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EXPERIMENTAL STUDY OF AN ALL-MASONRY INFILLED FRAME SYSTEM UNDER IN-PLANE LATERAL LOADING

Foroushani, Saber[1] and Liu, Yi[2]

ABSTRACT

This paper presents an initial experimental study of on-going research on the in-plane behaviour of an all-masonry infilled frame system and their performance in comparison with masonry infilled RC frames. An all-masonry infilled frame system is an infilled frame system where both the infill and bounding frame is constructed simultaneously and using masonry units. In this study, masonry columns and beams were constructed from prototype masonry boundary element units and were reinforced and fully grouted, while the infill panel was constructed with half-scale standard 200 mm concrete masonry units. Six specimens were tested under monotonically increased lateral loading to failure. The results showed that all-masonry infilled frame and its RC frame counterpart exhibited similar behaviour in terms of stiffness and strength. However, while the RC framed infill showed pronounced corner crushing at failure, the masonry framed infill failed by severe diagonal cracking extending into the boundary columns. The latter appeared to have a better ability to sustain the ultimate load as displacement increased and the post-ultimate behavior was more ductile than the former. The results also showed that the use of horizontal reinforcement in all-masonry infilled specimens had an insignificant effect on the ultimate load but marked impact on increasing stiffness and ductility of the frame system.

KEYWORDS: *concrete masonry infills, masonry frames, RC frames, experimental study, stiffness, strength*

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[1] MASc, Department of Civil and Resource Engineering, Dalhousie University, Halifax, NS, Canada, saber.foroushani@dal.ca

[2] Professor, Department of Civil and Resource Engineering, Dalhousie University, Halifax, NS, Canada, Yi.liu@dal.ca

INTRODUCTION

Masonry walls have been commonly used in modern building construction to infill either steel or reinforced concrete (RC) frames. Often referred to as masonry infills, these walls with large inherent in-plane stiffness can inevitably affect the behaviour of infilled frame system when subjected to in-plane loading. Previous research (eg, [1]-[6]) has shown that presence of masonry infill contributes significantly to the lateral stiffness, strength, ductility and energy dissipation of the frame system. To evaluate the contribution of the infill to the system stiffness and strength, a so-called "equivalent diagonal strut method", has been established as the most widely accepted approach. In that method, the entire infill is replaced by a single diagonal strut connecting the loaded corners resulting in a braced frame. Once the strut width is known, a simple frame analysis by commercially available software or by hand can then be performed to determine the system stiffness. And the strength of the infill can also be related to the diagonal strut width. For design, the "diagonal strut method" has also been adopted in both the Canadian Masonry Standard CSA S304-14 [7] and the American Masonry Design Standard, TMS402/602 [8] but with different formulation for the strut width. Despite that all the scientific information and standard practice for design is available, the common industry practice is still to treat the masonry infills as non-structural elements and design the frame to resist gravity and lateral loading. One factor for this disconnect is attributed to the difficulty in accurately quantifying the exact interaction between the infill and its bounding frame. The construction method employed in the conventional infilled RC or steel frames does not enable the easy implementation of mechanical anchorage between the infill and the frame.

This paper proposes an all-masonry infilled frame system where the frame is also constructed from masonry units. While conceptually similar to a masonry infilled RC frame, in this case, masonry reinforced columns and tied beams form the masonry frame and the masonry infill may be constructed in the same manner as in the conventional infilled RC frames. From both construction and design perspectives, all-masonry infilled frames are advantageous as design for the frame and infill can be carried out in the same consulting firm and constructed at the same time with one material and thus eliminating the need to coordinate with concrete or steel trades as in the case of steel or RC frames. In addition, simultaneous construction of the frame and infill makes it easier to include vertical reinforcement in the infill as well as provide alternative forms of interfacial connection where mechanical anchorage between the frame and infill may be implemented as opposed to simple mortar bedding.

In this study, masonry columns were formed with prototype boundary element units fully grouted and reinforced and masonry beams were formed using bond beams and tied into columns. The boundary element units contain a thinner than usual face-shell permitting large open areas in walls for reinforcement and grouting. To the applicant's best knowledge, this proposed research is one of the first which investigates this type of all-masonry infilled frames as defined herein. It is also recognized that the use of boundary elements to increase ductility and energy dissipation of masonry shear walls has been studied in recent years ([9]-[12]). The use of enlarged boundary elements constructed of hollow masonry units has been shown to significantly improve the flexural ductility of walls. However, different from the masonry shear wall, the uniqueness of all-masonry infilled frame systems is that they rely on combined frame-action and frame-to-infill interaction to achieve their lateral resistance, which can improve construction efficiencies by having large portions of masonry (in the infills) with little-to-no reinforcement.

It is recognized that while sharing some similarities with masonry infilled RC frames, the all-masonry infilled frame system is essentially a unique system with potentially different behavioural characteristics. An experimental program was underway to provide an overall understanding of behaviour of this all-masonry infilled frame systems. This paper presents some preliminary results of this program to demonstrate the performance of this type of infilled frame subjected to in-plane loading and the comparison with conventional masonry infilled RC frames.

EXPERIMENTAL SET-UP

The experimental 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 mounted on an independent frame (not shown). A load cell was attached to the actuator to measure the lateral load. A steel plate was placed between the load cell and the frame to ensure a uniform distribution of the concentrated load. Two linear variable differential transformers (LVDTs) (LVDT 1 and 2) were mounted at the centerline of the top and bottom beam respectively to measure the in-plane lateral displacements. Another two LVDTs were positioned at the half height of the masonry infill and at the central point of the top beam respectively, both on the back side, to monitor any possible out-of-plane movements. The bottom base beam of each specimen was held tightly to the floor with two w-shape steel beam using threaded rods. Additionally, two hydraulic rams were placed at two ends of the bottom beam between the specimen and the reaction frame to further restrain against lateral sliding of the bottom beam.

Figure 1: General view of test set-up

Prior to each test, the specimen was positioned in place and was aligned carefully in both in-plane and out-of-plane directions. The load cell and all the LVDTs were then checked to ensure that they functioned properly. The lateral load was applied gradually until the failure of the specimen. Failure was deemed to have occurred when the specimen lost approximately 15% of its peak strength or the system sustained significant deformation without taking additional load. 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 when necessary.

TEST SPECIMENS

Table 1 presents a list of specimens. The first four specimens were used to compare the performance between RC and all-masonry frames. The last two specimens were used to evaluate the effect of infill horizontal reinforcement on the behaviour of all-masonry infilled frames. All the infilled frame specimens had the same dimensions as shown in Figure 2. The infills were constructed using custom-made, half-scale standard 200 mm concrete masonry units (CMUs) laid in the running bond. The infills were unreinforced (no vertical rebar) and ungrouted.

Table 1: Summary of test specimens

No.	Spec. ID	f'_m (MPa)		f'_c (MPa)	Parameter
		Bound.	Infill		
1	BF-RC	-	-	42.3	Bare RC frame
2	BF-AM	33.1	-		Bare masonry frame
3	IF-RC	-	16.7	42.3	Infill RC frame
4	IF-AM	33.1	16.7	-	Infill masonry frame
5	IF-AM-BB	35.6	17.1	-	Bond beam,3rd and 8th course
6	IF-AM-BJ	35.6	17.1	-	Bed-joint reinf., every second course

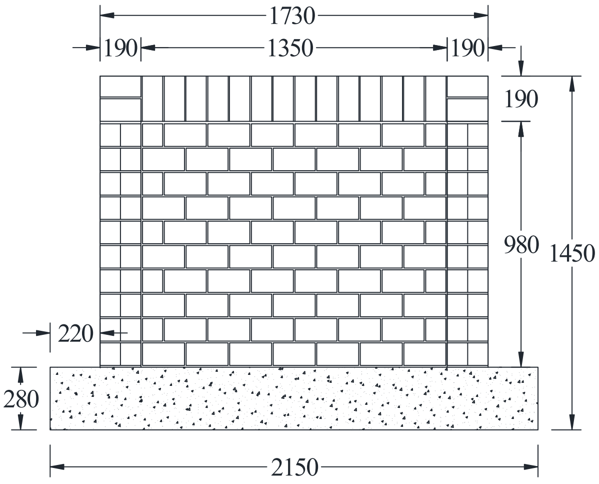


Figure 2: Geometric properties of infilled frame specimens, unit (mm)

The frame top beam and columns had a 180 mm square section reinforced with 4-10M deformed rebars and 10M stirrups spacing at 100 mm center-to-center. The base beam had a 250 mm square section reinforced with 4-15M longitudinal rebars and 10M stirrups spacing at 100 mm center-to-center. It is noted that four 300×300 mm L-shaped 10M bars were used at each top beam-column corner for additional strengthening. The concrete cover used for the frame members was 25 mm. Details of the reinforcement are shown in Figure 3. This detail was the same for RC and masonry frames.

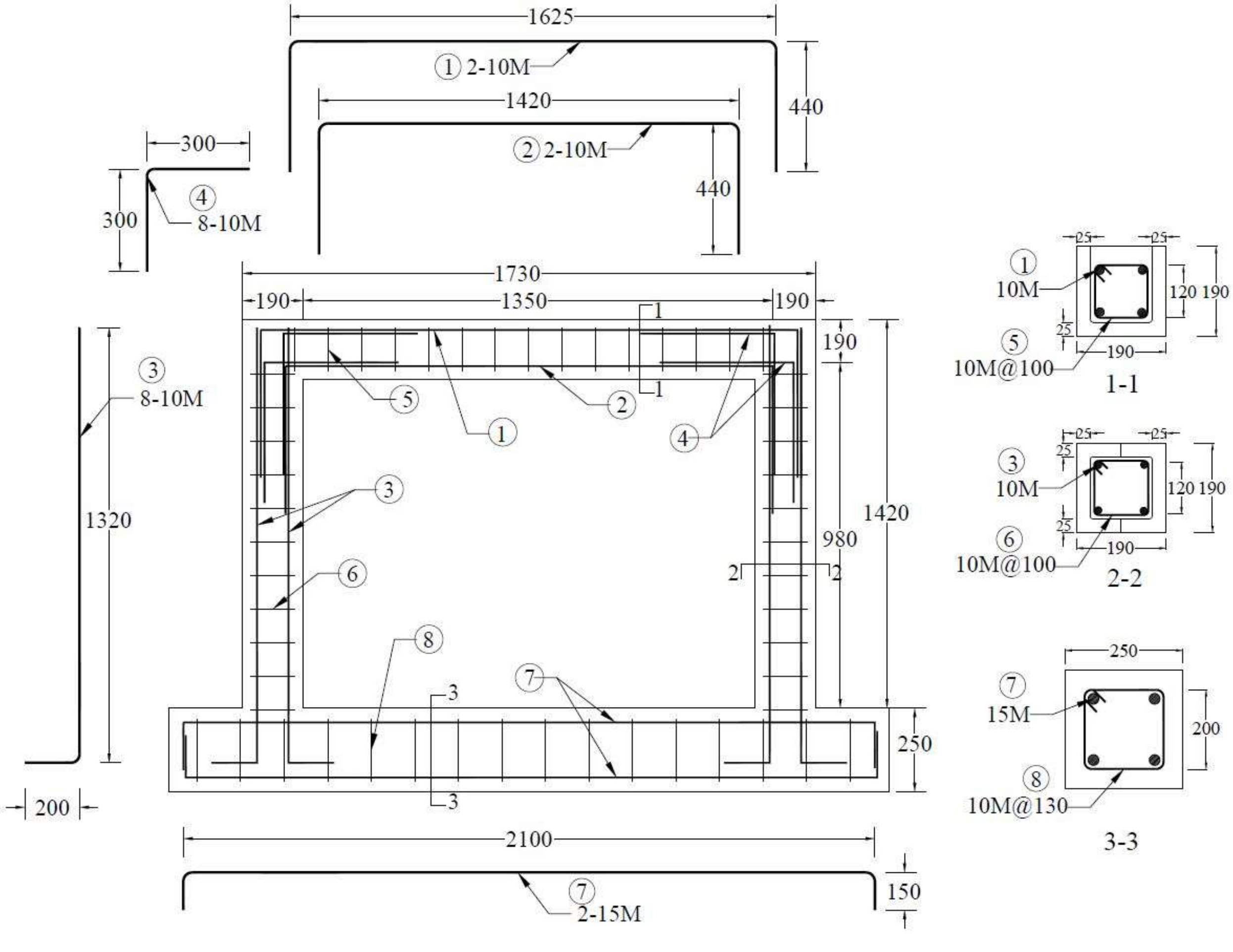


Figure 3: Details of reinforcement in the bounding frame

For specimens IF-AM-BJ, a ladder type joint reinforcement was employed every second course in the mortar joint. The reinforcement was extended into the column to be grouted together forming a mechanic anchorage (Figure 4a). For specimen IF-AM-BB, one 10M deformed rebar was used as the reinforcement of the bond beam and extended into the frame column with a 90 degree bent leg (Figure 4b).

a) Bed-joint reinforcement detail **b) Bond beam detail**

Figure 4: Infill horizontal reinforcement detail for: a) IF-AM-BJ; and b) IF-AM-BB

RESULTS AND DISCUSSION

Bare Frames

The load vs. lateral displacement curves of two bare frames are compared in Figure 5. It shows that two specimens attained almost the same ultimate load and the general behavioral trend was also similar. The RC frame showed more ductile behaviour post-ultimate than the masonry frame. The RC frame had a higher initial stiffness (20.2 vs. 5.2 kN/mm) which might be attributed to the fact that RC member is a monolithic whole while the masonry frame is assemblage of masonry unit, mortar, and grout which results in an inherently "non-tight" system. The "slack" between components shows a softer system. However, the stiffness of two specimens at ultimate (defined as the slope of the line connecting the ultimate strength and the origin) was in the same order (1.69 vs. 1.74 kN/mm), indicating that after extensive cracking, two frames behaved similarly.

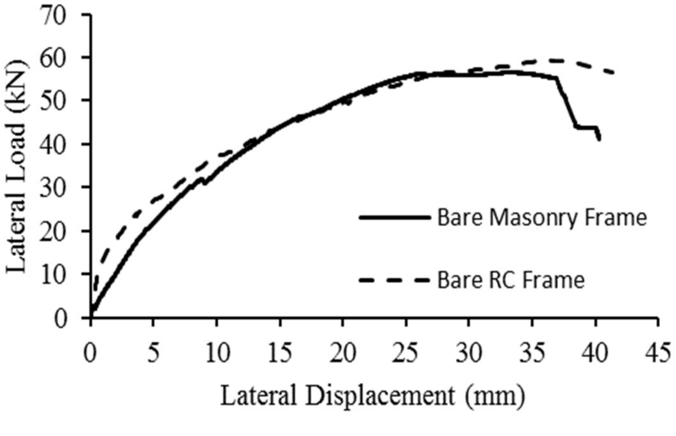


Figure 5: Load-displacement curves for bare RC frame and masonry frame

The comparison of failure mode showed that the RC frame failed by extensive cracking mainly concentrated around the beam-column connections at the loaded corner and flexural cracks at the bottom column-beam connections. While the masonry frame also failed by cracking, the cracks were more distributed through the length of the columns and the beam, mostly through either the bed or head mortar joints. The frame deformed such that the bottom course of the columns began to de-attach from the base beam which was attributed to the load drop on the response curve after ultimate.

Infilled Frames

In the case of infilled frames, two specimens yielded similar ultimate loads with all-masonry infilled specimen (IF-AM) having a slightly (6%) higher value than the infilled RC specimen (IF-RC). As shown in Figure 6, the initial and crack stiffness of both specimens are more or less in the same range. The most distinctive difference appears in the post-ultimate behaviour. All-masonry infilled frame showed more ability to maintain the capacity over a large displacement while the RC framed specimen had a pronounced load drop immediately after the ultimate load. In other words, the all-masonry infilled frame seems to display greater ductility and potential more energy dissipation ability. A side-by-side failure mode comparison as seen in Figure 7 showed that IF-AM failed due to two-branch diagonal cracking mode, with cracking extending into the boundary columns while IF-RC experienced diagonal cracks as the initiation of failure prior to corner crushing as the final failure mode.

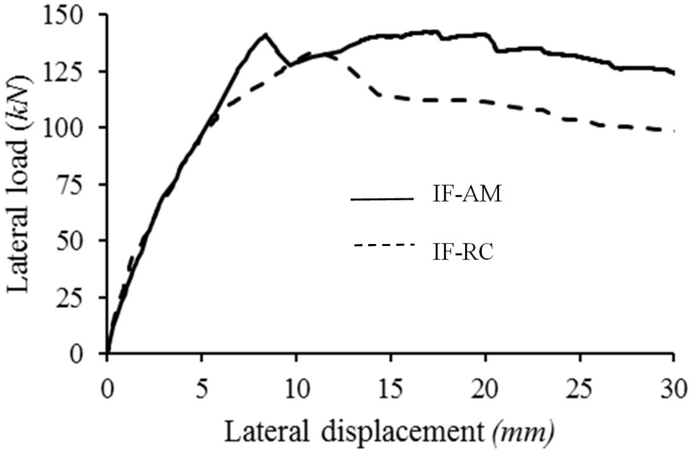
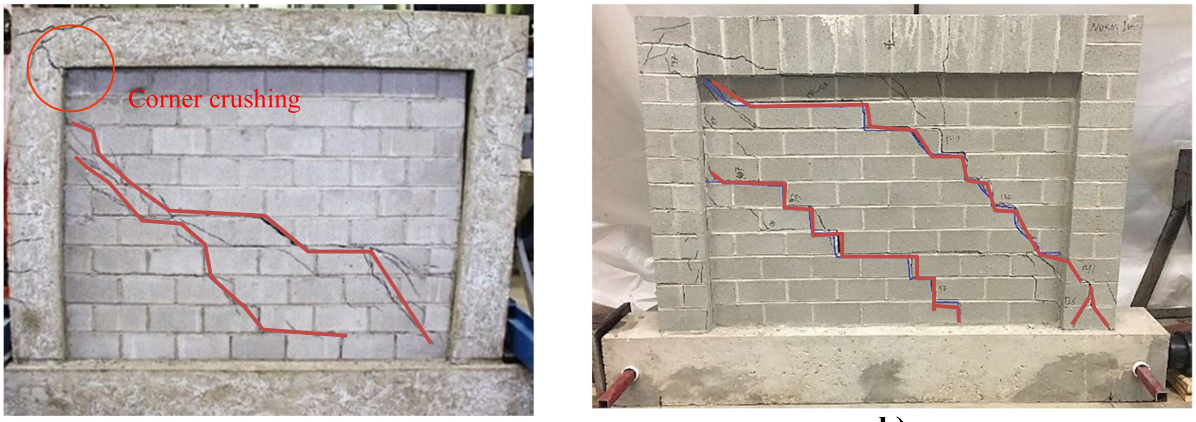


Figure 6: Load-displacement curves for infilled RC frame and all-masonry infiled frame specimens



a) b)

Figure 7: Failure mode: a) IF-RC and b) IF-AM

Effect of Infill Reinforcement

The effect of infill reinforcement is illustrated in Figure 8 where load responses of specimens IF-AM, IF-AM-BB, and IF-AM-BJ are compared. In terms of strength, while the infills with reinforcement attained higher ultimate loads, the degree of the capacity increase was small, about 5%, which may be insignificant from a practical standpoint. The more pronounced effect is observed in the stiffness. Both the initial and cracking stiffness of IF-AM-BJ and IF-AM-BB were noticeably higher than IF-AM. Further, the former two specimens showed a greater capability of sustaining displacement, especially IF-AM-BJ, before reaching the ultimate load than the latter specimen. A comparison between IF-AM-BB and IF-AM-BJ seems to suggest that a more distributed reinforcement scheme (IF-AM-BJ) performed better than a concentrated one (IF-BB) where the load and displacement at ultimate were slightly higher for the former.

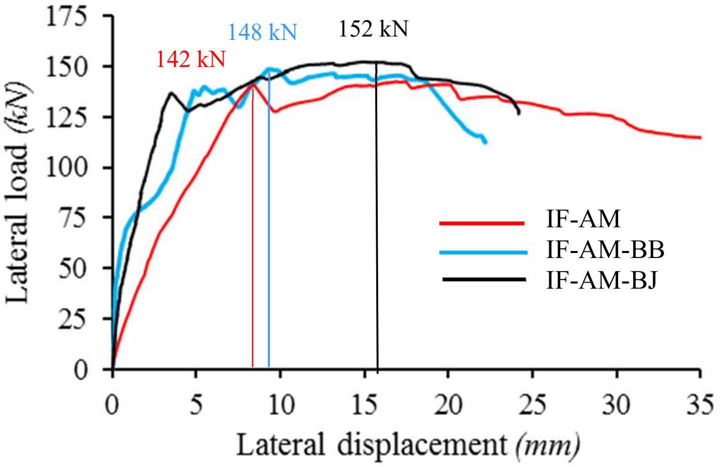
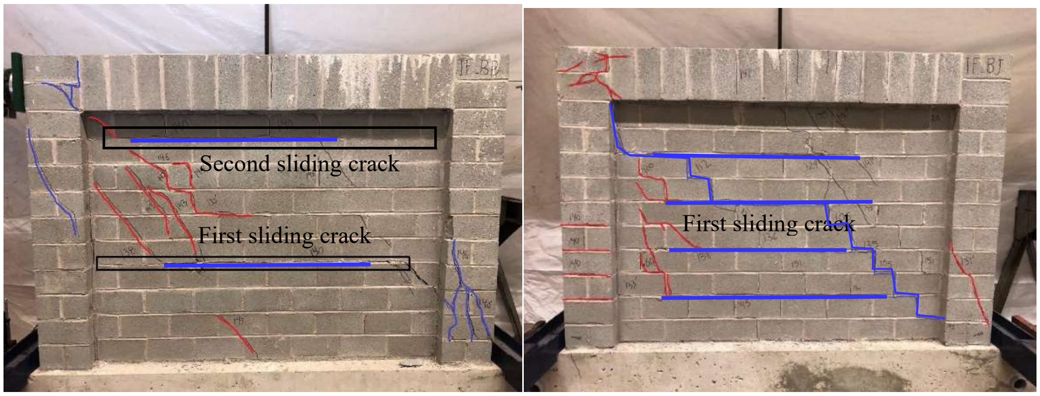


Figure 8: Load-displacement curves for infill reinforcement study

A side-by-side failure mode comparison for the two specimens with reinforcement is shown in Figure 9. Comparing with the failure mode of IF-AM (see Figure 6), the distinctive difference in terms of failure lies in the cracking pattern. While IF-AM sustained mostly diagonal cracking, similar to its IF-RC counterpart, the specimens with horizontal reinforcement showed pronounced sliding failure in the mortar joints, albeit some inclined cracks also occurred. The sliding cracking location was in the vicinity of the reinforcement. It seems to suggest that the reinforcement "arrested" the cracking in the diagonal direction and changed it into sliding. The bond beam specimen also sustained the most severe cracking into the right column.

Horizontal reinforcement is often used in masonry shear walls to increase the shear resistance of the wall. It is thus interesting to observe that the horizontal reinforcement in the infilled frame application did not markedly increase the capacity of the infill, indicating a different failure mechanism between the infill and the shear wall. The failure mode observed herein seems to suggest that in the case of infills, the failure shifted from a predominant diagonal cracking to shear sliding. The horizontal reinforcement is not known to increase sliding capacity.



a) b)

Figure 9: Failure mode: a) IF-AM-BB, b) IF-AM-BJ

CONCLUSIONS

An initial testing of six specimens was conducted to investigate the performance of all-masonry infilled frames under lateral loading. The results were used to compare with the conventional infilled RC frames. The following conclusions were drawn from this study.

The general behaviour of all-masonry infilled frames is similar to infilled RC frames. In particular, the ductile behaviour exhibited by all-masonry infilled frames is comparable to RC frames. The noted difference is in the experimentally observed failure mode. While both types of infilled frames sustained pronounced diagonal cracking within the infill, the final failure of the infilled RC frame was by corner crushing whereas the all-masonry infilled frames by severe diagonal cracking extending into the boundary columns.

The infill reinforcement, whether in the form of joint reinforcement or bond beam, did not have a significant effect on the ultimate strength. However, both specimens with infill reinforcement showed a remarkably higher initial and cracking stiffnesses than the control specimen. In terms of failure mode, infill reinforcement was shown to change the diagonal cracking to shear sliding at courses where the reinforcement was present. The reinforced infilled frame showed greater displacement before reaching the ultimate and more ductile behaviour post-ultimate. Overall, the bed-joint reinforced specimen performed better than the bond beam reinforced specimen.

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