13TH CANADIAN MASONRY SYMPOSIUM
HALIFAX, CANADA
JUNE 4TH – JUNE 7TH 2017

IN-PLANE LOADING TESTS FOR CONFINED AND INFILLED MASONRY PANELS IN RC FRAMES WITH ECCENTRIC DOOR OPENINGS

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ABSTRACT

In-plane static loading tests were performed to study the behavior of masonry panels with eccentric openings. This type of masonry panels is commonly placed at the weak axis of typical low-rise RC street-buildings. Four full-sized specimens were designed with two test factors: the construction type and the presence of openings. Confined and in-filled masonry panels were surrounded by identical RC frames with a non-ductile design to simulate old buildings. A constant vertical force was applied to the specimens during testing. A cyclic lateral load with controlled displacement was applied in a double-curvature manner. The test results showed that the cracking pattern of the masonry panels was affected by the confining condition. Diagonal cracks appeared in the specimens with no openings. In the specimens with openings, cracks occurred along the column-panel interface, and the panels slid due to the lack of confinement around the openings. The type of construction affected the failure mode. The maximum strengths of the confined and in-filled masonry specimens were governed by diagonal tension and bed-joint sliding failure, respectively. The damage behavior of the columns was affected by both the construction type and the openings. Shear failure occurred at the columns in the two specimens without openings and at the column adjacent to the confined masonry panel with openings. The column adjacent to the in-filled masonry panel with openings showed flexural behavior similar to that of the independent columns. The stiffness and strength of the specimens increased, and the deformation capacity decreased when the masonry panels had better confinement.

KEYWORDS: *confined masonry, infilled masonry, in-plane, opening*

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INTRODUCTION

In Taiwan, most of the existing low-rise buildings use RC frames as the skeleton and masonry panels as the partition walls. Before a major revision in the seismic regulations for building codes in 1997, most of the low-rise RC buildings were not constructed with a ductile design. The consideration for masonry panels depended on their construction type. Confined masonry (CM) panels that are constructed prior to the boundary frame and connected to the frame with shear keys are regarded as structural elements. The panels in a CM building should provide 75% of the lateral resistance for the building, and the frame should provide the remaining 25%, in accordance with the building codes. However, CM buildings are not allowed to exceed three stories. When numerous residences were built due to the rapid economic growth in the 1980s, in-filled unreinforced masonry (URM) panels began to be used in place of CM to reduce construction time and meet the demand for higher buildings. These in-filled panels are usually considered to be non-structural and are not included in the structural design. CM buildings are still built currently in rural regions in Taiwan, but they are quite different from the standard CM buildings in Southern Europe, Latin America, and other parts of Asia [1]. Taiwanese CM buildings have larger beam and column sections, typically 300-350mm x 400-450mm. The beam-column joints are moment-connected. There is no requirement for placing tie members around the openings, as required for the standard CM buildings [2].

Figure 1 shows a typical plan for the ground floor of street-buildings in Taiwan. Each single span unit has a main entrance facing the arcade and the street on the west. Therefore, the interior partition walls in the north-south direction usually have eccentric door openings for access. Figure 2 shows an example of this type of partition wall in a street building damaged during the February 6th Meinong earthquake in 2016. Although some of the masonry panels separating two adjacent building units were demolished to create a larger store space, the building was still weaker in the street direction than in the entrance direction. The masonry panels with door openings on the right shown in Figure 2 appeared to be the CM type. A shear crack occurred on the column close to the cracked region on the adjacent panel. This suggests that a panel with an opening can contribute lateral resistance and might affect the behavior of the frame. Figure 2 also shows the strong-beam-weak-column behavior of typical RC buildings in Taiwan. The beams cast along with the slab became relatively stiffer and stronger than the columns. As shown in Figure 2(a), the beam above the damaged masonry panel remained almost intact.

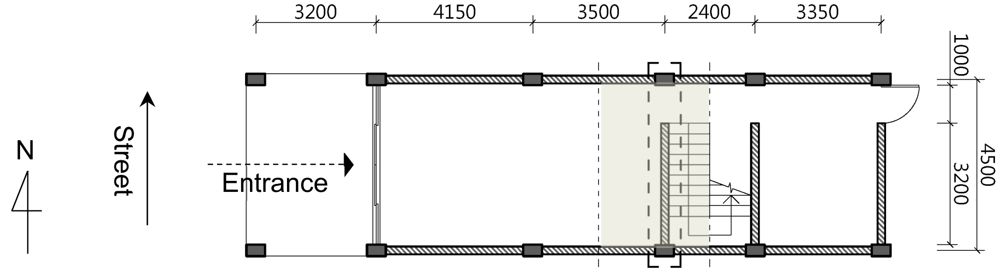
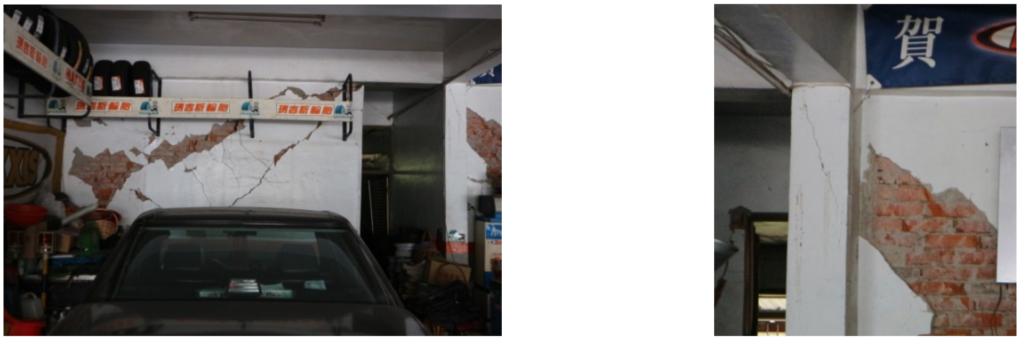


Figure 1: Typical Ground Floor Plan of a Street-building (Unit:mm)



(a) Damaged masonry panel with eccentric door opening (b) Shear crack on the column

Figure 2: A Street-building Damaged During the 2016 Meinong Earthquake

Most of the experimental research on CM panels [3][4][5][6][7][8][9] has been aimed at panels without openings. Yáñez et al. [10] investigated the behavior of sixteen CM specimens with openings of different shapes. There were no confining members around the openings, but a slight reinforcement was placed there instead. More experimental studies can be found on in-filled masonry panels with openings [11][12][13][14]. The experimental results indicated that even with openings, in-filled masonry panels can provide remarkable stiffness and strength contributions to frames.

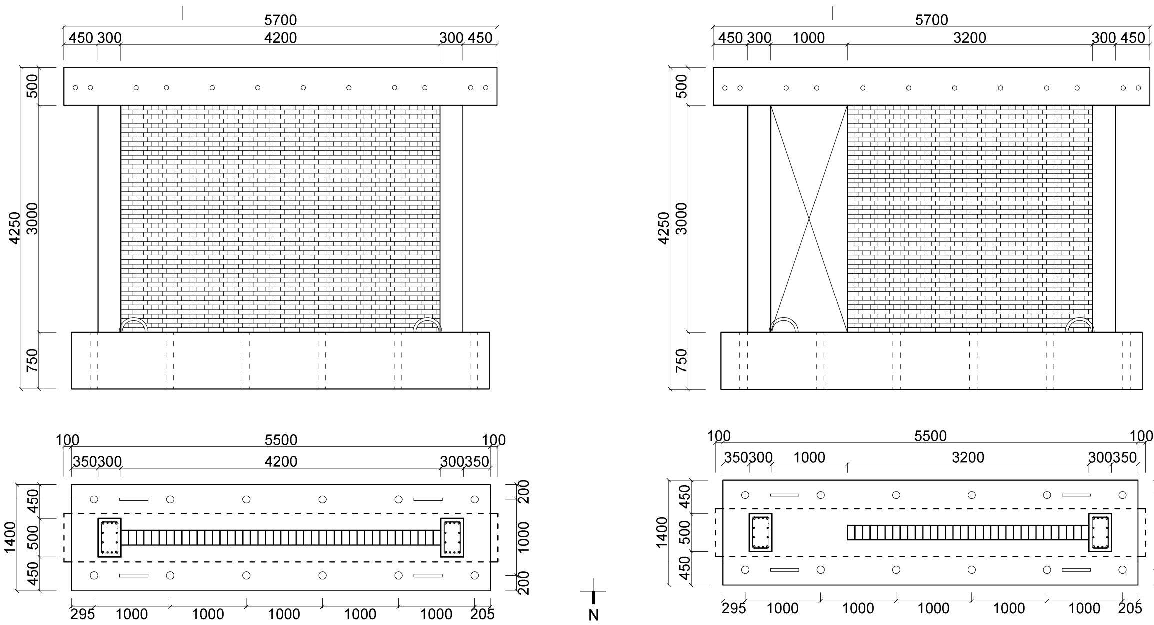
There has however, been no research into the difference between confined and in-filled panels in identical frames. Therefore, the authors performed a series of tests for confined and in-filled masonry panels with centric door and window openings surrounded by portal frames [15]. This paper presents a sequential series of the tests for confined and in-filled masonry panels with and without eccentric door openings. The experimental results are provided and discussed.

EXPERIMENT

Specimens

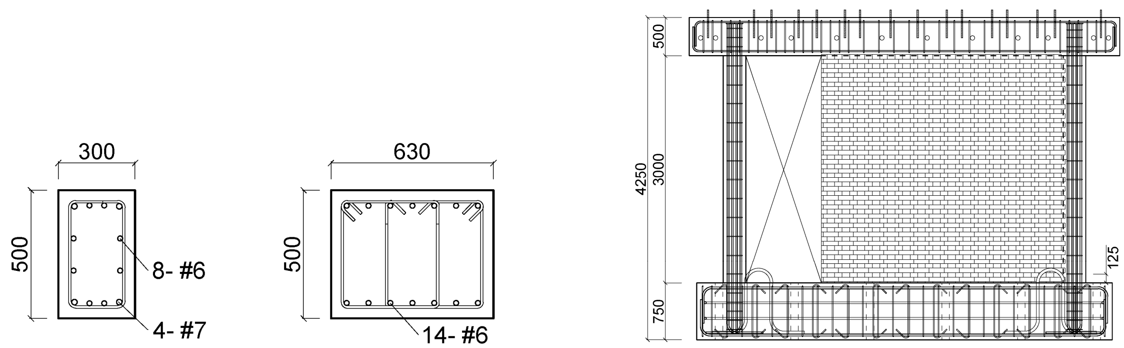
The specimen prototype is a partition wall next to the stairway of a typical street-building, as marked with the dotted square in Figure 1. The test factors included the construction type and the presence of openings. There were four specimens with full-scale double-wythe masonry panels surrounded by identical RC frames. The size of the frame was determined by the average dimensions obtained from a databank of street-buildings [16]. Figure 3 shows the dimensions of the specimens. The two specimens with solid confined and in-filled masonry panels were labeled CS and IS, respectively. The other two with eccentric door openings and confined and in-filled panels were labeled CD-e and ID-e. The confined masonry panels were built prior to the boundary frame with the panel edges adjacent to the columns toothed as shear keys and the panel tops inserted 10-20mm into the beam. The in-filled masonry panels were built after the frames were constructed. The interfaces between the in-filled panels and the frame were only filled with mortar, and there was no shear connection.

Figure 4 shows the frame sections and the reinforcement. In order to simulate the strong-beam-weak-column behavior of existing buildings, the beam sections were purposely enlarged and heavily reinforced. This was intended to limit damage to the panels and the columns. The column sections used #3 hoops with 90-degree hooks and 250mm-spacing to represent the non-ductile designed columns in old buildings.



(a) Specimens CS/IS (b) Specimens CD-e/ID-e

Figure 3: Elevations and Plans of the Specimens (Unit: mm)



(a) Column section (b) Beam section (c) Reinforcement of specimen CD-e

Figure 4: Frame Sections and Reinforcement of the Specimens (Unit: mm)

Loading and Test Apparatus

Figure 5 shows the test apparatus. Displacement-controlled lateral cyclic loading with increasing drift was applied in the in-plane direction. Each drift was loaded for three cycles. The loading was terminated when the specimen lost vertical load-carrying capacity after the resistance force was decreased to less than 85% of the maximum strength. In order to simulate the shear-building behavior of typical low-rise RC buildings subjected to lateral load, two vertical actuators were installed on both sides of the specimen. They provided vertical compression that simulated the dead load plus a force couple that kept the top beam from rotating. A steel beam and lead mass blocks were fixed on the top of the specimens to increase the stiffness of the RC top beam. The weight of the steel beam and mass blocks plus the forces from the vertical actuators provided a constant vertical load of 390.68 kN during the test. This represented the dead load carried by the prototype frame in a three-story building, as calculated based on the shaded area shown in Figure 1. Vertical displacement gauges were installed on the top beam to monitor its rotation. Horizontal displacement gauges were installed at different heights along the columns and vertical edges of the opening to measure the deformation patterns. Strain gauges were attached to the longitudinal steel and hoops to study the stress condition in the columns. Angle gauges were installed at the top and bottom ends of the columns to measure the rotation at the column ends.

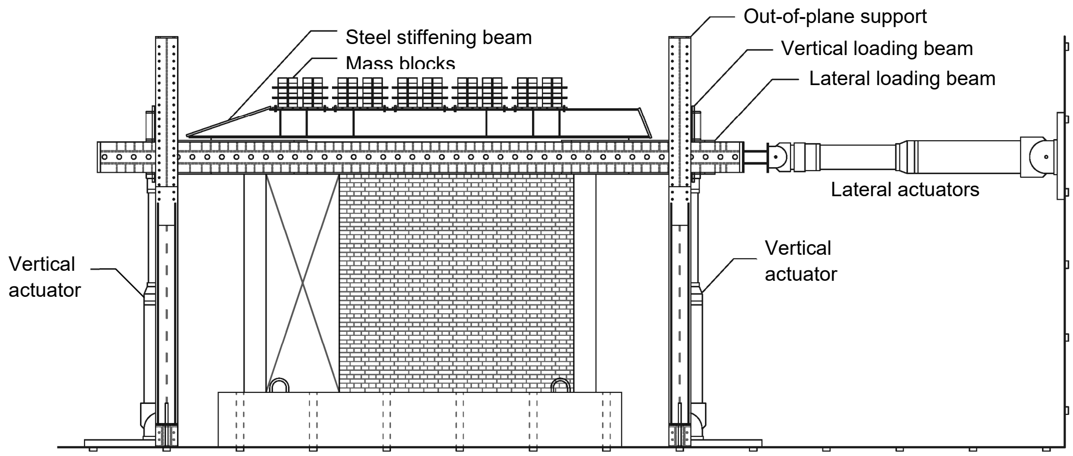


Figure 5: Test Apparatus

Materials

Cement mortar and solid clay brick were used in the masonry panels. The material tests include the tension tests for the steel, compression tests for the bricks, mortar, prisms with five bricks, and concrete cylinders, bed-joint shear tests with masonry triplets, and diagonal tension tests of 1200mm x 1200mm x 200mm masonry plates in accordance with ASTM E519. The averaged test results are summarized in Table 1. Figure 6 shows the masonry triplet for the bed-joint shear test with zero compressive stress in accordance with the test method suggested by Drysdale [17]. Figure 7 shows one of the diagonal tension test specimens.

Figure 6: Masonry Triplet

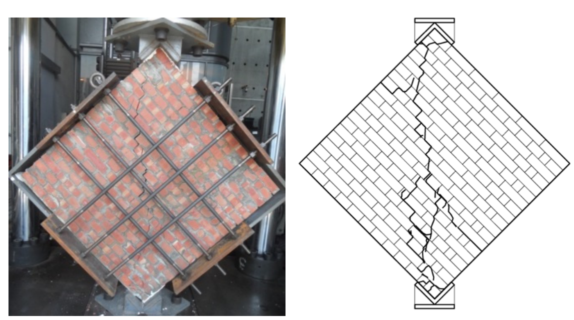


Figure 7: Diagonal Tension Test Specimen

Table 1: The Material Strength (Unit: MPa)

Specimen	Steel			Concrete	Masonry				
	Yield stress			Compressive strength	Compressive strength			Bed-joint shear strength	Diagonal tensile strength
	#3	#6	#7		Brick	Mortar	Prism		
CS, CD-e	377.4	463.5	483.9	33.85	23.88	24.79	15.50	0.82	1.034
IS, ID-e	377.4	463.5	483.9	33.85	23.88	14.10	21.32	1.21	1.034

TEST RESULTS

Figure 8 shows the lateral load-displacement relationships. The crack patterns after the specimens exhibited maximum strength in both loading directions (push and pull) are shown in Figure 9. Figure 10 shows the test specimens at the end of the tests. The drifts at maximum strength and the end of the test were different in each specimen due to differences in the failing behavior. Diagonal cracks that went across the panel centers formed in both solid panel specimens when they exhibited maximum strength. Cracks on the panels with openings appeared either near the edges (CD-e) or on the interfaces between the panel and the frame (ID-e). The overall behavior of each specimen is described below.

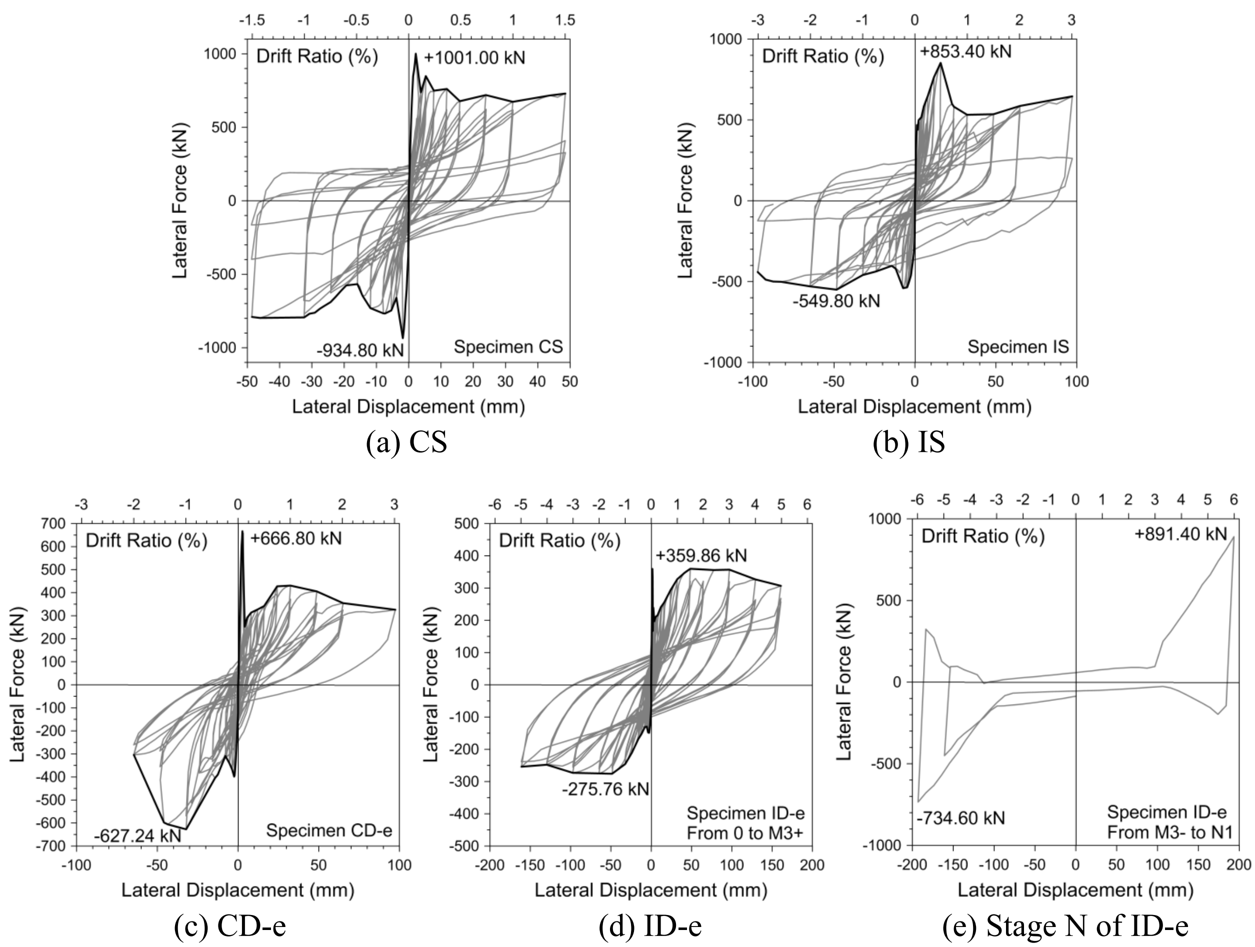
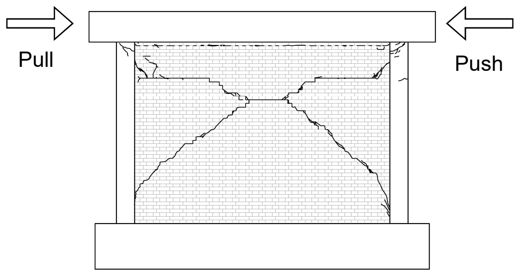


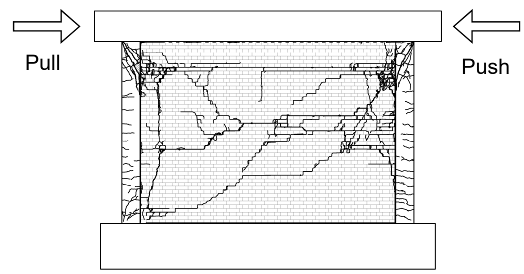
Figure 8: Lateral load-displacement relationships

Confined Masonry Specimen with Solid Panel (CS)

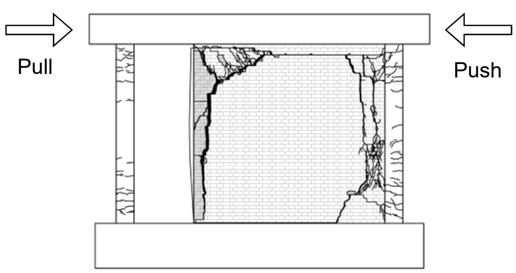
Specimen CS reached maximum strength in both push (+) and pull (−) directions at the first loading stage and showed symmetric diagonal cracks across the panel. Shear cracks that appeared to be an extension of the panel cracks also formed on the column top ends. The panel segment above the diagonal cracks then slid along the bed-joints, accompanied by multiple small cracks appearing at the ends of the diagonal cracks, and horizontal cracks formed on the outer side of columns. The diagonal cracks kept extending into the columns. Yielding of the column hoops occurred at about 0.2% drift when widening of the shear cracks on the columns was observed. The lateral resistance at this state was lower than the maximum strength but remained at a stable value for several loading stages. The loading terminated when both top ends and one bottom end of the columns obviously failed due to extensive shear and brick crushing.



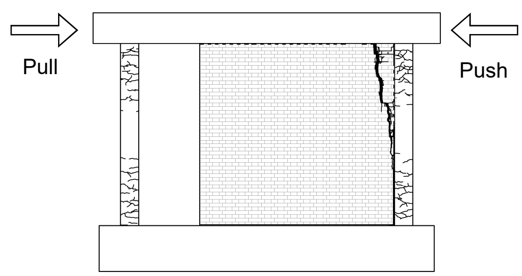
(a) CS (−0.081%)



(b) IS (−1.499%)



(c) CD-e (−0.995%)

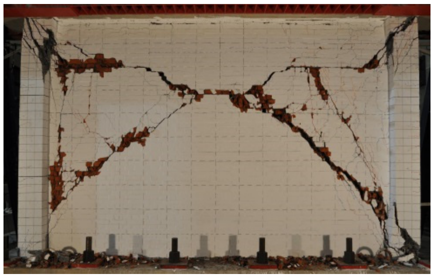


(d) ID-e (−1.504%)

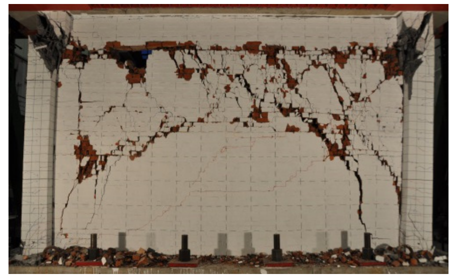
Figure 9: Crack Patterns at Maximum Strength

In-Filled Masonry Specimen with Solid Panel (IS)

A horizontal crack across the length of the entire panel occurred at the seventh bed-joint from the top during the first loading stage. The panel segment above the bed-joint crack then slid along with the lateral loading. The portion below the crack remained stable and restrained the deformation of the lower parts of the columns like a high windowsill. This semi-short-column effect only occurred when the columns deformed inward of the frame and caused shear cracks on the column top ends. When the specimen reached maximum strength in the push (+) direction, a diagonal crack cut across the lower portion of the panel and appeared to be connecting with the shear crack on the top end of the pushing column. The lateral resistance then dropped but remained at a stable value in the following loading stages. The maximum strength in the pull (−) direction also showed as a reversed diagonal crack occurred across the lower portion panel. The two diagonal cracks shared a common horizontal section of bed-joint in the middle. This might explain why the maximum pull strength was lower than the maximum push strength.

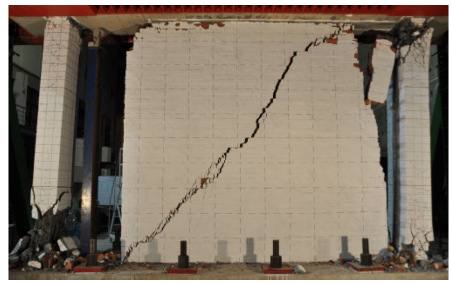


(a) CS (−1.505%)



(b) IS (−3.008%)

(c) CD-e (+3.016%)



(d) ID-e (+5.990%)

Figure 10: The Specimens at the End of the Tests

Confined Masonry Specimen with Eccentric Door (CD-e)

In the case of the specimen CD-e, the maximum strength in the push (+) direction showed in the first loading stage, when a horizontal-inclined crack cut across the upper portion of the panel. The crack that started from the column-panel interface went along a bed-joint close to the panel top and then inclined toward the opening edge until it reached it. A vertical crack showed near the panel-column interface when the loading was in the pull direction in the first loading stage. The vertical crack then extended to the entire height of the panel and separated the panel from the column. In the following stages, the panel slid to the opening when it was pushed by the column and slid back slightly when it was pulled by the top beam due to friction along the bed-joints. Local inclined and split cracks appeared on the panel at the top corner near the opening when the maximum strength in the pull (−) direction occurred. The top corner segment cut by the previous horizontal-inclined crack then collapsed. Another steep, inclined crack appeared at the half panel close to the column, indicating that a new equivalent strut had formed in the remaining panel. The load-displacement relationships in the push and pull directions were not identical.

The behaviors of the two columns were different. The column adjacent to the panel had more flexural cracks on the outer edge and was seriously damaged by shear at the top end when the test was terminated. The independent column was only cracked by flexure.

In-Filled Masonry Specimen with Eccentric Door (ID-e)

In specimen ID-e, instantaneous peak resistance showed at the beginning of the test when the interfaces between the panel and the frame were all cracked. The panel then kept sliding to the opening when it was pushed by the column and did not slide back when the loading changed direction in the following stages. It appeared that the panel did not restrain the adjacent column. The two columns showed identical crack patterns and damage modes. The maximum strengths in the push (+) and pull (−) direction occurred in the loading stage when split cracks occurred on the compressive edges of the column ends. The integrity of the panel remained, and the panel slid to the opening when the columns exhibited the ultimate flexural state. It seemed that the one-way interaction between the panel and the push-side column caused a constant difference in the lateral resistance between the push and pull load-displacement relationships. The columns were failed by shear after they exhibited flexural ductility. During the final loading stage (stage N), both of the columns lost vertical load-carrying capacity. The vertical load was then carried by the masonry panel, which suddenly split along the compression diagonal after showing exceptionally high strength, as shown in Figure 8(e).

COMPARISON AND DISCUSSION

Figure 11 shows a comparison of the load-displacement envelopes for the four specimens. The unusual last cycle of specimen ID-e is excluded. All the specimens showed higher strength under push loading. The lateral strength in sequence was CS>IS>CD-e>ID-e, where the initial stiffness exhibited the same trend. The deformation capacity in sequence was ID-e>IS>CD-e>CS.

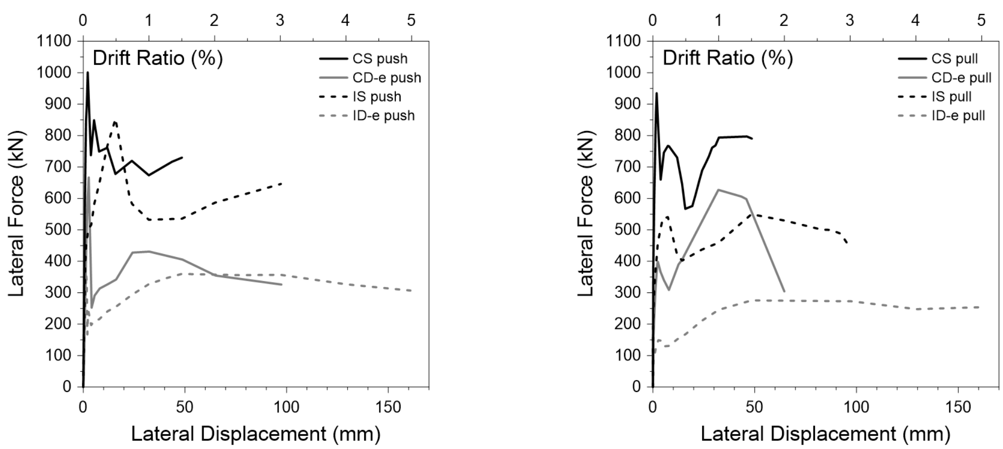


Figure 11: Comparison of the Load-Displacement Envelopes

Effect of the Opening

The specimens with solid panels showed higher strength and initial stiffness and lower deformation capacity than the specimens with openings. The differences were more obvious in the case of the in-filled masonry specimens. The crack patterns and behavior of the panels were apparently affected by the confining condition. Both solid panel specimens developed symmetrical diagonal cracks. The panels with openings cracked at the panel-frame interfaces and slid due to the absence of a confining member on the opening side. There was also a difference in the structural behavior when the loading changed direction.

Comparison of Confined and In-Filled Masonry Specimens

With or without openings, the confined masonry specimens showed higher strength and initial stiffness and lower deformation capacity than the in-filled masonry specimens. The difference in construction type also affected the failure mode. The maximum strengths of the confined masonry specimens were revealed when the panel was cracked due to diagonal tension that occurred at an early stage. However, the maximum strengths of the in-filled masonry specimens were governed instead by bed-joint sliding after the horizontal crack formed. The diagonal cracks in specimen CS extending into the columns suggested that the columns and the confined masonry panel behaved as a composite section. Diagonal cracks also occurred in specimen IS, but they were limited within the panel. The columns separated from the in-filled panels when they deformed outward, which resulted in better ductility for the in-filled masonry specimens. The differences between the two specimens with openings were more obvious when the loading was pulling. This indicated that the confined masonry panel was connected better to the top beam and was therefore able to contribute higher resistance.

Column-Panel Interaction

The behaviors of the columns were affected by both the construction type and the presence of openings but the greatest role was played by the latter. The columns had more restraint from the solid panels since the movement of the panels was also better confined. The restrained columns tended to be failed by shear, which resulted in decreases in the deformation capacity.

CONCLUSIONS

This paper presents a series of cyclic load experiments for confined and in-filled masonry panels with and without openings surrounded by moment-connected RC frames. The effects of the construction type and the presence of openings were discussed. The test results suggested that the effect of an opening is greater than that of construction type. The lack of confinement around the opening caused differences in the panel behavior and the panel-frame interaction. When the panels were better confined, the strength of the specimen increased, but the deformation capacity decreased. The specimens with openings showed asymmetric behavior under cyclic loading. The difference between the two loading directions was more obvious in the in-filled panel specimen with an opening because the panel-frame connection was weaker than that of the confined panel. The good performance in terms of both the strength and stiffness of the confined masonry specimen with no opening indicated that the CM panels are quite effective in resisting lateral load. Although the in-filled panel specimen with an opening showed the lowest lateral strength, it also allowed the columns to display ductility before shear failure. This suggests that an in-filled panel might become a useful seismic element if it is properly retrofitted.

ACKNOWLEDGEMENTS

The research was funded by the National Center for Research on Earthquake Engineering (NCREE). The authors gratefully acknowledge the NCREE staff for supporting the experiment.

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