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Procedia Engineering 171 (2017) 1043 – 1051
Procedia Engineering
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Sustainable Civil Engineering Structures and Construction Materials, SCESCM 2016

Seismic performance evaluation of Indonesian existing R/C building considering brick infill

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Abstract

This paper presents the seismic performance of an existing building in Padang, Indonesia, considering the brick infill effect by applying a developed analytical model. In this model, masonry infill was replaced by a diagonal compression strut which represented distributed compression transferred diagonally between infill/frame interfaces. The infill/frame contact length could be determined by solving two equations, i.e., static equilibriums related to the compression balance at infill/frame interface and lateral displacement compatibility. Consequently, the equivalent strut width is presented as a function of infill/frame contact length. Two calculations of seismic performance of an existing R/C building, with and without considering brick infill, were performed. A distinct difference was identified between the lateral strength of such building with and without infill effects. As the results, the nonstructural brick masonry infill significantly contributed to the seismic performance of the R/C building.

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Keywords: brick masonry infill; compression strut model; existing R/C building; seismic performance.

1. Introduction

R/C frame structures with brick infill are widely used in most of buildings in Indonesia. Related to the last earthquakes in Sumatra, Indonesia, a lot of R/C buildings were damaged and collapsed in Padang, the capital city of West Sumatra [1−2]. An investigation on two damaged R/C buildings, one totally collapsed and other moderately damaged, was conducted by author after the September 2007 Sumatra Earthquake [1]. It was promptly found that the brick wall in survived R/C building contributed to resist seismic load and prevented the collapsing of the building.

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Peer-review under responsibility of the organizing committee of SCESCM 2016.
doi:10.1016/j.proeng.2017.01.450

In most cases of seismic resistant design procedures, particularly in Indonesia, the brick masonry infill in R/C frame buildings is ignored assuming as nonstructural walls. This consideration may result inaccurate prediction of the lateral stiffness, strength, and ductility of RC frame buildings.

Several researchers have found that brick masonry wall in R/C frame increased the lateral stiffness of R/C building [3]. Author had also conducted structural tests on R/C frame with and without brick infill and observed that the lateral strength of R/C frame with infill was more than four times that of bare frame. However, the ductility of R/C frame with infill decreased by half [4]. Furthermore, author developed an analytical method for modeling the brick masonry infilled frames based on diagonal struts caused in masonry infill with simplified equations. The shear force of column affected by diagonal strut was given as a function of infill/frame contact length which could be determined by solving two equations, i.e., static equilibriums related to the compression balance at infill/frame interface and lateral displacement compatibility [5].

The analytical model can be used as a tool to evaluate the seismic performance of existing buildings by considering brick infill in high seismic areas. In this study, seismic performance of an existing R/C building in Padang, West Sumatra was evaluated by applying the developed analytical model to nonstructural brick infill.

2. Modeling of Masonry Infill Frame

This method targets a brick masonry infilled R/C frames with relatively stiff beams which are typically used in Indonesian buildings as shown in Fig. 1(a). Such infilled frames may also represent the lower part of multi-story confined masonry structures where beam flexural deformation is constrained by the existence of infill. When they deform under lateral loads, contact/separation is caused between the bounding column and infill due to column flexural deformation and infill shear deformation, as shown in Fig. 1(b). In this method, the contact length is derived from a simple procedure for the seismic performance evaluation of the targeted structures. The masonry infill panel is replaced by a diagonal compression strut having the same thickness and material properties as those of the panel. A compression stress distribution at the infill/frame interface is replaced by an equivalent rectangular block, as shown in Fig. 1(b), where the averaged compressive strength, f_m', is evaluated by multiplying the uniaxial compressive strength of infill, f_m, by a reduction factor, α, which is evaluated by Eq. (1). The diagonal compression, C_s', which acts on the bottom/top of the compressive/tensile column as shown in Fig. 1(c), is given by Eq. (2a). However, assuming reaction forces at the column ends, an unbalanced moment causes a rotation of a free body of the infill, as shown by the solid red arrows in Fig. 1(d). Therefore, reaction forces are considered at the beam ends, as shown by the dashed arrows in the figure. As a result, the total diagonal compression, C_s, is represented twice as C_s', as given by Eq. (2b). Then, C_s is resolved into the horizontal and vertical components, which are represented by the distributed forces along column height, as shown in Eqs. (2c) and (2d).

$$\alpha = \frac{\Delta_{ave}}{\Delta_{\max}} = \frac{\int_0^{hs} \Delta(y)dy / hs}{\Delta_{\max}} \tag{1}$$

$$C_s' = 1/2\, w'\, t\, f_m' \tag{2a}$$

$$C_s = W\, t\, f_m' \tag{2b}$$

$$c_h = t\, f_m' \cos^2\theta \tag{2c}$$

$$c_v = t\, f_m' \sin\theta\cos\theta \tag{2d}$$

in which, α: reduction factor, $\Delta(y)$: difference between flexural ($\delta_f(y)$) and shear ($\delta_s(y)$) deformation along column height, so $\Delta(y)=\delta_s(y)-\delta_f(y)$, Δ_{ave}: averaged difference between flexural and shear deformation, Δ_{max}: maximum difference between flexural and shear deformation, *w'*: half strut width from diagonal axis, *t*: thickness of infill, *W*: strut width, *W=2w '*, *θ*: inclination angle of strut, as shown in Fig. 1(c).

Assuming that the compressive column yields in flexure at the bottom, the moment distribution along column height, $_cM(y)$, is obtained with Eq. (3). Yield moment, however, is calculated with Eq. (4) based on the Japanese standard [6].

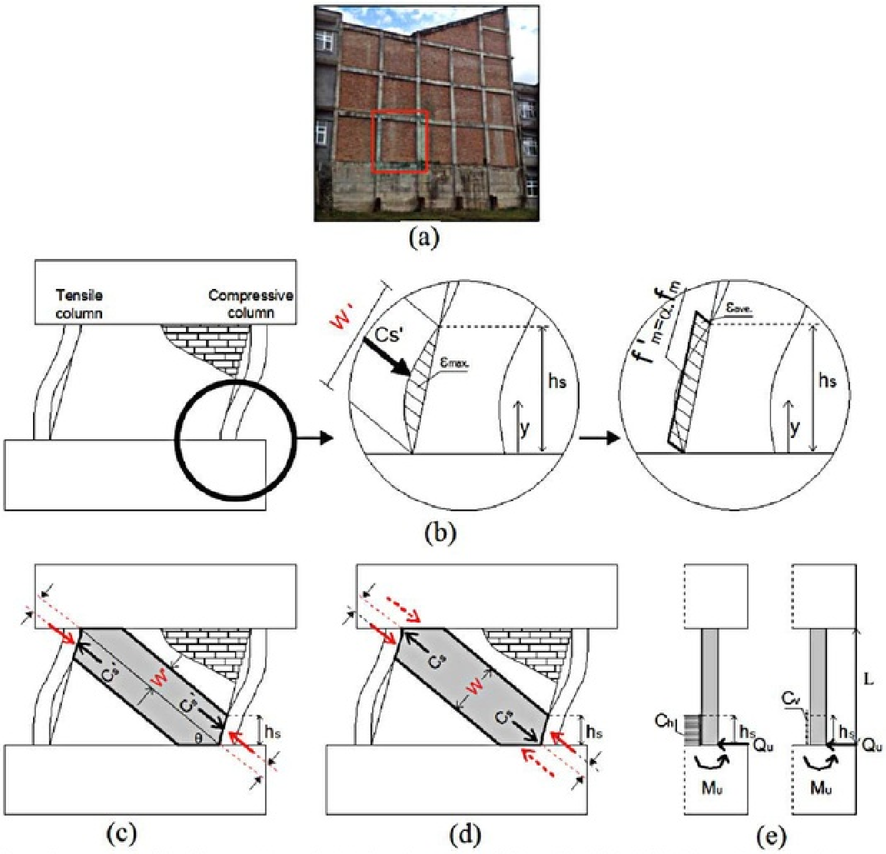


Fig. 1: Modeling of masonry-infilled frame: (a) Typical Indonesian R/C building with brick infill; (b) Modeling and close up infill/frame interface under lateral deformation; (c) diagonal compression at infill; (d) derivation of srut width; (e) distributed strut force

In the case of $0 \le y \le h_s$

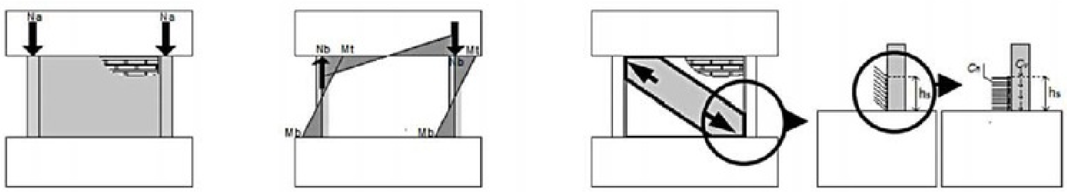
$$_cM(y) = {}_{y=0}M_u - Q_u y + 1/2\, C_h y^2 \tag{3a}$$

In the case of $h_s \le y \le L$

$$_cM(y) = {}_{y=0}M_u - Q_u y + C_h h_s y - 1/2\, C_h h_s^2 \tag{3b}$$

$$M_u = 0.8\, a_t\, \sigma_y D + 0.5\, N\, D\left(1 - \frac{N}{b\, D\, F_c}\right) \tag{4}$$

where, h_s: infill/column contact height, as shown in Fig. 1(b), L: clear column height, as shown in Fig. 1(e), M_u: flexural strength of column, Q_u: shear force at column bottom, which is determined with Eq. (6), as derived later, a_t: total cross-sectional area of tensile reinforcing bars, σ_y: yield stress of longitudinal reinforcement, D: column depth, N: axial force, b: column width, F_c: compressive strength of concrete. However, the axial force at the bottom of column is calculated as a summation of building weight (initial axial load), N_a, axial force due to shearing force in the beam, N_b, and vertical component of the strut force, $C_v h_s$, as shown in Fig. 2.



(a) (b) (c)

Fig. 2. (a) initial axial load; (b) axial load due to shearing force in the beam; (c) axial load due to strut force

By double integrals of Eq. (3)/EI, lateral displacement along column height, $_c\delta(y)$, is obtained with Eq. (5).In the case of $0 \leq y \leq h_s$

$$_c\delta(y) = \frac{1}{EI}\left(1/24\, C_h y^4 - 1/6\, Q_u y^3 + 1/2\, M_u y^2\right) \tag{5a}$$

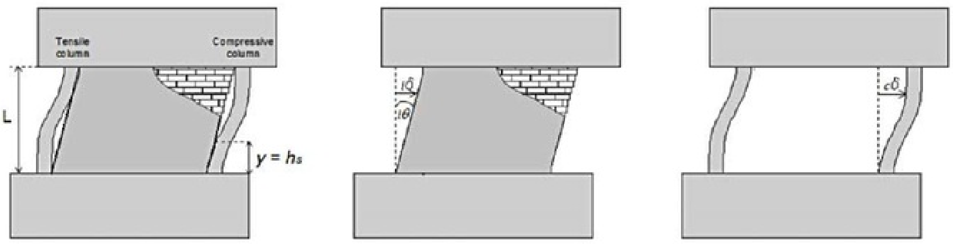
In the case of $h_s \leq y \leq L$

$$_c\delta(y) = \frac{1}{EI}\left(\left(1/6C_h h_s - 1/6Q_u\right)y^3 + \left(1/2M_u - 1/4C_h h_s^2\right)y^2 + 1/6C_h h_s^3\, y - 1/24C_h h_s^4\right) \tag{5b}$$

where, E and I are Young's modulus and the second moment of inertia of columns. Assuming the rotation at the column top of zero, the shear force at the bottom of compressive column, Q_u is obtained by Eq. (6).

$$Q_u = \frac{2M_u}{L} + C_h h_s - \frac{C_h h_s^2}{L} + \frac{C_h h_s^3}{3L^2} \tag{6}$$

Assuming a uniform shear strain, $_I\theta$, lateral deformation along infill height, $_I\delta(y)$, is defined by Eq. (7). Therefore, intersection height between column and infill deformation can be evaluated by solving Eq. (8), as shown in Fig. 3. Therefore, unknown h_s is obtained through an iteration after satisfying $y = h_s$.



(a) (b) (c)

Fig.3. Lateral displacement of (a) infilled frame; (b) infill; (c) R/C frame

$$ {}_i\delta(y) = {}_i\theta\, y = \frac{{}_c\delta(y = L)}{L}\, y \tag{7} $$

$$ {}_c\delta(y) = {}_i\delta(y) = \frac{{}_c\delta(y = L)}{L}\, y \tag{8} $$

According to the above procedure, the contact length between infill/column, h_s, is obtained for tension and compressive columns. Consequently, the width of compression strut, W, is determined as a function of the smallest contact lengths between infill/column given by Eq. (9).

$$ W = 2h_s \cos\theta \tag{9} $$

3. Verification of Analytical Model

The analytical method has been verified through the authors' past experiments of R/C bare frame (BF) and infilled frame (IF) as report in References [4−5]. Fig. 4 shows the relationships between lateral force and drift ratio for both specimens according to the test results. The experimental infill contribution was evaluated by extracting the difference between lateral forces of IF and BF specimens at the same drift ratio, as shown in Fig. 5.

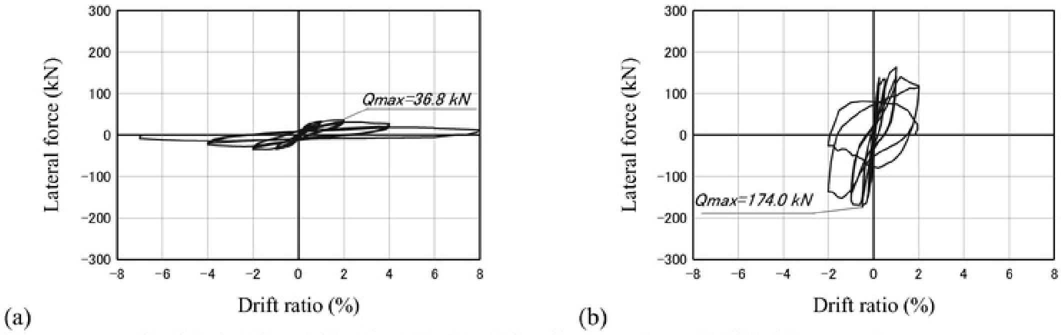


Fig. 4. Lateral force-drift ratio relationship; (a)Bare Frame specimen; (b) Infilled Frame specimen.

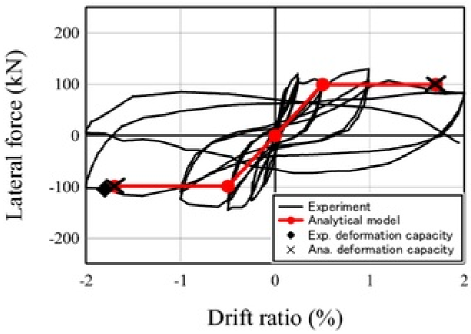


Fig. 5. Lateral force-drift ratio relationship of brick infill.

The analytical model was applied to the IF specimen to evaluate the column-infill contact length, h_s, which was evaluated at 272 mm. Consequently, the strut width, W, and the diagonal compression strut, C_s, were obtained based on Eq. (9) Eq. (2), respectively. Moreover, the infill performance was replaced by a bilinear curve with a yield point of $({}_iV_y, {}_i\delta_y)$. The Eqs. (10) and (11) give the yield strength ${}_iV_y$ and drift ${}_i\delta_y$, respectively. As the result, good agreement was obtained between the experimental and analytical ultimate strengths of infill, as shown in Fig. 5.

$$ {}_iV_y = C_s \cos\theta = W\, t\, f_m' \cos\theta \tag{10} $$

$$ {}_i\delta_y = \frac{{}_iV_y}{{}_iK_y} = \frac{{}_iV_y}{E_m W\, t \cos^2\theta / d} \tag{11} $$

where ${}_iK_y$ was the secant stiffness to the yield point of the infill, E_m is the elastic modulus of the infill, and d was diagonal length of infill.

Moreover, the shear performance of compressive column was evaluated by replacing by a bilinear model, as shown in Fig. 6. In the figure, however, the column shear was represented by the average of shear force, ${}_cQ(y)$ which was the first differential of Eq. (3), along the column height equal to column depth $(y=D)$ from the end, because the severe damage occurred across this section. The drift at the maximum shear, D_y, should be given by Eq. (12) considering the lateral displacement compatibility. On the other hand, the shear capacity of column was evaluated by Eq. (13) [7], where the parameters of P and a were evaluated considering the strut effects. The deformation capacity of column was defined as a drift where shear force attained to the capacity, as shown in Fig. 6. Consequently, it was 0.017 rad. which agree with the experiment. This deformation capacity is also plotted in Fig. 5.

$$ D_y = V_m / (K.L) \tag{12} $$

$$ V_n = k\sqrt{F_c}\,(0.8A_g) + \frac{A_v f_y D'}{s}\cot 30^o + \frac{D-c}{2a}P \tag{13} $$

where, k: degradation factor of concrete strength which was 0.29 up to a drift of 0.01 and 0.1 at a drift of 0.02, as shown in Fig. 7, A_g: gross cross-sectional area of column, A_v: cross-sectional area of hoop, f_y: yield stress of hoops, D': distance between the centers of hoop, s: spacing between hoops along the axis, c: neutral axis depth, P: axial force, a: shear span.

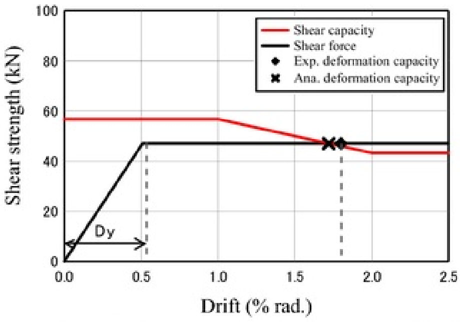


Fig. 6. Performance curve of column with infill effects.

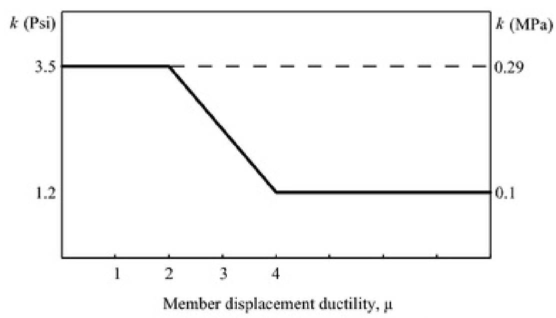


Fig. 7. Concrete strength degradation.

4. Seismic Performance Evaluation of R/C Building

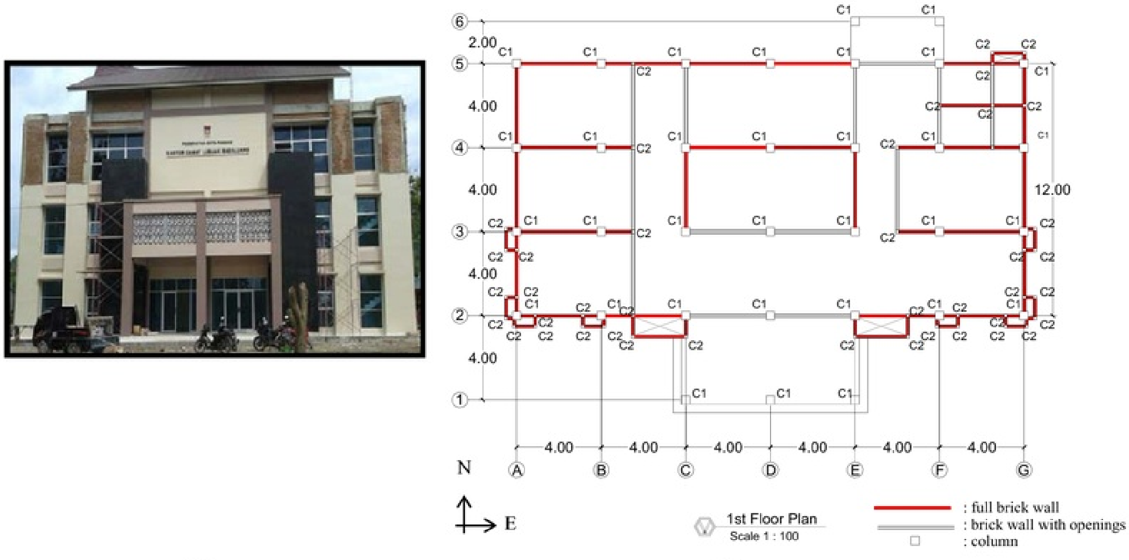
4.1. Description of building

An existing three-story R/C building in Padang, Indonesia, as shown in Fig. 8(a) was evaluated by applying the analytical model to non-structural brick walls. The investigated building was constructed in 2014 representing the typical Indonesian building with the first story plan illustrated in Fig. 8(b). The cross sectional dimensions of columns, c_1, were 400x400 mm with 10D19 of longitudinal rebars and the cross sectional dimensions of column, c_2, were13x13 mm with 4Ø12 of longitudinal rebars. The both columns have 2Ø10-100 of transverse hoops. Many brick walls with and without openings were used as infill in R/C frames as shown in Fig. 8(b). Compressive strengths of concrete of 24.32 MPa and brick wall of 12.45 MPa were obtained through hummer tests. The yield strengths of longitudinal and transverse rebars were 320 MPa and 240 MPa, respectively.

4.2. Seismic performance of building without infill

Seismic performance of existing R/C building was evaluated only for the first story on the basis of the Japanese standard [6] along East-West and South-North directions. The seismic performance of investigated building was presented in relationship between strength index and ductility index. The cumulative strength index, C, at a certain ductility index, F, was calculated by Eq. 14.

$$C = C_i + \sum \alpha_j C_j \qquad (14)$$



(a) (b)

Fig. 8. (a) front view of investigated building; (b) first floor plan of investigated building

$$C_i = \frac{Q_u}{\sum W} \qquad (15)$$

where, C_i was strength index of the i-th group of vertical members having the same ductility index, given by Eq.15, α_j was an effective strength factor of the *j-th* group, C_j is strength index of the *j-th* group having the same ductility index larger than that of *i-th* group, Q_{ui} was ultimate lateral load-carrying capacity of the *i-th* group of columns which was evaluated as the smaller value between the shear force at flexural yielding,

The ductility index, F represents deformability of certain vertical members, was calculated according to structural specifications based on the reference [6].

As the results, the seismic performance of the first story building without brick infill effects was exhibited in East-West and South-North directions in terms of the relationships between the strength index and ductility index, as shown in Fig. 10. The figure shows that the no difference in seismic performance in both directions.

4.3. Seismic performance of building considering brick infill

The analytical model was applied to evaluate the infill effects. In the case of multi-span infilled frames, as illustrated in Fig. 9(a), however, each column was categorized into an exterior tensile column, interior column and exterior compressive column, as shown in Figs. 9(b), 9(c) and 9(d), respectively. In particular, distributed forces due to the struts were unsymmetrically applied to the bottom and top of interior column, as shown in Fig. 9(b). Consequently, shear force at the interior column end was determined by Eq. (16)

$$Q_u = \frac{2M_u}{L} + C_h h_s - \frac{C_h h_s^2}{L} \tag{16}$$

Calculated seismic performance of R/C building was compared between with and without infill effects in both directions, as shown in Fig. 10. The figure exhibits that the strength of R/C building by considering brick infill is higher than those of without infill. The strength of R/C building by considering brick infill in East-West direction is muach higher than those of in South-North direction, as shown in Fig. 10(a), as weel as the amount of brick wall in East-West direction is much larger than those of South-North direction, as ilustrated in Fig. 8(b). However, the strength of building with infill dropped earlier than without infill in both directions. It observed that the brick infill contributed to seismic performance of R/C building particularly on lateral strength dan ductility.

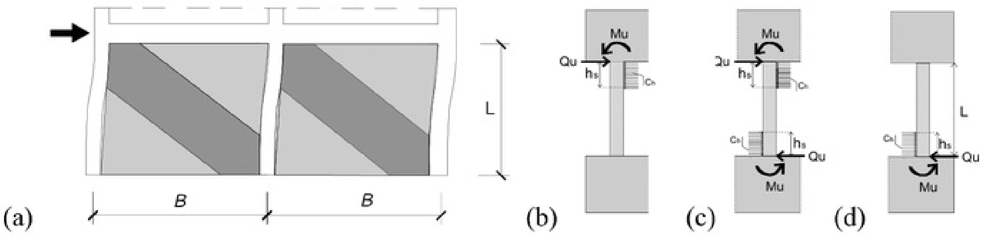


Fig. 9. (a) strut model of infill in multi-span infilled frames; (b) exterior tensile column; (c) interior column; (d) exterior compressive column

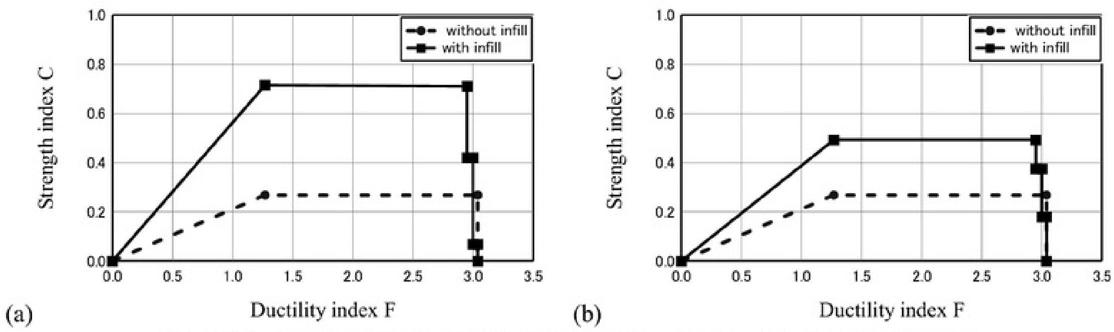


Fig. 10. Seismic performance of R/C building; (a) in East-West direction; (b) in South-North direction

5. Conclusion

The seismic performance of an existing three-story R/C building was evaluated by considering the brick infill effects by applying a developed analytical model to assess the brick infill contributions to seismic performance of the building. Two calculation were conducted; one with infill and one without infill. As the results, a distinct difference of lateral strength of building was obtained when considering the brick infill. The result indicates that the brick infill significantly contributed to the seismic performance of building.

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