The seismic responses of RC frames infilled with full and partial masonry walls under cyclic lateral load

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Abstract. This paper presents the seismic responses of full and partial brick masonry infilled frames under lateral load. Four test specimens of ¼ scale-down single-story single-bay, including one RC bare frame, one RC frame with a full brick masonry wall, and two RC frames with partial brick masonry walls were tested under quasi-static cyclic loading. During the tests, initial crack, cracks propagation, and failure processes of specimens were monitored. Lateral forces and displacements in-plane direction at several points on specimens were recorded. Consequently, it was found the differences of seismic responses between a bare frame, fully masonry infilled frame, and partially masonry infilled frames. Installing full or partial masonry infills in the RC frames structure can change the failure mechanism, increase the lateral strength and stiffness, but decrease the ductility performance of the whole structure.

1. Introduction

According to the strong earthquakes that have been struck Indonesia in the last decades, such as the 2009 West Sumatera earthquake [1], 2016 Aceh earthquake [2], and 2018 Palu-Sulawesi earthquake [3], many elements of RC frame buildings including the infills were damaged during these events. Observation after the Palu earthquake shows the damage of the RC buildings includes the failure of the beam-column joints, shear and flexural failures of the columns, and shear failure of the short columns. The authors conducted the observation on October 4-6, 2018 [3], after the Palu earthquake in September 2018. The low-quality of the construction materials, improper construction techniques, poor reinforcement detailing, and inappropriate placement of non-structural elements like masonry infill walls were identified as the reasons for damage to these RC buildings. The authors also observed the damage modes of the bare frame as well as the partially infilled of the RC frame structures. The partially brick masonry infill contributes a large shear force to the columns along with the end of infill height.

The burned clay bricks are known as the material for masonry walls, which are very commonly used as infill as well as for partition for low and middle-high RC buildings in high seismic areas such as Indonesia. Recently, the influence of masonry infill to seismic response of RC frame structures has been intensively investigated by several researchers, as were well-reported in references [4-9]. They conducted experimentally as well as analytical studies. These studies have clarified that the presence of masonry infill influences the seismic response of RC frame structures includes their lateral strength,
stiffness, ductility, and failure modes. Unfortunately, the studies for the partially brick masonry infills are still very limited; for instance, see the works of Tanjung et al. [2] and Pradhan et al. [10]. Therefore, in this paper, the experimental results for studying the effect of the partially brick masonry infill to the seismic response of the RC frame structures are presented.

![Damage to the columns due to the 2018 Palu earthquake](image)

(a). Damage on ends of columns  
(b). Damage on short columns

Figure 1. Damage to the columns due to the 2018 Palu earthquake

2. Experimental works

2.1. Description of test specimens

A series of experimental tests was done to point out the seismic response of RC frames infilled with fully and partially brick masonry infills. Four of ¼ scaled-down single-bay and single-story RC frame specimens were constructed. The configuration, cross-sectional dimensions and bars arrangement of RC frame specimens are detailly drawn in Figure 2. The columns have 750 mm clear height, 125 mm x 125 mm cross-section dimensions, 4D10 longitudinal reinforcements, and $\phi4@50$ transversal rebars. The dimensions of the lower-beam were 700 mm wide, 200 mm deep, and 1650 mm length with 12D13 longitudinal bars and $\phi6@50$ transverse stirrups. The dimensions of top-beam were 200 mm wide, 200 mm deep, and 1550 mm length with 4D13 longitudinal bars and $\phi6@50$ transverse stirrups. One RC frame specimen was a bare frame specimen (BF). Brick masonry walls infilled three RC frame specimens, one specimen has a fully brick masonry wall (IFSW), and two specimens with partially brick walls, i.e., with $3/4$ infilled (IFPW-1) and 1/2 infilled (IFPW-2), as are shown in Figure 3. The masonry infills were assembled of the brick units of 60 mm in length, 30 mm in width, and 13 mm in height and were composed by using mortar beds with the composition of cement and water = 1:0.5. Finally, the surfaces of the brick masonry infills were plastered with 5 mm mortar thickness.

2.2. Material properties of test specimens

The mechanical properties of the materials used for constructing the specimens were defined based on standard material testing procedures. The testing results are given as follows. The compressive strengths of the concrete cylinder and brick masonry prism were 49.9 N/mm² and 10.9 N/mm², respectively. The yield and tensile strengths of reinforcements were 390.2 (598.3) N/mm², 346.8 (448.6) N/mm², 462.0 (619.7) N/mm², and 421.1 (582.4) N/mm² for rebars of Ø4, Ø6, D10, and D13, respectively.
Figure 2. The configuration and rebar arrangement of RC frame

Figure 3. Type of specimens
2.3. Test setup
The structural tests were conducted at the Structural and Construction Material Laboratory of Civil Engineering Department, Syiah Kuala University, Banda Aceh, Indonesia. Figure 4.a shows the schematic test setup and loading system. At first, a specimen was placed on the rigid-floor, then was fastened to the rigid-floor by using six post-tensioning rods to keep the specimen in its place while applying the lateral load. A double-action lateral actuator force equipment was attached and fastened to the strong wall by using four post-tensioning rods, as shown in Figure 4. In order to prevent the applied force caused the out of plane deformation during testing, the top-beam was constrained by two horizontal steel beams. These two horizontal beams were connected to the actuator force, which mounted on the strong wall. Several LVDTs were placed at several points of columns and top beam to measure the horizontal and vertical relative displacements of RC frame and infill, as it is shown in Figure 4.b.

2.4. Test method
The specimens were tested under a quasi-static cyclic loading test, referring to FEMA 461 [11] but without applied vertical load. This cyclic procedure was in lateral displacement control. The drift angle R is used to control the incremental lateral load applied on specimens with the loading speed of approximately 0.05 mm/s. The cyclic loading history is given in Figure 5. The cyclic loading test was begun with a drift angle of 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 column of the RC frame specimen failed before the final cycles, then the applied loading should be stopped. The incremental of the applied lateral load and its deformation were recorded throughout the tests. For identifying the failure mechanism of the specimen, the initial cracks and its crack propagation were marked on the specimen in every loading cycle.
3. Experimental results and discussion

3.1. The failure mechanism of the specimens

3.1.1. The bare frame (BF) specimen. The failure process for all specimens was investigated during the experimental works. Consequently, differences in failure mechanisms were identified among the specimens. In the case bare frame specimen, an initial flexural crack was observed at the top of the tensile column at a drift ratio of 0.15% during the cyclic at drift angle R=1/400. Further, the initial shear crack appeared at the bottom of the compressive column at a 0.5% drift ratio during the cyclic 1/200. The shear and flexural cracks appeared at the ends of both columns after R=1/25, as is shown in Figure 6.a. However, the lateral strength can be maintained by a 7.85% drift ratio. The strength was degraded at a drift ratio of 8.0, as is shown in Figure 7.a.

3.1.2. The Fully infilled frame (IFSW) specimen. The failure mechanism of a fully masonry infilled frame specimen was different when compared to the bare frame. A separation crack has appeared between column and masonry wall at the first cycle of loading at drift angle R=1/800. Initial flexural and shear cracks were detected at the tensile column during the cycle of 1/400 at a drift ratio of 0.17% and 0.21%, respectively. An initial diagonal shear crack raised at the central area of the panel wall at a 0.45% drift ratio with a drift angle of the cycle 1/200. Shear failure of brick wall occurred during the cycle 1/50 at drift ratio 2.0%, and then the lateral strength degraded significantly, as is shown in...
Figure 7.b. The shear cracks appeared along with the column height—the failure of the brick masonry wall in out of the plane direction. The boundary column failed in shear at the cycle of 1/25. Figure 6.b shows the crack pattern of the IF\textsubscript{SW} specimen at the cycles of 1/25 rad.

3.1.3. The Partially infilled frames (IFPW-1 and IFPW-2) specimens. A similar cracks pattern was found on two partially brick masonry infilled frames that the flexural cracks mostly occurred at the interface between the columns and masonry infill. However, the shear cracks developed at columns without infill, as shown in Figures 6.c and 6.d. For both specimens, an initial flexural crack appeared on the top edge of columns during the cycle 1/800. The first shear crack was detected during the cycle 1/400 for IFPW-1 specimen and during the 1/200 for IFPW-2. In the case of the IFPW-1 specimen, the masonry infill failed in shear during the cycle 1/50, and then it was followed by shear failure of the tensile column at the cycle 1/12.5. On the other hand, the IFPW-2 specimen failed in shear at the cycle 1/12.5 after the shear failure of the tensile column. The presence of this partially brick masonry infill made the stiffness of the specimen, where the partially brick masonry installed, relatively higher compared to other parts of the specimen. As a consequence, the column behaves as a short column behavior. This fact evidence that the partially brick masonry infill in the RC frame structure has significantly played a role in the damage of the RC columns of the specimen.

3.2. Performance of the infilled frames

Figure 7 shows the comparison of the seismic performance of specimens. It is presented in the relationship between the lateral force and the drift ratio. The maximum lateral strengths of BF, IF\textsubscript{SW}, IF\textsubscript{PW-1}, and IF\textsubscript{PW-2} were 51.3 kN, 127.7 kN, 86.0 kN, and 68.4 kN, respectively. These maximum lateral strengths were reached at drift ratios 8.0%, 1.0%, 1.0% and 4.0%, respectively. A specimen with fully brick masonry infill has the lateral strength greater about 2.5 times compared to the bare frame specimen. The lateral strengths of the partially infilled frame specimens were about 67% and 54% of the lateral strength of the fully brick masonry specimen for IFPW-1 and IFPW-2, respectively. It means the strength of the partially infilled frame specimens about 1.7 times for IFPW-1 and 1.3 times for IFPW-2 of the bare frame specimen.

The deformation capacity of the specimen under lateral load was defined as a deformation when the post-peak strength dropped to 80% of maximum strength, i.e., at the deformation of 8.4%, 1.9%, 3.9% and 7.2% for BF, IF\textsubscript{SW}, IFPW-1, and IFPW-2, respectively. It exhibits that the presence of the masonry infill decreases the ductility of RC frame specimens. The inclined compression strut formed in the masonry infill when subjected to the shear deformation in the surrounding frame. The partially infill frames more ductile than the fully masonry infilled frame specimen. Particularly infilled frame with half part infill (IFPW-2), the lateral strength was maintained after yielding, as shown in Figure 7.d. This phenomenon is similar to the behavior of the bare frame specimen.

The masonry infill contributes to the lateral stiffness of the specimen was described by the slope of the line joining the extreme displacement points in each cycle. The initial stiffness of the full infilled frame specimen was about 4.7 times the bare frame specimen. In the cases of partially infilled frame specimens of IFPW-1 and IFPW-2, their initial stiffness was about 2.8 times and 1.9 times bare frame specimen, respectively.

3.3. Lateral strength-drift ratio relationship of the infills

The contribution of infills was calculated by extracting the distinction between the lateral forces of envelope curves infilled frame specimens and the bare frame specimen at the same drift ratio, as is presented in Figure 8. As a result, the lateral force-drift ratio of the fully brick masonry and partial brick masonry infills are given in Figure 9. The maximum lateral strength was 82.7 kN, 49.4 kN, and 21.7 kN for fully brick masonry infill, ¾ part of brick masonry infill, and ½ part of brick masonry infill specimens.
Figure 7. Lateral force – drift ratio relationship of specimens

Figure 8. Envelope curves of infilled frames

Figure 9. Infills performance
4. Conclusions
The seismic response of RC frame specimens infilled with full and partial brick masonry walls has been experimentally investigated under cyclic loading tests. Based on these works can be concluded that the full and partial brick masonry infills in RC frame specimens contribute to increasing the lateral strength and stiffness of the specimens. The full brick infill increases the lateral strength of the specimen about 2.5 times the lateral strength of the bare frame specimen. For the partially brick infills of ¾ part and ½ part increase the lateral strength of about 1.7 times and 1.3 times of the bare frame specimen, respectively. In the case of partially infilled frames, the parts of the columns without infill is the weak area. These columns are known as short columns.

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