$ according to CSA 304.1 (R2010). Both the yield strength and the ultimate strength (shown in the bracket) of steel is shown in the table.

Table 1 Material properties

	Block	Mortar	Prisms	Concrete	Steel
Compressive/tensile strength (MPa)	22.0	21.0	16.7	42.3	446 (665)
COV (%)	5	9	10	3	2 (1)
Modulus of elasticity (MPa)	-	-	14195	28424	247357
COV (%)	-	-	-	4	1

7 RESULTS AND DISCUSSION

7.1 General Behaviour

The load vs. lateral displacement responses of all the infilled specimens were obtained and their general behaviour can be divided into three stages. Figure 4 plots the load vs. lateral displacement curve of specimen IFNG as an example. At the first stage, the specimen behaved almost linearly with an initial stiffness, K_{ini}, taken as the slope of the tangent line of the initial linear portion of the curve. As the load increased to about 30% ~ 40% of the ultimate load, the specimen began to enter the second stage showing noticeable non-linearity as hairline cracks emerged in the infill and flexural cracks in the frame columns. The hairline cracks in the infill then developed into the first visible diagonal crack. The slope of the line connecting the origin and the point of the first visible diagonal crack is defined as the first crack stiffness, K_{cra}. As the load increased, more cracks formed and developed in the general diagonal direction before reaching the ultimate load of the system. Beyond the ultimate load, the specimen was in the falling branch stage. In this stage, the specimen was still capable of sustaining the resistance with significant deformation accompanied by the development of cracking and crushing in the infill. The slope of the line connecting the origin and the ultimate load is considered as the ultimate stiffness, K_{ult}. Also observed was the significant flexural cracking development in the RC frame columns.

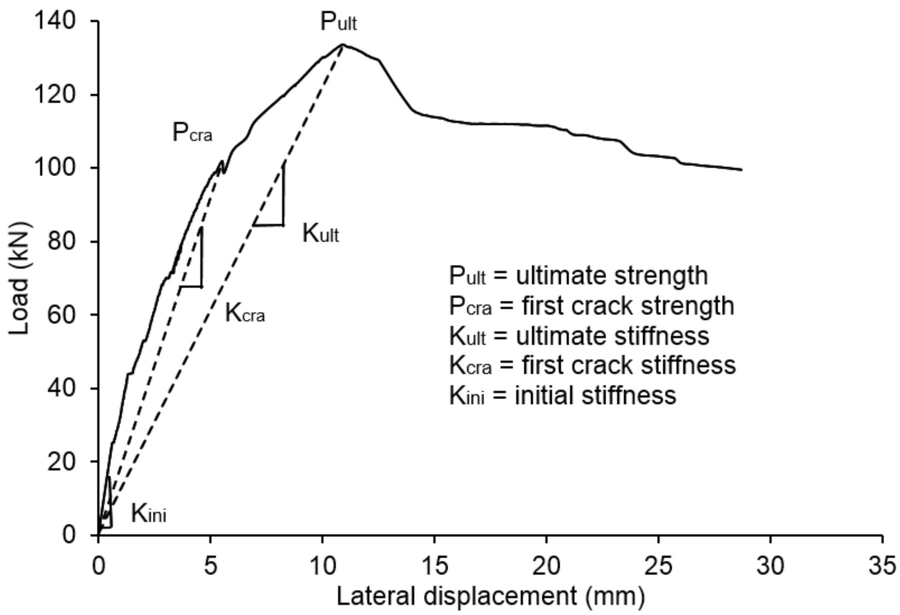


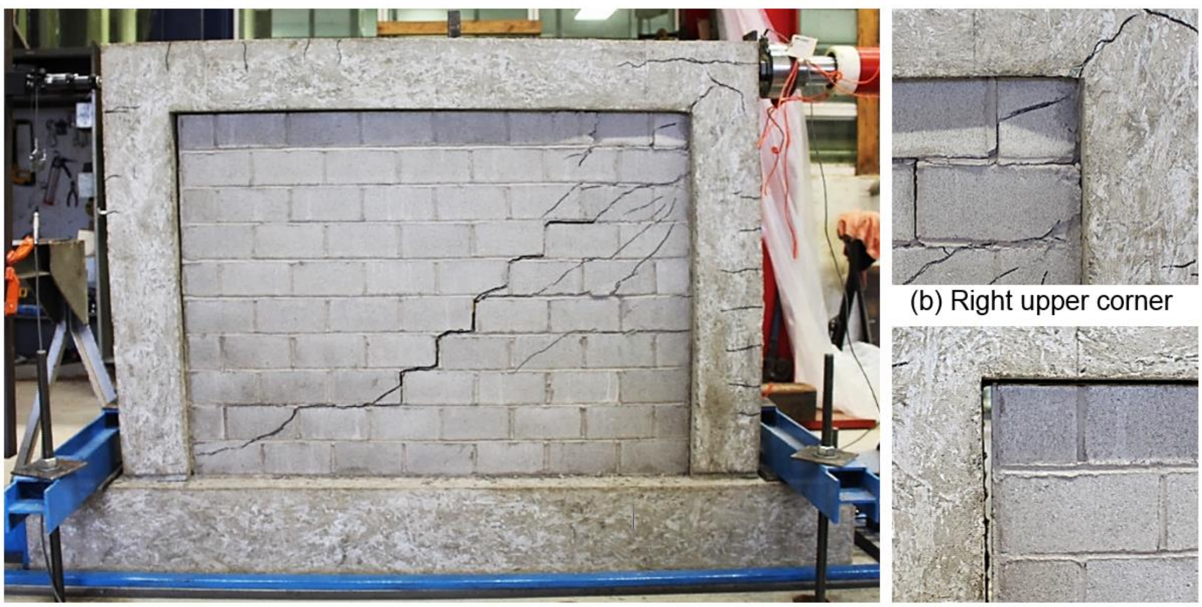
Figure 4 General behaviour of infilled frame specimens

7.2 Failure Modes

All the infilled frame specimens were failed ultimately by corner crushing initiated by diagonal cracking in the infill. Specimen IFNG and IFTG7 experienced evident detachment of the column and the infill at the unloaded side at the loads of about 50 kN and 40 kN, respectively, while specimen IFTG12 did not show this feature, as shown in Figure 5(c), 6(c) and 7(c), accordingly. Although separation of the column and the infill was observed in specimen IFNG at the unloaded side, the frame top beam and the infill remained in contact throughout the test as shown in Figure 5(b) and 5(c). The 7 mm top gap of specimen IFTG7 was closed at about 80% of the ultimate load as shown Figure 6(b) and 6(c), while specimen IFTG12 still had a remaining obvious gap along the top beam after failure as shown in Figure 7(b) and 7(c). Additionally, as shown in Figure 5(a), 6(a) and 7(a), the presence of the top gap changed the diagonal cracking extent: specimen IFNG and IFTG7 only saw one major diagonal crack while specimen IFTG12 experienced three significant diagonal cracks. The cracking extent of the infill increased as the top gap size increased.

(a) Overview (b) Right upper corner (c) Left upper corner

Figure 5 Failure pattern of specimen IFNG



(a) Overview (b) Right upper corner (c) Left upper corner

Figure 6 Failure pattern of specimen IFTG7

(a) Overview (b) Right upper corner (c) Left upper corner

Figure 7 Failure pattern of specimen IFTG12

7.3 Effects of Top Interfacial Gaps

Table 2 presents test results of the frame specimens for analyzing the effect of top interfacial gaps on the stiffness and strength. The load vs. lateral displacement curves of all the specimens are shown in Figure 8. Both the table and figure show that compared with the bare frame (BF), the presence of infills significantly increased the initial stiffness, ultimate stiffness, and ultimate strength of the infilled frames. In the case of the infilled frame without any gaps (IFNG), these increases were about 98%, 618% and 132%, respectively. Even when a top gap was present with the studied magnitudes, these increases due to the infill were pronounced. Also observed was that the presence of the top gap increased the ductility of the infilled system where the ultimate load occurred at an increasingly larger lateral deflection as the size of the gap increased.

Table 2 Test results of frame specimens

ID	K_{ini} (kN/mm)	K_{cra} (kN/mm)	K_{ult} (kN/mm)	P_{cra} (kN)	P_{ult} (kN)	Deflection at ultimate (mm)	Failure Mode
BF	20.2	-	1.7	-	57.7	33.5	-
IFNG	39.9	18.2	12.2	101.9	133.6	11.0	Corner Crushing
IFTG7	28.7	10.0	7.3	100.0	129.6	17.7	Corner Crushing
IFTG12	28.6	16.4	3.4	44.3	103.6	30.8	Corner Crushing

Table 3 presents variations of stiffness and strength of specimen IFTG7 and IFTG12 in comparison with specimen IFNG. As shown in the table, the ultimate stiffness of specimen IFTG7 and IFTG12 decreased by 40% and 72%, respectively, which indicated that the ultimate stiffness decreased more as the top gap size increased. This trend was not observed for the initial stiffness and first crack stiffness where the initial stiffness of specimen IFTG7 and IFTG12 decreased by the same amount of 28%; and specimen IFTG7 showed more reduction in the first crack stiffness than specimen IFTG12. For the strength comparison, a 7 mm top gap had little influence on either the first crack or the ultimate strength, which resulted in only 2% and 3% reductions, respectively. However, a 12 mm top gap resulted in 57% and 22% reductions in the first crack and the ultimate strength, respectively.

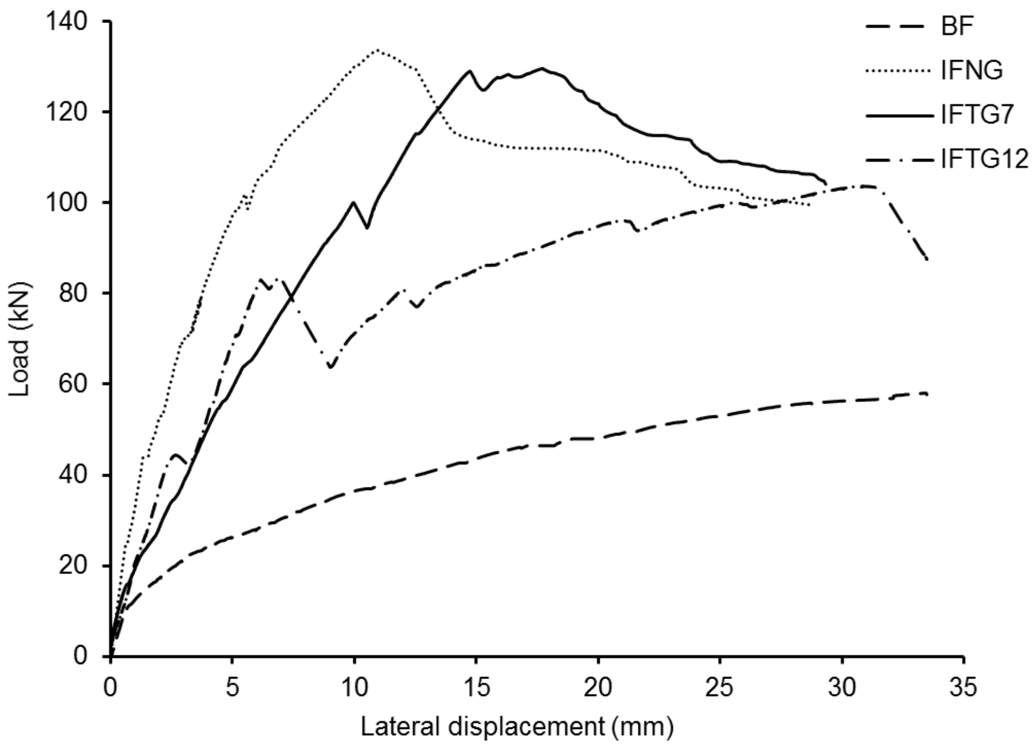


Figure 8 Load vs. lateral displacement curves

Table 3 Variations of strength and stiffness

ID	ΔK_{ini}	ΔK_{cra}	ΔK_{ult}	ΔP_{cra}	ΔP_{ult}
IFTG7	-28%	-45%	-40%	-2%	-3%
IFTG12	-28%	-10%	-72%	-57%	-22%

8 CONCLUSIONS

Four scaled specimens, including three concrete masonry infilled RC frames and a bare RC frame were tested to investigate the effect of top interfacial gaps on the in-plane behaviour and strength of masonry infilled RC frames. Two magnitudes of interfacial gaps, 7 and 12 mm, between the frame top beam and the infill were considered. The following conclusions are drawn from this study.

Compared with the bare frame, the presence of infills significantly increased the initial stiffness, ultimate stiffness and ultimate strength of the infilled frames. Even when a top gap was present with the studied magnitudes, these increases due to the infill were pronounced.

Compared with the infilled frame with no gaps, a top gap of 7 mm resulted in 40% reduction on the lateral stiffness and 3% decrease in the lateral strength of the infilled system; a top gap of 12 mm resulted in 72% and 22% reductions on the lateral stiffness and the lateral strength of the infilled system, respectively. In general, the ultimate stiffness, first crack strength and ultimate strength of the infilled frame decreased as the top gap size increased while the deflection at the ultimate load increased as the top gap size increased.

For all the infilled frames, failure was initiated by diagonal cracking in the infill and corner crushing was observed as the final failure mode. The presence of top gaps resulted in more extensive diagonal cracking before the ultimate load than the case of no gaps.

9 ACKNOWLEDGEMENTS

The authors wish to recognize the contribution of financial assistance by the Canadian Concrete Masonry Products Association and in kind assistance from Wildwood Masonry Ltd and Masonry Industry Association of Atlantic Canada for providing the labor and materials.

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