Seismic performance analysis of multi-span masonry infilled RC frame based on analytical strut model

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Abstract. According to previous studies, it was accepted that masonry infills have a contribution to lateral strength, stiffness, and ductility of reinforced concrete (RC) frames structures. In the past studies, an analytical method of diagonal strut model has developed for evaluating the seismic performance of masonry infill. In this model, the masonry infills were presented by compression struts as distributed forces at the frame-infill interfaces in which the frame-infill contact lengths were evaluated by static equilibrium related to compression balance and lateral displacement compatibility. The lateral strength of infill was determined based on frame-infill contact length. In the current study, an experimental study of quasi-static cyclic lateral loading tests was conducted to evaluate the seismic performance of two-bay brick masonry infilled RC frames. This paper discusses the results of seismic performance brick infills based on experimental and analysis results of the multi-span masonry RC frame applying the diagonal strut model. According to the analytical model, antisymmetric strut was acted at the top and bottom of the middle column of the multi-span infilled frame from each infill. As a result, good agreements of lateral strength of structures were obtained between the experimental and analytical values.

1. Introduction
Masonry infills are a non-structure element which generally used as a partition on reinforced concrete (RC) buildings in Indonesia as high seismicity. According to Indonesian code, the masonry infill is ignored in seismic design calculation of RC buildings, only consider for self-weight estimation. A lot of experimental and analytical results have been confirmed that masonry infills contributed to the seismic performance of surrounding frames structures [1-5]. Therefore, neglecting the masonry infills in seismic design calculations may result in unprecise assessments for the lateral stiffness, strength, and ductility of the buildings.

The authors [1-3] have been performed cyclic loading tests on single-span brick masonry infilled frames finding that the lateral strength, stiffness, and ductility performance of overall structures were affected by the presence of the masonry infills. Many analytical approaches have been proposed by many researchers such as Smith and Carter [6, 7], Mainstone [8], Leuchars and Scrivener [9], Paulay and Priestley [10], Maidiawati and Sanada [11, 12] who developed the diagonal strut models for evaluating the seismic performance of masonry infill in framed structures. Most of the developed strut models were concentrated to evaluate the strut width of infill based on the frame-infill contact length. In the case of the diagonal strut model developed by Maidiawati and Sanada [11, 12], the infill
contribution was distributed compression transferred diagonally between frame-infill interfaces. The frame-infill contact length can be determined by static equilibriums related to compression balance and lateral displacement compatibility at the frame-infill interfaces. As a result, the equivalent strut width is given as a function of frame-infill contact length. The effectiveness of the proposed model was accepted based on comparisons with the experimental results of a series of structural tests of brick masonry-infilled RC frames representing a typical RC building with non-structural masonry elements.

In the current study, an experimental study of quasi-static cyclic lateral loading tests was conducted to assess the seismic performance of two-bay brick masonry infilled RC frames. This paper presents the comparison of seismic performance between experimental and analytical results based on the diagonal strut model.

2. Methodology

2.1. Specimens

Two 1/4 scale two-bay RC frames specimens, one without infill (BF-2B) and one with brick infills (IF-2B-BM), were prepared. Figure 1 presents the drawing of the configuration and bar arrangements of the two-bay RC frame specimens. In the case of infilled frame specimen, as shown in figure 1(b), bricks with length of 60 mm, width of 30 mm and height of 15 mm were arranged in the interior clear height of one RC frame with mortar beds at a volume ratio of cement: sand: water = 1: 4: 1.4. The infill surfaces were plastered with finishing mortar with a thickness of 10 mm. Consequently, the thickness of the infills was 50 mm. Material properties of specimens included compressive strength of concrete of 28.4 N/mm$^2$, young modulus of concrete of 25045.0 N/mm$^2$, compressive strength brick masonry prism of 7.6 N/mm$^2$, yield strengths of longitudinal dan transversal reinforcements of columns of 449.5 N/mm$^2$ and 390.2 N/mm$^2$, respectively.

2.2. Test method

Both specimens, BF-BM and IF-2B-BM, were tested under quasi-static cyclic lateral load. Figure 2 shows the view of the experimental test set up in which the specimen was fixed on rigid-floor by using six post-tensioning rods at the lower beam. Lateral actuator equipment for lateral force action was attached and fastened to the strong wall. Several transducers (LVDTs) were placed at the upper beam and at columns to measure the lateral displacement of the RC frame.

The cyclic lateral load was applied to specimens based on according to the FEMA 461 [13]. Figure 3 was the lateral loading history applied to specimens with initial cycles to $R=1/800$ followed by two cycles to $R=1/400$, $R=1/200$, $R=1/100$, $R=1/50$, $R=1/25$, $R=1/12.5$ and a final load by a pushover to $R=+1/10$ rad. The $R$ was drift angle, a ratio of lateral displacement to column height, used for controlling the incremental loading. The incremental lateral load and lateral deformation of RC frame were measured during the tests.

2.3. Test results

Experimental seismic performance of BF-2B and IF-2B-BM specimens were presented by the relationship between lateral force and drift ratio, as shown in figure 4. The maximum lateral strength of bare RC frame of 64.2 kN was observed at a drift ratio of 8.0%, while the maximum lateral strength of brick infilled RC frame of 159.7 kN was detected at a drift ratio of 1.0%, as shown in figure 4. It revealed that the lateral strength of brick infilled frame structure was higher about two and half times than those of bare RC frame. Due to lateral deformation of the structure, a diagonal compression force occurred on infill which acted as a punching shear force at the bottom/top of compressive/tensile column.
Figure 1. a) the configuration and rebars arrangement of two-bay RC frame specimen b) drawing of the two-bay brick infilled specimen (IF-2B-BM).

Figure 2. Schematic view of test.
Figure 3. Cyclic loading to specimen.

Figure 4. a) two-bay bare RC frame; b) two-bay brick infilled RC frame.

Figure 5. Envelope curves of infilled frame performance.
The infill contribution is presented in envelope curve of the lateral force-drift ratio relationship, as shown in figure 5 which were evaluated by extracting the difference of envelope curve between the lateral forces of the infilled frame and the bare frame at each load step (at the same drift ratio).

3. Results and discussion

3.1 Analytical model

In the previous study, an analytical strut model for evaluating the seismic performance of masonry infilled frames have been developed by the first author. The proposed model has been verified using experimental study results single-bay masonry infilled RC frames, and it has been applied for seismic performance analysis of RC buildings by considering masonry infills as explained in references [11, 12]. The developed analytical model replaces masonry infill with a diagonal compression strut, which represents distributed compression transferred between frame-infill interfaces. The equivalent strut width is presented as a function of the frame-infill contact length $h_s$, as shown in figure 6(a), which can be evaluated by static equilibriums related to compression balance and lateral displacement compatibility at the frame-infill interfaces. The minimum $W'$ was accepted because two different contact lengths were usually obtained from the two ends of the strut. An equivalent rectangular stress block was applied for replacing the stress distribution at the frame-infill interface, as shown in figure 6(a). Therefore, the averaged compressive strength $f_m'$ can be calculated by multiplying the uniaxial compressive strength of the infill $f_m$ by a reduction factor defined by equation (1a). The $\alpha$ was obtained according to the stress profile at the frame-infill interface, which was assumed to correspond to a strain profile $\varepsilon(y)$ by equation (1b) under uniform strains along the strut.

$$\alpha = \frac{\varepsilon_{ave}}{\varepsilon_{max}} = \frac{\int_0^{h_s} \varepsilon(y) dy}{\varepsilon_{max}}$$

$$\varepsilon(y) = \frac{\delta f(y) - \delta s(y)}{l(y)} \cos \theta$$

where, $\delta f(y)$ is the flexural deformation of the column and $\delta s(y)$ is shear deformation of the infill along a height of $y$, $l(y)$ is the diagonal length of the strut crossing the column at the height of $y$; and $\varepsilon_{ave}$, $\varepsilon_{max}$, and $h_s$ is infill-column contact length, as in figure 6(a), $\theta$ is inclination angle of the strut, as shown in figure 6(b).

The diagonal compression $C_s'$, which acts on the bottom/top of the compressive/tensile column, as shown in figure 6(b), is given by equation (2a). As a result, the total diagonal compression $C_s$ was represented by twice $C_s'$, as given by equation (2b). $C_s$ was then resolved into the horizontal and vertical components $C_h$ and $C_v$, which were represented by uniformly distributed forces along the column height, as shown in figure 6(d). The $C_h$ and $C_v$ were calculated by equations (2c) and (2d), respectively.
Figure 6. Modelling of masonry-infilled frame; (a) lateral deformation; (b) Diagonal compression force at the frame-infill interfaces, (c) Strut width of infill, (d) Distributed strut force.

\[ C_s' = W' \cdot t \cdot f_m' \]  
\[ C_s = 2W' \cdot t \cdot f_m = W \cdot t \cdot f_m' \]  
\[ c_h = t \cdot f_m' \cdot \cos^2 \theta \]  
\[ c_v = t \cdot f_m' \cdot \sin \theta \cdot \cos \theta \]

where, the total width of strut \( W \) is twice of \( W' \), and \( t \) is the thickness of the infill.

The column was assumed to yield in flexure at the end of the column-infill contact. Therefore, equations (3a) and (3b) present the moment distribution from the end \( \delta M(y) \) for the cases of \( 0 \leq y \leq h_s \) and \( h_s \leq y \leq H \), respectively.

\[ \delta M(y) = (M_u - Q_u y + \frac{1}{2} C_h y^2 \) \]

where, \( H \) is the clear height of column (figure 6d), \( M_u \) is the flexural strength at the column end based on the Japanese standard [14], and \( Q_u \) is the shear force at the column end given in equation (5).

Lateral displacement along column height \( \delta y \) was generated by the twice integrals of equation (3)/\( EI \) (= elastic flexural rigidity of the column) as follows:

In the case of \( 0 \leq y \leq h_s \)

\[ \delta y = \frac{1}{EI} \left( \frac{1}{24} C_h h_s y^4 - \frac{1}{6} Q_u y^3 + \frac{1}{2} M_u y^2 \right) \]

In the case of \( h_s \leq y \leq H \)

\[ \delta y = \frac{1}{EI} \left[ \left( \frac{1}{6} C_h h_s - \frac{1}{6} Q_u \right) y^3 + \left( \frac{1}{2} M_u - \frac{1}{4} C_h h_s^2 \right) y^2 + \frac{1}{6} C_h h_s^3 y - \frac{1}{24} C_h h_s^4 \right] \]

\( Q_u \) for equations (3) and (4) is given by equation (5) with assuming that rotation of zero at a column height of \( H \) \( (\delta y = H)/dy = 0 \) from equation (4b) assuming a column-sway mechanism.

\[ Q_u = \frac{2M_u}{H} + C_h h_s - \frac{C_h h_s^2}{H} + \frac{C_h h_s^3}{3H^2} \]
Even though the above equations were derived based on the elastic rigidity, only the drift profile along the column height was applied to obtain the frame-infill contact length in the following calculations. The contact length $h_c$ was calculated based on a lateral shear drift profile along the infill height $\delta(y)$ which was obtained by equation (6), considering the infill shear deformation assumed above and the compatibility between the column and infill drifts at the ends. Ultimately, an intersection height $y_i$ between the column and the infill can be evaluated by solving equation (7). The process for determining of $h_c$ are presented in figure 2, where the intersection height should equal $h_c$. The unknown $h_c$ was found iteratively after satisfying equation 6. The minimum $h_c$ between both ends of the strut was used to determine the width of the compression strut $W$, as given in equation (8).

$$i\delta(y) = \frac{c\delta(y=H)}{H} y$$  \hspace{1cm} (6)$$

$$c\delta(y_i) = i\delta(y_i)$$  \hspace{1cm} (7)$$

$$W = 2h_c \cos \theta$$  \hspace{1cm} (8)$$

In the case of modeling the multi-bay infilled frames, each column was classified into end columns on the tensile and compressive sides and a middle column, as shown in figure 8(a). In particular of the middle column, antisymmetric strut actions were considered for the top and bottom of the column, as shown in figure 8(b), assuming the formation of a single diagonal strut in each infill. Similar to analytical strut model of single-infilled frame mentioned above, $C_i$ was resolved into the horizontal and vertical components, which represented the distributed forces along column height at the bottom and top of the column, as shown in figure 8(c). As a result, the shear force at the end of the middle column is given in equation (9), where $h_i$ is the minimum contact length from both column-infill interfaces.
Figure 8. Modelling of multi-span masonry-infilled frame; (a) lateral deformation; (b) strut model on middle column, (c) distributed strut model.

\[ Q_u = \frac{2M_u}{H} + c_h h_s - c_h h_s^2 \frac{H}{H} \]  

(9)

3.2 Analytical analysis of the seismic performance of masonry infills

The seismic performance of brick infills in the two-bay infilled frame was evaluated by applying the analytical method mentioned above. Consequently, the frame-infill contact lengths \( h_s \) were evaluated at 234.3 mm. Thus, the strut width of infill was 357.9 mm. Moreover, the infill performance was replaced by a bilinear curve with a yield point of \((V_y, \delta_y)\), where the yield strength \( V_y \) and drift \( \delta_y \) are given in equations (10) and (11), respectively.

\[ V_y = C_s \cos \theta = W t f_m' \cos \theta \]  

(10)

\[ \delta_y = \frac{V_y}{K_y} = \frac{V_y}{E_m W t \cos^2 \theta / d} \]  

(11)

where, \( K \) is secant stiffness, and \( d \) is the diagonal length of infill.

As a result, the maximum lateral strength of brick infills was 135.1 kN at a drift of 0.37%. The evaluated lateral strength and drift of infill are compared to the experimental results in figure 9. Good agreements were obtained between experimental and analytical results. It was verified that the strut model was applicable for estimating the seismic performance of masonry infill of multi-span infilled frame.

Figure 9. Comparisons of infill performance.
4. Conclusion

Experimental study of static cyclic lateral loading was conducted on specimens of two-bay RC frames, without infill and with infills. Test results revealed that brick infills in two-bay RC frame increase lateral strength of overall structure about two and half time. A developed diagonal strut model was implemented to evaluate the infill-frame contact length and strut width of infills as parameters for assessing the lateral strength and drift of brick infills at a yield point. As a result, good agreements of lateral strength were obtained between experimental and analytical results. It indicates that the diagonal strut model is compatible with the multi-span brick infilled RC frame.

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