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EXPERIMENTAL INVESTIGATION OF SEISMIC PERFORMANCE OF REINFORCED BRICK MASONRY INFILLED REINFORCED CONCRETE FRAMES WITH A CENTRAL OPENING

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ABSTRACT: This paper discusses the experimental results for defining the seismic performance of the brick masonry infilled reinforced concrete (RC) frame with a central opening under lateral static reversed cyclic loading. The influence of the presence of the rebar reinforcements on the opening interface to the masonry is compared to the opening without rebar reinforcement. In this study, six of 1/4 scale-down of single-story single-bay RC frame specimens have been constructed and tested. These specimens included one bare RC frame, one unreinforced brick masonry infilled RC frame, two unreinforced brick masonry infilled RC frames with a central opening and two brick masonry infilled RC frames with a central opening embedded with 2Ø6 horizontal steel reinforcements above and below of the opening. The ratios of opening size to the panel area of the infilled specimens were 25% and 40%. The experimental results confirm that the existence of the opening reduces the stiffness, the lateral strength and energy dissipation of the RC infilled frame system. However, the infilled frames with 25% and 40% opening ratios show better performance compare to bare frame specimen. Although the strengthening by using embedded rebars does not significantly increase the performance of the RC frame system, the brick infill with horizontal reinforcements installed above and below the opening was verified to resist large deformation of masonry infill in out of plane direction.

Keywords: Brick wall with opening, Lateral strength, Reinforced concrete frame, Reinforced masonry infill, Stiffness

1. INTRODUCTION

Contributions of brick masonry infills have been ignored for seismic design of buildings in many countries. It seems because of deficiency of understanding on seismic performance of brick infills under seismic loads. Several studies have been performed by researchers for evaluating the effects of masonry infill on the seismic performance of RC frame buildings [1]-[5].

The first author has been conducted a series of studies related to RC frame structure with brick masonry infills [4]-[7]. A field investigation after the 2007 Sumatra earthquake in Padang city and nearby was conducted by the first author for evaluating the damage RC building with unreinforced brick masonry infill as reported in [4]. It was found that brick infill contributed to resist the seismic load in the RC building, and it made the building can survive during the earthquake. Further, the author performed a series of experimental test on RC frames with and without brick infill under reversed cyclic lateral loading. The test results revealed that brick infill increases the lateral strength and stiffness of the whole structure however it decreases ductility of structure [5]. Different failure modes of column element between the bare frame and infilled frame structures were observed during the experimental tests. Moreover, an analytical method was developed to calculate the lateral strength of infill in the elastic range based on the diagonal compression strut concept. In this method, the lateral force of infill can be derived as a function of strut width [6,7]. The proposed analytical model has successfully been verified through experimental results of brick infilled frames mentioned above.

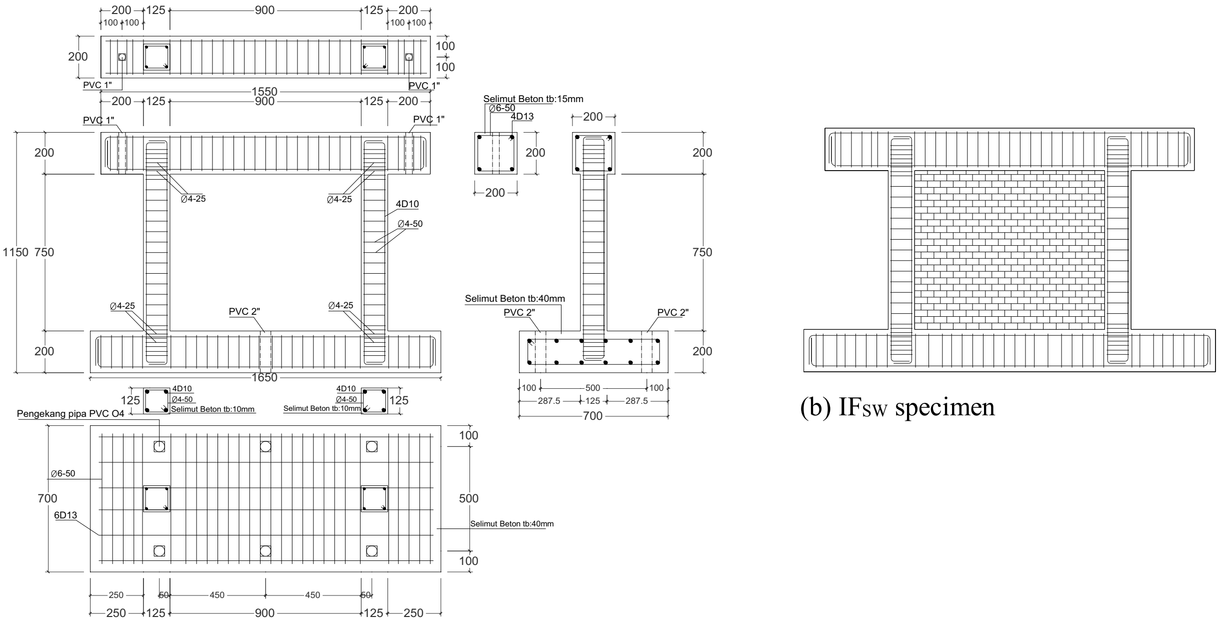
All the past studies mentioned above are focused only on the performance of RC frames with fully brick infills and neglected the presence of infills with openings assuming no contribution from infills with openings on seismic performance of RC frame [8]. However, a lot of studies reported that masonry infills with the opening may reduce the lateral strength and stiffness of infilled frame structure in which it depends on area and location of the opening in panel wall [9]-[12]. This circumstance revealed that the seismic behavior of the infilled frames with openings still was not well-known. Two laboratory tests were carried out by the authors on brick infilled frames with openings through monotonic and reversed cyclic lateral tests, respectively [9,10]. The results disclosed that the openings in brick-masonry infills control the failure mechanism, the lateral strength and the stiffness of the overall structure. Failure of infill occurred at the corners of openings as the weakest part of the panel.

In the current study, the behavior of RC frames with brick infills with a central opening with embedded rebars reinforcements horizontally located above and below openings was investigated through lateral static reversed cyclic loading tests.

2. EXPERIMENTAL PROGRAM

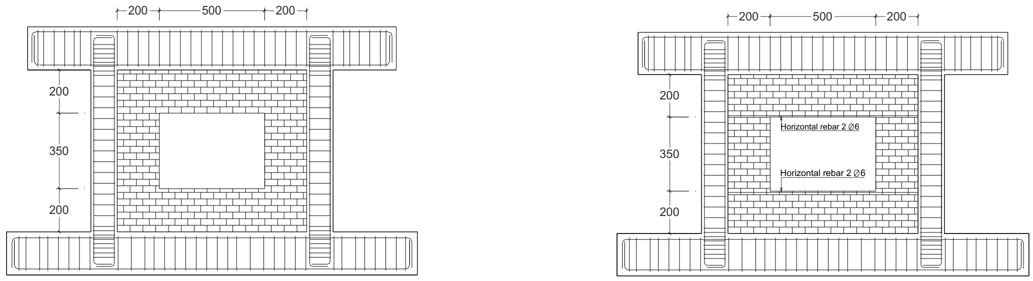
2.1 Test Model

Six of 1/4-scaled-down of single bay and single story RC frame specimens have been constructed, i.e. bare RC frame (BF), RC frame with fully brick infill (IFSW), RC frames with brick infills having a central opening in ratio of the opening of 25% without reinforcements (IF$_{O-1}$) and with reinforcements (IF$_{OR-1}$), and RC frames with infills having a central opening in ratio of the opening of 40% without reinforcements (IF$_{O-2}$) and with reinforcements (IF$_{OR-2}$) as exhibited in Fig.1.



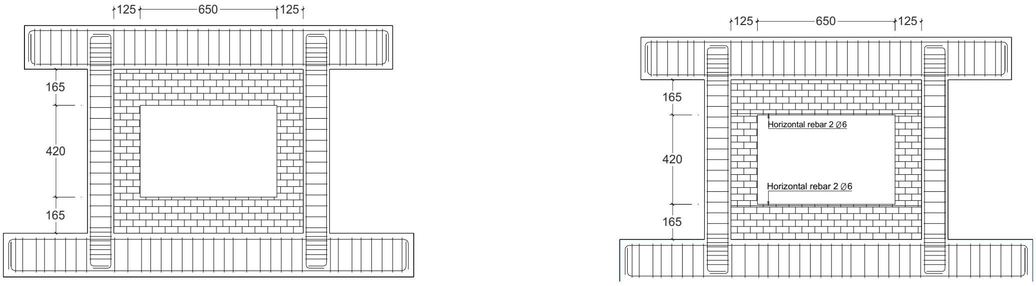
(a) Bare frame specimen

(b) IF$_{SW}$ specimen



(c) IF$_{O-1}$ specimen

(d) IF$_{OR-1}$ specimen



(e) IF$_{O-2}$ specimen

(f) IF$_{OR-2}$ specimen

Fig. 1 Detailed drawing of the specimen

All RC frame specimens were constructed in identical dimensions in which the detailing of the structures represents the first story of typical Indonesian low-rise RC buildings. The cross-sections and reinforcements' arrangement of frame elements are shown in Fig. 1(a). The figures 1(b) to 1(f) show the specimens of IF$_{SW}$, IF$_{O-1}$, IF$_{OR-1}$, IF$_{O-2}$, and IF$_{OR-2}$, respectively. The parameters studied in this experimental evaluation were influence of ratio of opening size to panel wall area, α, of 25% and 40% and effects of 2Ø6 reinforcements horizontally embedded below and above the openings. No shear connectors were used between columns and infills. Table 1 summarized the specimens and their variance. Brick units of 1/4 scale clay bricks of dimensions of 60 mm in length, 30 mm in width and 13 mm in height and mortar beds with the composition of cement: water = 1: 0.5 were used to construct the infills. The wall surfaces were plastered with mortar of 5.0 mm in thickness.

Table 1 Experimental parameters of the specimens

Specimens	Column	Brick infill	
		α (%)	Rebars
BF	cross-section: 125x125 main bar: 4D10 hoop: 2-Ø4-50	0	-
IF$_{SW}$		0	-
IF$_{O-1}$		25	-
IF$_{OR-1}$		25	2Ø6
IF$_{O-2}$		40	-
IF$_{OR-2}$		40	2Ø6

2.2 The Material Properties

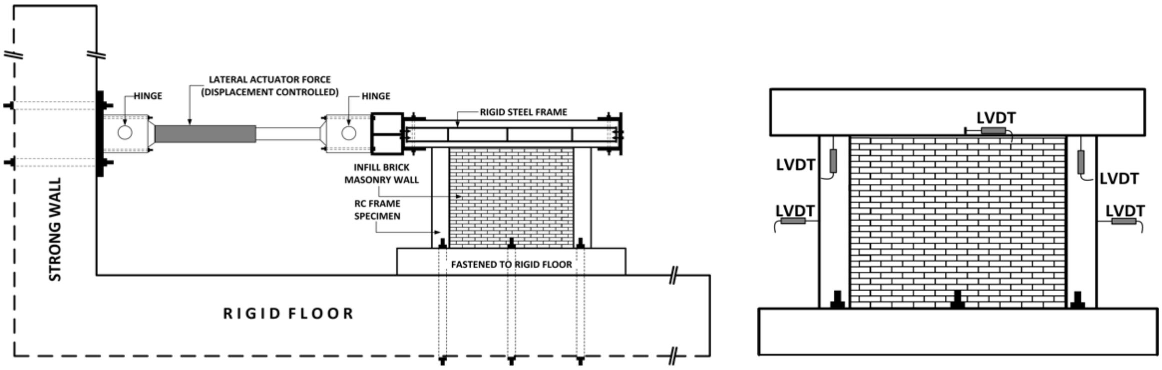
The mechanical properties were the same for all specimens which were obtained through material samples tests. The compressive strengths of concrete and brick masonry prism were 49.9 N/mm^2 and 13.0 N/mm^2, respectively. The yield strengths of reinforcements were 390.2 N/mm^2, 346.8 N/mm^2, 462.0 N/mm^2, and 421,1 N/mm^2 for rebars of Ø4, Ø6, D10, and D13, respectively. The tensile strengths of reinforcements were 598.3 N/mm^2, 448.6 N/mm^2, 619.7 N/mm2 and 582.4 N/mm^2 for rebars of Ø4, Ø6, D10, and D13, respectively. The average compressive strength of brick was 10.9 N/mm^2.

2.3 Loading Method and Measurement

The structural tests were conducted at the Structure and Construction Material Laboratory of Civil Engineering Department, Syiah Kuala University, Banda Aceh, Indonesia. The specimen was subjected to reversed cyclic lateral loads as shown in the schematic of the test setup and loading system in Fig. 2(a).

The horizontal and vertical displacements of the specimens were measured with transducers in several positions on specimens as shown in Fig. 2(b). The applied loads, as well as the displacements, were monitored throughout the tests. To identify the failure process and mechanisms of specimens, initiated cracks and crack propagation were marked on the specimens at the peak and residual drifts in each loading cycle.

Figure 3 shows the loading history of cyclic loading which was referred to [13]. The drift angel R used to control the incremental lateral load applied on specimens was an initial cycle to R=1/800 and then followed by two cycles to R=1/400, 1/200, 1/100, 1/50, 1/25, 1/12.5 and 1/10. If the specimens failed before the final cycles, the loading was stopped.



(a) Actuators set up

(b) Transducers set up

Fig. 2 Schematic view of the test setup

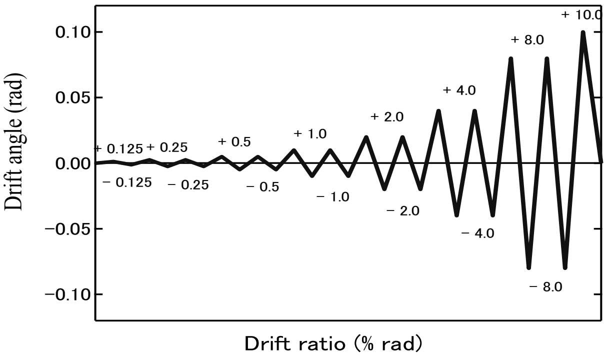


Fig. 3 Loading history

3. TEST RESULTS AND DISCUSSION

3.1 Failure Process and Mechanism

The failure process and mechanism for all specimens were investigated during experimental works and described as follow.

3.1.1 BF specimen.

The initial flexural crack was detected during the cycle to R=1/400 at the top of the tensile column at the lateral displacement of 1.2 mm and the initial shear crack appeared during the cyclic to R=1/200 at 3.8 mm lateral displacement at the bottom of the compressive column. The cracks developed during the next cycle loading. During the cycle to R=1/12.5, the compressive column failed in shear at 58.8 mm lateral displacement. Soon after the shear failure of both columns, the lateral strength significantly degraded. Fig 4(a) shows the form of BF specimen under the cyclic loading to drift angle 1/50 rad.

3.1.2 IF$_{SW}$ Specimen.

The separation crack was discovered between column and wall at loading cycle of R=1/800. Initial flexural and shear cracks were found out at the tensile column during the cycle to R=1/400 at the lateral displacements of 1.3 mm and 1.6 mm, respectively. The initial diagonal shear crack was observed during cycle to R=1/200 at 3.4 mm displacement at the center of the panel wall. Shear failure of brick wall occurred during the cycle to R=1/50, and then the lateral strength degraded significantly. After the failure of the brick wall in out of plane direction, the boundary column failed in shear at the cycle of R=1/12.5. The crack pattern of the IF$_{SW}$ specimen at cycles of 1/50 rad is shown in Fig. 4(b).

3.1.3 IF$_{O-1}$ Specimen.

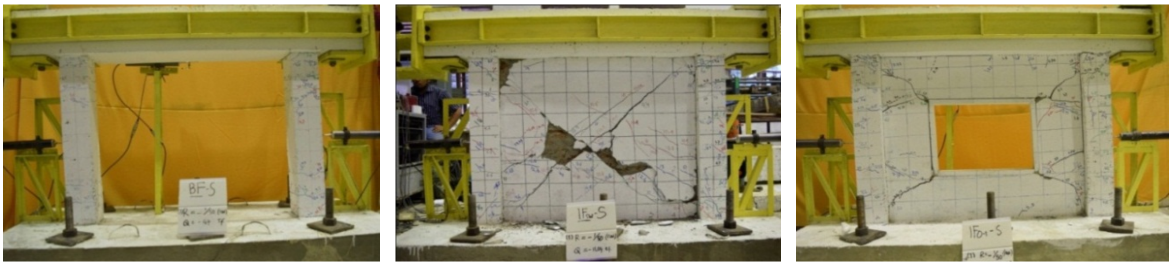
The shear cracks in infill existed at the top left corner of the opening and the bottom right corner of the opening at a displacement of 0.45 mm during the first cycle of loading. Initial flexural crack at the tensile column occurred at 1.9 mm displacement during the cycle to R=1/400. The initial shear crack appeared at the tensile column at 3.5 mm displacement during the cycle to R=1/200. The infill wall failed in shear at the corner of opening at the cycle of R=1/25 and column failed in shear at the cycle of R=1/12.5. The condition of the IF$_{O-1}$ specimen at the cycle to R=1/50 rad is presented in Fig. 4(c).

3.1.4 IF$_{OR-1}$ Specimen.

Initial shear crack at the left corner of the opening and initial flexural crack above the opening of infill was observed at 0.75 mm displacement during the cycle of R=1/800. Initial flexural crack was observed at the tensile column at the displacement of 1.7 mm during the cycle to R=1/400. The initial shear crack appeared at the tensile column at the displacement of 3.8 mm during the cycle to R=1/200. During the subsequent cycles, flexural cracks at along height of both columns and shear cracks at the bottom of the compressive column were developed. Shear cracks propagated in infill at the left and right sides of the opening and below the opening. Shear failure of tensile column occurred at the cycle of 1/12.5. Infill failed in out of plane direction at the cycle of 1/10. Fig. 4(d) shows the condition of the IF$_{OR-1}$ specimen during the cycles to R=1/50 rad.

3.1.5 IF$_{O-2}$ specimen.

During the first cycle of loading, it was found out the initial flexural crack at the tensile column at 0.4 mm displacement and the initial shear crack in infill at the left top corner of the opening at the displacement of 0.8 mm. During the cycle to R=1/200, the initial shear crack at the top of the tensile column has appeared at 2.4 mm displacement. Shear failure of the bottom compressive column occurred during the cycle to R=1/12.5 followed by failure of the wall in out of direction. The condition of the IF$_{O-2}$ specimen under cycle to 1/50 rad is displayed in Fig. 4(e).



(a) BF specimen (b) IF$_{SW}$ specimen (c) IF$_{O-1}$ specimen

(d) IF$_{OR-1}$ specimen (e) IF$_{O-2}$ specimen (f) IF$_{OR-2}$ specimen

Fig. 4 Specimen at drift angle, R=1/50

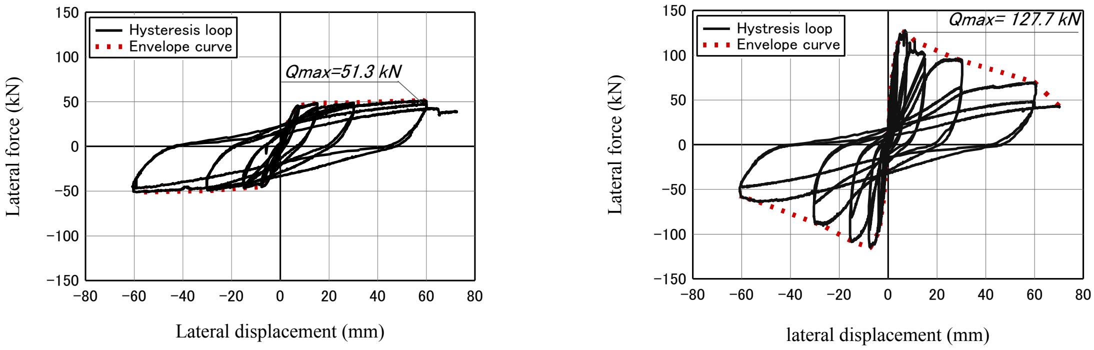
3.1.6 IF$_{OR-2}$ Specimen.

During the cycle of R=1/800, initial flexural and shear cracks in infill were detected at the top left corner of the opening at 1.4 mm displacement. Initial flexural crack at the top of the tensile column was observed at the displacement of 1.1 mm during the cycle to R=1/400. The initial shear crack appeared at the top of the tensile column at the displacement of 2.9 mm. At the subsequent cycles, propagation of flexural and shears cracks in both columns and development of shear cracks at the left side was noticed. The top of the tensile column failed in shear during the cycle to R=1/12.5. Moreover, brick infill failed in out of plane direction at the cycle of R=1/10. Fig. 4(f) shows the condition of the IF$_{OR-2}$ specimen under the cycle to 1/50 rad.

3.2 Comparison of the Seismic Performance

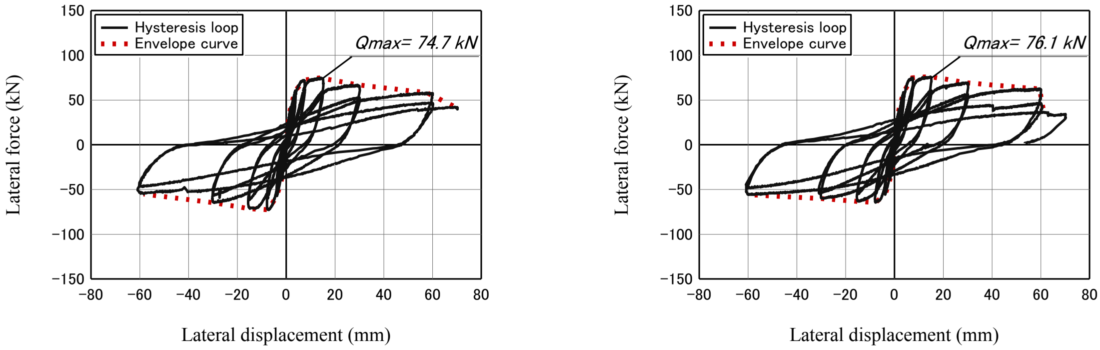
Figure 5 shows the relationship between lateral force and lateral displacement in hysteresis loops and envelop curves to indicate the seismic performance of specimens. The bare frame (BF) and fully brick infilled frame (IF$_{SW}$) specimens achieved their maximum lateral strength of 51.3kN and 127.7kN at the 57.8 mm and 7 mm displacements, respectively.

In the cases of the infilled frames with opening specimens, the maximum lateral strength of 74.1kN, 76.1kN, 61.5kN and 60.4kN at 14.0 mm, 14.8 mm, 14.9 and 13.9 mm of the lateral displacements for IF$_{O-1}$, IF$_{OR-1}$, IF$_{O-2}$, and IF$_{OR-2}$, respectively. It revealed that the presence of the center opening reduces the lateral strength and stiffness of the overall infilled frame structure. The fully brick infilled increase the lateral strength of the RC frame about 2.5 times compared to the bare frame. The opening ratios of 25% and 40% in infill decrease the lateral strength of the fully brick infilled frame to 0.59 times and 0.48 times, respectively. However, the lateral strengths of infills with opening rations of 25% and 40% were higher 1.4 times and 1.2 times than that of the bare frame, respectively. According to A comparison of seismic performance shown in Figs. 5(c), 5(d), 5(e) and 5(f), it seems that the horizontal reinforcements installed under and above the opening were ineffective to increase the lateral strength of the overall structure. These reinforcements effectively controlled the growth of the shear cracks at the corners of the opening and contributed to preventing the failure of the infill in out of plane direction. The deformation capacities of the structures, which were determined when the lateral force degraded to 80% after the maximum of the lateral force, were reached at displacements of 63.0 mm for BF, 27.7 mm for IF$_{SW}$, 57.7 mm for IF$_{O-1}$, 59.5 mm for IF$_{OR-1}$, 69.6 mm for IF$_{O-2}$ and IF$_{OR-2}$ specimens. It indicates that the infilled frames with the central opening more ductile than the fully infilled frame. However, the reinforced opening infills were not more ductile than unreinforced opening infills.



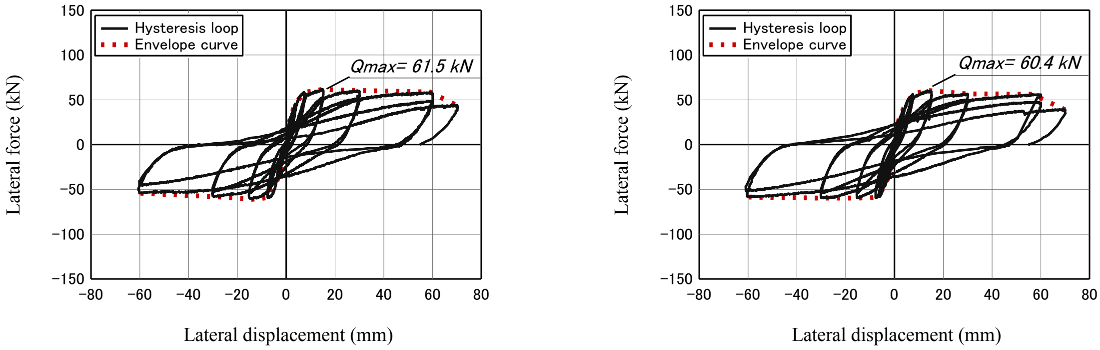
(a) BF specimen

(b) IF$_{SW}$ specimen



(c) IF$_{O-1}$ specimen

(d) IF$_{OR-1}$ specimen



(c) IF$_{O-2}$ specimen

(d) IF$_{OR-2}$ specimen

Fig. 5 Lateral strength-displacement relationship.

3.3 Energy Dissipated

The energy on frame structure due to the seismic force can be dissipated by the response of the hysteresis loop without a significant reduction in strength of structure [14]. Therefore, the area enclosed by the hysteresis loops indicated in Fig. 5 can be evaluated to represent the energy dissipated of the specimen. The comparisons of the cumulative energy dissipation for all specimens are presented in Fig. 6. The figure exhibits that the dissipated energy of the infilled frame decreased as opening existed in the infill. The energy dissipation of the infilled frame with the opening ratio of 40% was almost the same as that of the bare frame. In the case of infilled frames with embedded rebar reinforcements, their energy dissipations were relatively the same as that of unreinforced ones.

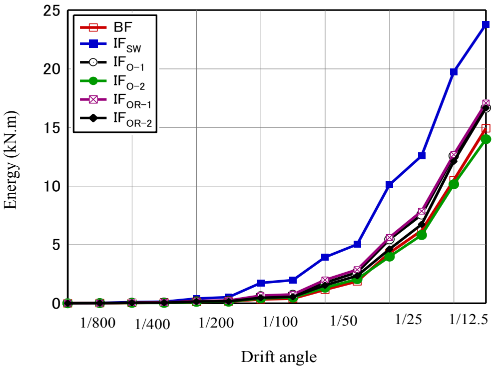


Fig. 6 Cumulative energy dissipated of specimens

4. CONCLUSION

The laboratory tests of the brick infilled RC frame with the central opening with/without reinforcements above and under the opening have been carried out under lateral static reversed cyclic loading to assess their seismic performance. As the results, the presence of the central opening on the infill reduces the lateral strength and energy dissipation when it was compared to the fully infilled frame. The horizontal reinforcements embedded in infill above and under the opening were ineffective to increase the lateral strength and energy dissipation, however, it verified to resist large deformation of masonry infill in out of plane direction.

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