RESIDUAL SEISMIC CAPACITY OF RC FRAMES WITH UNREINFORCED BLOCK WALL BASED ON THEIR CRACK WIDTHS

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ABSTRACT: The main objective of this study is to develop post-earthquake seismic evaluation method of concrete block wall infilled RC frames. For this purpose, full-scale, one-bay, single-story specimens having different axial loads in columns and different opening configurations in walls are tested under cyclic loadings. In this paper, the simplified models to estimate residual deformations from residual crack widths in columns and concrete block walls are proposed, and the relation of residual crack width (or damage level) and residual seismic capacity is discussed.

Key Words: concrete block (CB) wall, reinforced concrete (RC) frame, residual crack width, residual seismic capacity, seismic capacity reduction factor, damage level

INTRODUCTION

In some regions of Asia, Europe, and Latin America where earthquakes frequently occur, serious earthquake damage is commonly found resulting from catastrophic building collapse. Such damaged buildings often have unreinforced masonry (URM) walls, which are considered as non-structural elements in a structural design stage, and building engineers therefore have paid less attention to their effects on structural performance although URM walls may interact with boundary frames as has been often found in the past damaging earthquakes.

After an earthquake, the major concerns to damaged buildings are their safety/risk to aftershocks, quantitative damage assessment to evaluate their residual seismic capacity and to identify necessary actions on the damaged buildings. Post-event damage evaluation is therefore essential for quick recovery of damaged communities as well as pre-event seismic evaluation and strengthening of vulnerable buildings. Few investigations on URM walls, however, have been made to quantitatively identify their damage level and criteria to judge necessary actions for their continued use, repair and rehabilitation although their damage has been often found in the past damaging earthquakes.

In this study, concrete block (CB) wall infilled RC frames for school buildings in Korea, where CB walls are typically unreinforced, are experimentally investigated to develop pre- and post-earthquake seismic evaluation methods. In the tests, full-scale, one-bay, single-story specimens having different axial loads in columns and different opening configurations in walls are tested under cyclic loadings. Furthermore, crack patterns and widths in columns and walls which may be of great significance for post-event damage assessment are carefully observed.

In this paper, the simplified models to estimate residual deformations from residual crack widths in columns and CB walls are proposed, and the relation of residual crack width and residual seismic capacity as well as that of damage level and residual seismic capacity are discussed.

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OUTLINE OF EXPERIMENT

Test Specimen

Figure 1 shows a standard design for Korean school buildings in the 1980s (The Ministry of Construction and Transportation 2002). As can be found in this figure, CB walls are commonly used as partition walls or exterior walls in Korean school buildings. In this study, 4 specimens representing a first or fourth story of 4 story RC school buildings are tested under cyclic loadings. They are infilled wall type 1 (IW1) assuming a first story, infilled wall type 2 (IW2) assuming a fourth story, and wing wall type (WW) and partial height wall type (PW) both having an opening in the wall.

The design details of specimen IW1 are shown in Figure 2. Since seismic design provisions for buildings were introduced in 1988 in Korea, the model structures studied herein are not designed to seismic loads. Therefore, they have (1) large spacing of hoops (300*mm*) and (2) 90-degree hooks at both ends of hoops as shown in the figure. Specimens IW1, WW, and PW have the identical re-bar arrangement in columns but different wall arrangement, while IW2 has fewer re-bars than other 3 specimens. Concrete block units are laid in the RC frame after concrete is hardened.

Test Setup and Test Program

Figure 3 shows the elevation view of the loading system. Cyclic lateral loads are applied to each specimen through a loading beam tightly fastened to the specimen. Figure 4 shows the loading history, where a peak drift angle (R_p) is defined as "lateral deformation (δ_p) / column height (h_0=2,400*mm*)". As shown in the figure, peak drift angles of 0.1, 0.2, 0.4, 0.67, 1.0, and 2.0% are planned and 2.5 cycles for each peak drift are imposed to eliminate one-sided progressive failure (unsymmetric failure pattern in positive or negative loadings). It should also be noted that 0.4% loading is imposed after 1.0% to investigate the effect of small amplitude loading after large deformation (i.e., aftershocks). After severe damage is found, the specimen is pushed over to collapse. A constant axial load of 1,440*kN* (720*kN* (4.0N/mm^2) for each column) is applied to specimens IW1, WW and PW while 360*kN* (180*kN* (1.0N/mm^2) for each column) to specimen IW2.

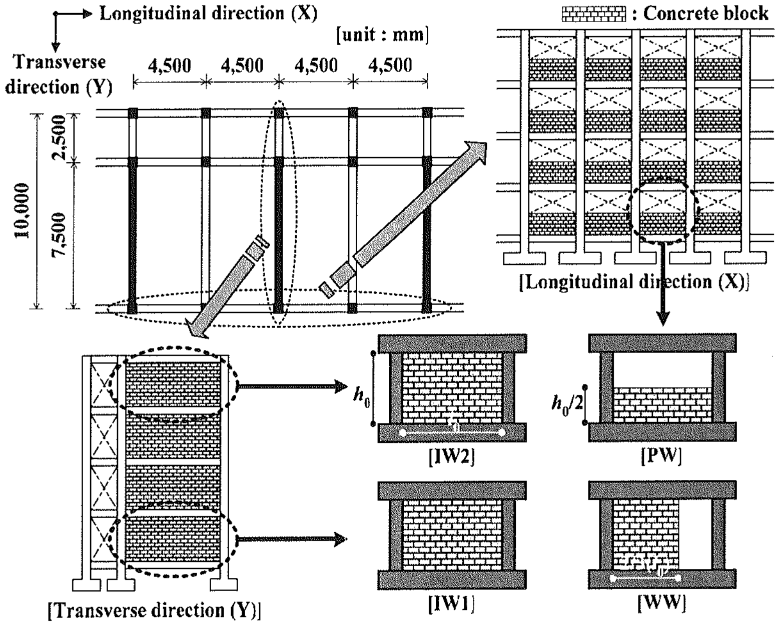


Figure 1. Standard design of Korean school buildings in the 1980s and specimen configuration

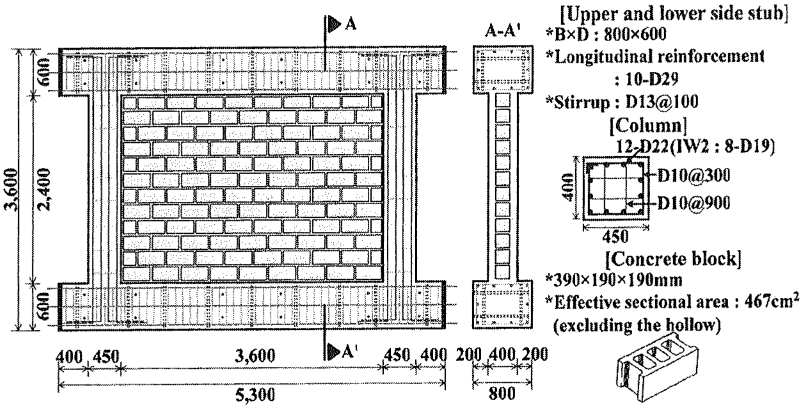


Figure 2. Detail of specimen IW1

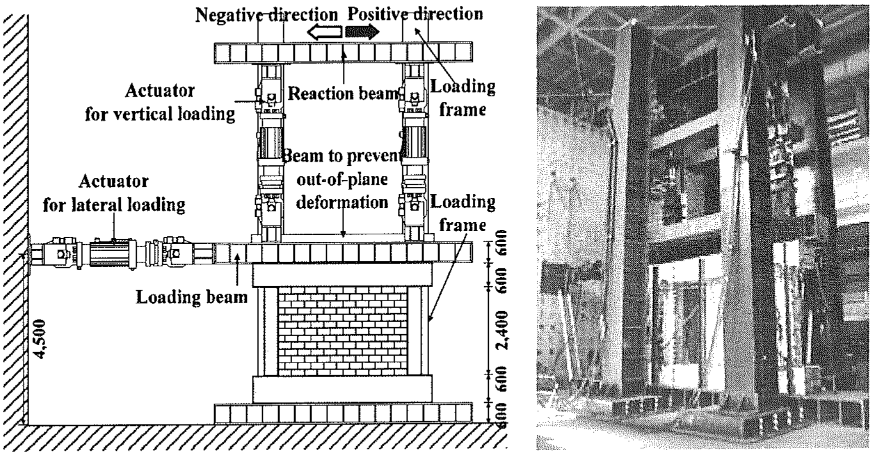


Figure 3. Test setup

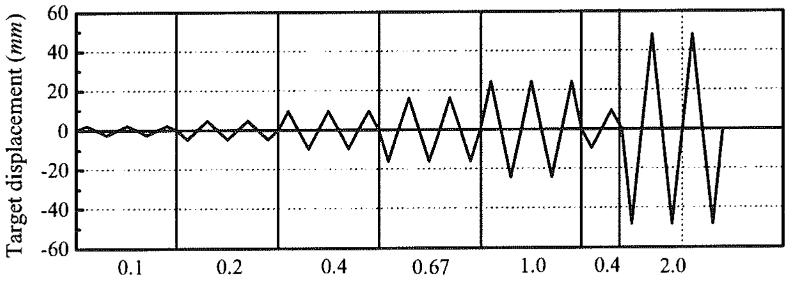


Figure 4. Loading history

BASIC CONCEPT TO ESTIMATE RESIDUAL SEISMIC CAPACITY

Figure 5 shows the basic concept to estimate the residual seismic capacity from residual crack widths observed damaged buildings after an earthquake.

If a test for members and frames is carried out under cyclic or dynamic loading in laboratory, the relationship between peak deformation (δ_p) and residual deformation (δ_0) can be obtained from the load-deformation curve as shown in Figure 5(a). As can be found the figure, the residual seismic capacity (E_r) by the discrepancy of initial (pre-earthquake) seismic capacity (E_T) and dissipated seismic capacity (E_d) can be calculated ($E_r = E_T - E_d$), and the residual seismic capacity (E_r) corresponding to the level of each residual deformation (δ_0) can be, therefore, estimated from test results.

Since only residual crack widths (W_0) are, however, observed in damaged buildings after an earthquake as shown in Figure 5(b), it is necessary to previously investigate the relationship between residual crack width (W_0) and residual deformation (δ_0) together with that of residual deformation (δ_0) and residual seismic capacity (E_r) in order to directly estimate the residual seismic capacity (E_r) from the residual crack widths on the damaged buildings.

In the following sections, the relationship between residual deformation (δ_0) and residual seismic capacity (E_r) obtained from test results (see Figure 5(a)) as well as that of residual crack width (W_0) measured in RC columns and CB walls and residual deformation (δ_0) by simplified models (see Figure 5(b)) are investigated to develop the relationship between residual crack width (W_0) and residual seismic capacity (E_r) for CB wall infilled RC frames (see Figure 5(c)).

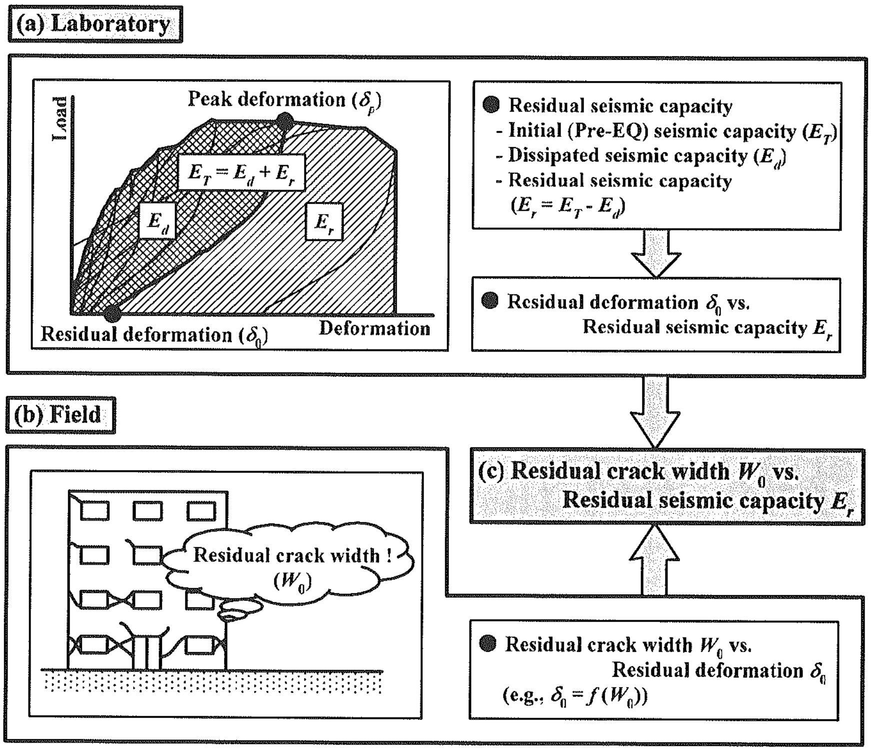


Figure 5. Basic concept to estimate residual seismic capacity

RELATION OF RESIDUAL CRACK WIDTH AND RESIDUAL DEFORMATION

In this section, the measurement points of crack widths set up in this study are briefly introduced, and the relationship between residual crack widths (W_0) carefully measured in RC columns and CB walls and residual deformation (δ_0) (see Figure 5(b)) is discussed by simplified models.

Measurement of Crack Width

In this study, crack widths in RC columns and CB walls are carefully measured at peak loads and unloaded stages. Figure 6 shows the measurement points in RC columns and CB walls made in this study.

The widths of flexural and shear cracks observed at the top and bottom of each column are visually measured with crack scales. Since crack widths are not necessarily uniform along the crack, its major width which is deemed to be largest along a crack is measured. It should also be noted that the width perpendicular to the crack is measured.

All visible cracks in the head joints found in stair-stepped diagonal cracks running through the CB wall are also measured to record the lateral dislocation of CB units (see (a) in Figure 6) while several cracks in the bed joints of one continued crack are measured to investigate a rotational behavior of wall (see (b) in Figure 6).

In the following sections, the crack widths measured in RC columns and CB walls of specimens IW1 and IW2 are investigated to understand the relationship between observed cracks and frame's behavior.

Relation of Residual Crack Width in RC column and Residual Deformation

Based on the studies by Maeda et al. (2000), AIJ Guidelines (2004) define the relationship between residual crack width (W_0) and residual deformation (δ_0) for RC members by a simplified model. In this model, the residual deformation (δ_0) of RC members is evaluated by means of dividing into flexural and shear deformations as shown in Figures 7(a) and (b). In this section, the simplified model is applied to CB wall infilled RC frames

Residual Flexural Deformation of RC Column

The total residual flexural crack width (ΣW_{f0}) measured in RC columns is almost same as the value of $D * R_{f0}$ (D : column depth, R_{f0} : residual flexural rotation angle) as shown in Figure 7(a), since the residual flexural deformation of RC columns can be approximately evaluated from the rigid body rotation (Maeda et al. 2000). The residual flexural deformation (δ_{f0}) of columns can be, therefore,

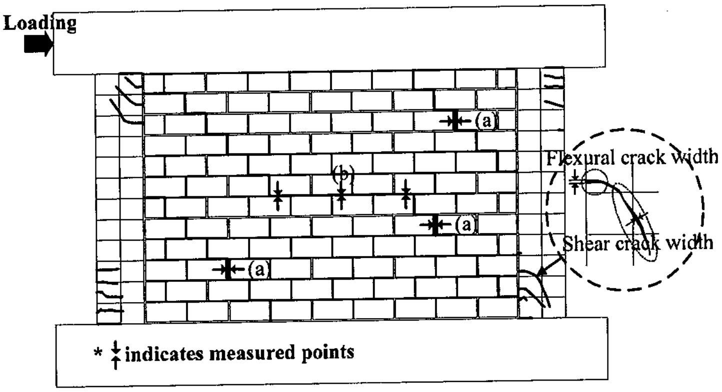


Figure 6. Schematic illustration of crack pattern and measured points

approximated using the average total residual flexural crack width (ΣW_{f0}) at the top and bottom of columns as shown in equation (1). Assuming that the ratios n_f ($=\Sigma W_{f0} / {}_{\max}W_{f0}$) have roughly constant value, the residual flexural deformation (δ_{f0}) can also be roughly estimated using the maximum residual flexural crack width (${}_{\max}W_{f0}$) as shown in the equation.

$$\delta_{f0} = R_{f0} \cdot h_0 = \left(\frac{1}{D-x} \cdot \left(\frac{\Sigma W_{f0,T} + \Sigma W_{f0,B}}{2} \right) \right) \cdot h_0 = \frac{\Sigma W_{f0}}{D-x} \cdot h_0 = \frac{n_f \cdot {}_{\max}W_{f0}}{D-x} \cdot h_0 \tag{1}$$

where,

δ_{f0} : residual flexural deformation of column (see Figure 7(a))
R_{f0} : residual flexural rotation angle of column (see Figure 7(a))
$\Sigma W_{f0,T}$: total residual flexural crack width at the top of column (measured)
$\Sigma W_{f0,B}$: total residual flexural crack width at the bottom of column (measured)
ΣW_{f0} : average total residual flexural crack width at the top and bottom of column
${}_{\max}W_{f0}$: maximum residual flexural crack width of column (measured)
D : column depth (=450*mm*)
x : distance from extreme compression fiber to neutral axis (0.2D is assumed herein)
n_f : ratio of total residual flexural crack width to maximum one ($=\Sigma W_{f0} / {}_{\max}W_{f0}$)
h_0 : column clear height (=2,400*mm*)

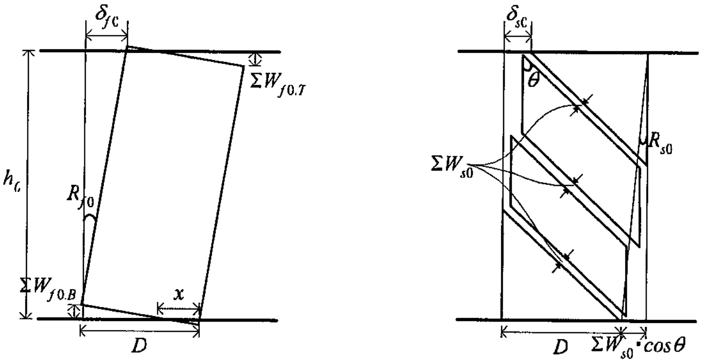
Residual Shear Deformation of RC Column

The residual shear deformation (δ_{s0}) of RC columns can be approximated using the multiplication of the maximum residual shear crack width (${}_{\max}W_{s0}$) by the ratio n_s ($=\Sigma W_{s0} / {}_{\max}W_{s0}$) as well as the measured total residual shear crack width (ΣW_{s0}) as shown in Figure 7(b) and equation (2).

$$\delta_{s0} = R_{s0} \cdot h_0 = \left(\frac{\Sigma W_{s0} \cdot \cos\theta}{h_0} \right) \cdot h_0 = \Sigma W_{s0} \cdot \cos\theta = n_s \cdot {}_{\max}W_{s0} \cdot \cos\theta \tag{2}$$

where,

δ_{s0} : residual shear deformation of column (see Figure 7(b))
R_{s0} : residual shear rotation angle of column (see Figure 7(b))
ΣW_{s0} : total residual shear crack width of column (measured)
${}_{\max}W_{s0}$: maximum residual shear crack width of column (measured)
θ : angle between shear crack and vertical direction of column (=45° is assumed herein)
n_s : ratio of total residual shear crack width to maximum one ($=\Sigma W_{s0} / {}_{\max}W_{s0}$)



(a) Residual flexural deformation (b) Residual shear deformation

Figure 7. Simplified model of column (Maeda et al. 2000)

Residual Deformation of RC Column

As shown in equation (3), the residual deformation of RC columns can be calculated from the sum of residual flexural deformation and residual shear deformations obtained by their crack widths.

$$\delta_0 = \delta_{f0} + \delta_{s0} = \frac{\Sigma W_{f0}}{D-x}\cdot h_0 + \Sigma W_{s0}\cdot \cos\theta = \frac{n_f\cdot{}_{\max}W_{f0}}{D-x}\cdot h_0 + n_s\cdot{}_{\max}W_{s0}\cdot\cos\theta \tag{3}$$

Estimation of Residual Deformation by Residual Crack Width Measured in RC Column

The total and maximum residual flexural crack widths (ΣW_{f0} and ${}_{\max}W_{f0}$), total and maximum residual shear crack widths (ΣW_{s0} and ${}_{\max}W_{s0}$), and their ratios, n_f and n_s, at unloaded stages after each first cycle in the positive domain are plotted for both columns of specimens IW1 and IW2 with respect to the peak drift angle in Figures 8 and 9, respectively. As can be found in the figures, those values (ΣW_{f0}, ${}_{\max}W_{f0}$, ΣW_{s0}, and ${}_{\max}W_{s0}$) tend to increase linearly with respect to the peak drift angle after residual crack widths develop, and their ratios, n_f and n_s, approximately lie in the range of 2.0.

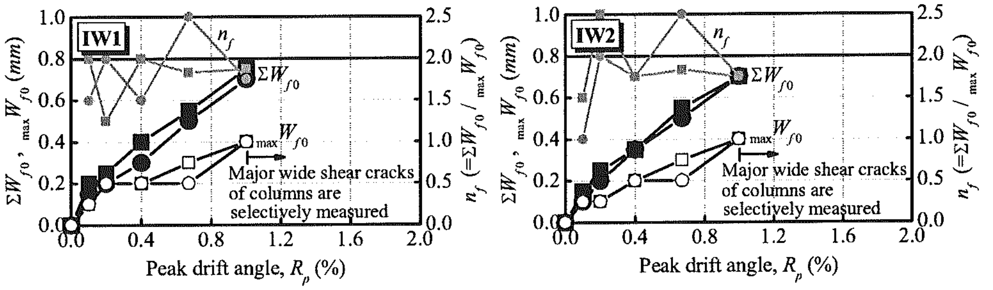


Figure 8. ΣW_{f0}, ${}_{\max}W_{f0}$, and n_f (RC column) vs. peak drift angle R_p

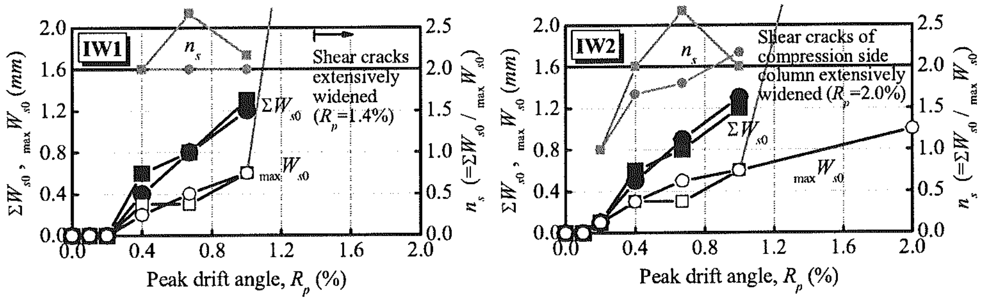


Figure 9. ΣW_{s0}, ${}_{\max}W_{s0}$, and n_s (RC column) vs. peak drift angle R_p

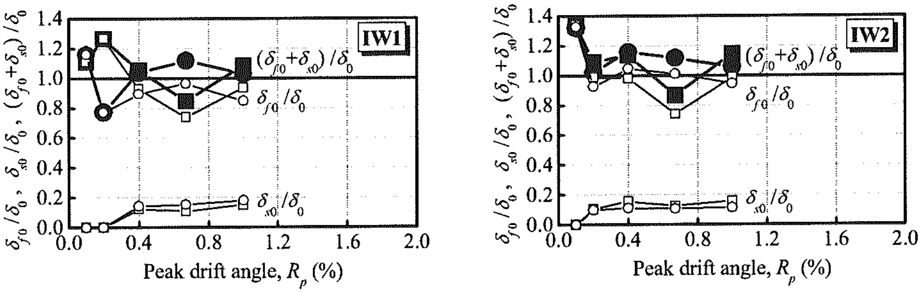


Figure 10. δ_{f0}/δ_0, δ_{s0}/δ_0, and $(\delta_{f0}+\delta_{s0})/\delta_0$ (RC column) vs. peak drift angle R_p

Figure 10 shows the ratios of the residual deformations (δ_{f0}, δ_{s0}, and ($\delta_{f0}+\delta_{s0}$)) calculated from maximum residual flexural and shear crack widths (${}_{\max}W_{f0}$ and ${}_{\max}W_{s0}$) to the residual deformation (δ_0) of frames. After peak drift angle R_p larger than 0.4% where the shear cracks develop, the estimated residual flexural and shear deformations approximately lie in the range of 80% and 20% of the measured residual deformations in frames, respectively. The sum of residual flexural and shear deformations calculated from their crack widths (${}_{\max}W_{f0}$ and ${}_{\max}W_{s0}$) generally compare well with the measured results, and the simplified model as shown in Figure 7 successfully explains the relationship between residual crack width (W_0) and residual deformation (δ_0) for RC columns. This result implies that the residual deformation (δ_0) of frames can be approximately estimated from maximum residual flexural and shear crack widths (${}_{\max}W_{f0}$ and ${}_{\max}W_{s0}$) observed in RC columns.

Relation of Residual Crack Width in CB wall and Residual Deformation

The relationship between residual crack width and residual deformation for RC members has been studied by lots of researchers including Maeda et al. (2000) as mentioned above. Nevertheless, few researches on such relationship for RC frames and/or CB wall infilled frames have been yet made to date. It is therefore of great interest and significance to investigate the applicability of analogous relationship to CB wall infilled frames.

Residual Crack Width in CB Wall

The residual deformation (δ_0), total and maximum residual crack widths ($\Sigma_{\max}W_0$ and ${}_{\max}W_0$) measured in CB wall, and its ratio n_b (=$\Sigma_{\max}W_0 / {}_{\max}W_0$) at unloaded stages after each first cycle in the positive domain are plotted for specimens IW1 and IW2 with respect to the peak drift angle in Figure 11. In this figure, ${}_{\max}W_0$ is defined as the maximum residual crack width, as shown (a) in Figure 6, in the head joints of a continued stair-stepped diagonal crack. When the CB wall has more than one major stair-stepped diagonal crack, ${}_{\max}W_0$ can be found along each continued crack and the sum of ${}_{\max}W_0$ (=$\Sigma_{\max}W_0$) is then calculated. As shown in the figure, the ratio n_b approximately lies in the range of 2.0.

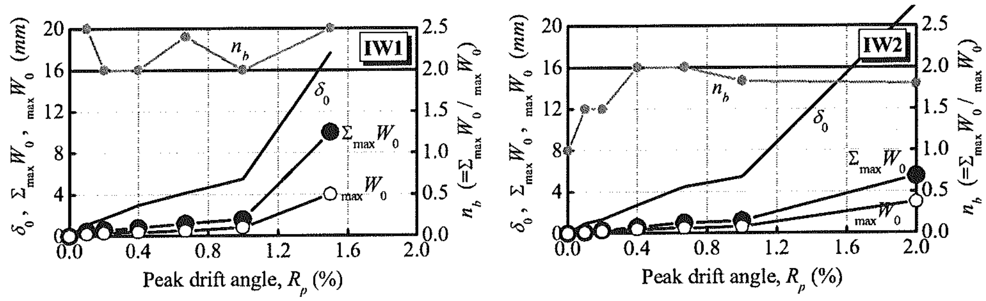


Figure 11. δ_0, $\Sigma_{\max}W_0$, ${}_{\max}W_0$, and n_b (CB wall) vs. peak drift angle R_p

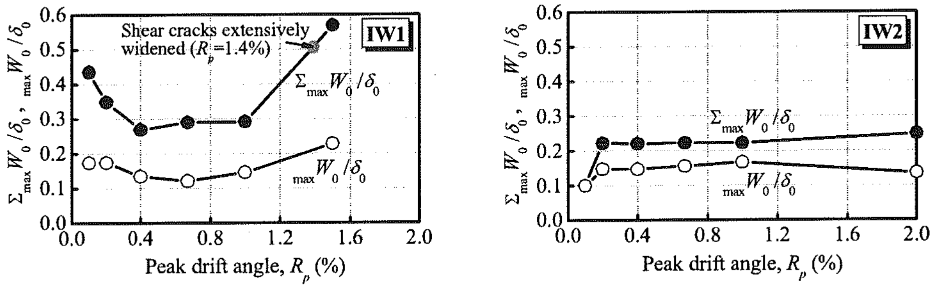


Figure 12. $\Sigma_{\max}W_0/\delta_0$ and ${}_{\max}W_0/\delta_0$ (CB wall) vs. peak drift angle R_p

Figure 12 shows the ratios, $[\Sigma_{\max}W_0/\delta_0]$ and $[{}_{\max}W_0/\delta_0]$, for both specimens. The ratio $[\Sigma_{\max}W_0/\delta_0]$ of specimen IW1 differs from that of IW2 over the peak drift angle R_p smaller than 0.2% and larger than 1.5%. The results can be attributed to the following observations.

(1) The ratio tends to be dependent on crack inspectors especially when the deformation is small (i.e., $R_p \leq 0.2\%$) since the observed crack widths are around 0.1mm which would be the limit for visual inspections. The calculated ratio is therefore sensitive to the measurement error and may not be consistent in the small drift range along different specimens.

(2) The crack widths in CB wall significantly increases after $R_p = 1.4\%$ in IW1 due to extensive shear cracks in columns, while IW2 performs well even in such a large deformation. The ratio is therefore higher in IW1 than in IW2.

It should also be noted that the ratio $[\Sigma_{\max}W_0/\delta_0]$ approximately lies in the range of 0.2 to 0.3 over the peak drift angle larger than 0.2 % and much smaller than 1.0. The reason can be found in the following section.

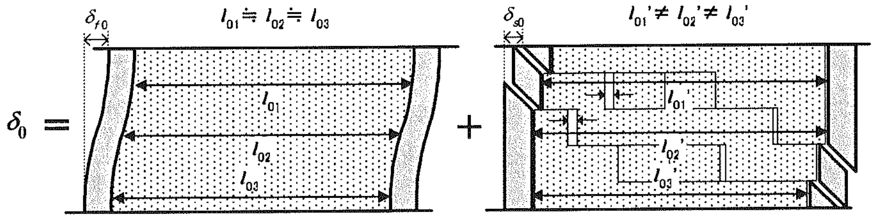
Estimation of Residual Crack Width Measured in CB Wall by Simplified Model

(1) General assumptions

In order to investigate the crack development mechanism and to estimate the residual crack width in CB wall, the following assumptions are set up.

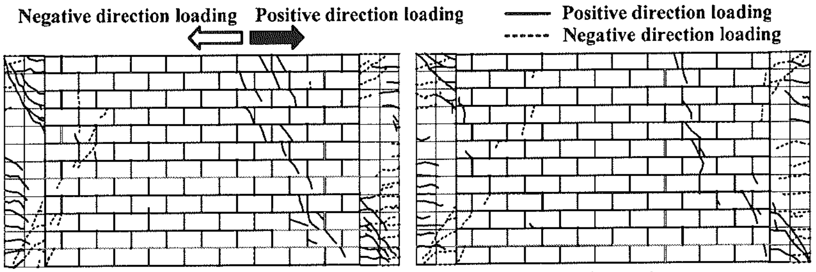
1) The residual deformation (δ_0) of frame can be approximated by the sum of residual flexural deformation (δ_{f0}) and residual shear deformation (δ_{s0}) of column as shown in Figures 13(a) and (b). (i.e., $\delta_0 = \delta_{f0} + \delta_{s0}$)
2) Residual cracks in head joints of CB wall result from the discrepancy of residual deformation distribution along its height in each column.

If each column has an identical anti-symmetrical residual flexural deformation and distribution as shown in Figure 13(a), no discrepancy should be found in the CB wall's clear span length l_{0i} along column height (i.e., $l_{01} \approx l_{02} \approx l_{03}$). Since a similar residual flexural deformation distribution is observed in each column during tests, no major cracks due to residual flexural deformation are expected.



(a) Residual flexural deformation (b) Residual shear deformation

Figure 13. Residual deformation of column and CB wall



(a) IW1 (b) IW2

Figure 14. Cracks in RC columns and CB walls at the first cycle with peak drift angle of 1.0%

The residual shear deformation distribution along its height in each column, however, is not obviously identical as shown in Figure 13(b), since the residual deformation due to residual shear cracks concentrates on the bottom of compression column and the top of tensile column resulting from a compressive strut action as can be found in specimens IW1 and IW2 (see Figure 14). This may cause the discrepancy of lateral deformation distribution in CB wall along column height (i.e., $l_{01}' \neq l_{02}' \neq l_{03}'$). The maximum discrepancy, which may be simply expressed by the residual shear deformation (δ_{s0}) as shown in Figure 13(b), then needs to be consistent with residual crack widths in head joints resulting in high correlation between the residual shear deformation (δ_{s0}) and total residual crack width in CB wall ($\Sigma_{\max} W_0$).

Bearing in mind that the residual flexural deformation may highly contribute to the overall residual deformation of long columns but that the residual flexural deformation, as is described earlier, may not cause major residual cracks in head joints, the ratio [$\Sigma_{\max} W_0 / \delta_0$] can be expected to be small as demonstrated in Figure 12. In the subsequent discussions, a simplified model considering the discrepancy of residual flexural and shear deformation distribution is proposed to estimate the residual crack width in CB wall, and the correlation between measured and estimated results is discussed.

(2) Crack width due to flexural deformation

Figure 15 shows the outline of the simplified model studied herein. The residual flexural deformations, ${}_t\delta_{f0}$ and ${}_c\delta_{f0}$, of each column can be approximated using the average total residual flexural crack width at the top and bottom of column as shown in equations (4) and (5) (AIJ 2004), where "t" and "c" denote "tension side" and "compression side", respectively. The maximum discrepancy between two columns due to residual flexural deformation distribution, which causes minor cracks in head joints as discussed earlier, is assumed herein to develop in the mid-height of column ($h_0/2$) as shown in equation (6).

$$ {}_t\delta_{f0} = {}_tR_{f0} \cdot h_0 = \frac{1}{D-x} \cdot \left(\frac{\Sigma_t W_{f0,T} + \Sigma_t W_{f0,B}}{2} \right) \cdot h_0 \tag{4} $$

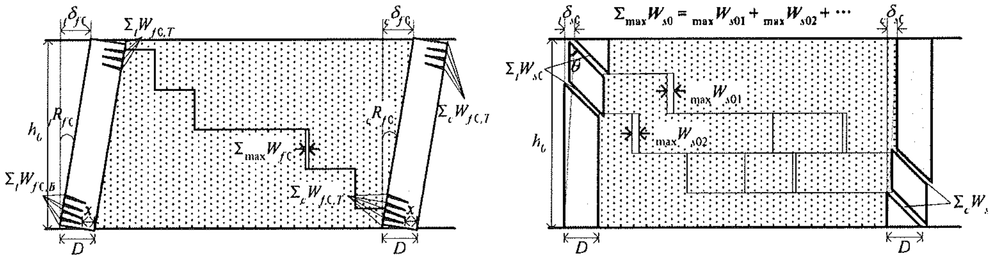
$$ {}_c\delta_{f0} = {}_cR_{f0} \cdot h_0 = \frac{1}{D-x} \cdot \left(\frac{\Sigma_c W_{f0,T} + \Sigma_c W_{f0,B}}{2} \right) \cdot h_0 \tag{5} $$

$$ \Sigma_{\max} W_{f0} = \left(\frac{\Sigma_c W_{f0,B} - \Sigma_t W_{f0,B}}{D-x} \right) \cdot \frac{h_0}{2} \tag{6} $$

where,

${}_t\delta_{f0}$, ${}_c\delta_{f0}$: residual flexural deformation of tension and compression side column, respectively (see Figure 15(a))

${}_tR_{f0}$, ${}_cR_{f0}$: residual flexural rotation angle of tension and compression side column, respectively (see Figure 15(a))



(a) Residual flexural deformation (b) Residual shear deformation

Figure 15. Simplified model of column and CB wall

$\Sigma_t W_{f0,T}$, $\Sigma_t W_{f0,B}$: total residual flexural crack width of top and bottom in tension column, respectively (measured)

$\Sigma_c W_{f0,T}$, $\Sigma_c W_{f0,B}$: total residual flexural crack width of top and bottom in compression column, respectively (measured)

$\Sigma_{\max} W_{f0}$: total residual crack width in CB wall due to the discrepancy of flexural deformation distribution

(3) Crack width due to shear deformation

The residual shear deformation, ${}_t\delta_{s0}$ and ${}_c\delta_{s0}$, of two RC columns can be approximated based on the measured total residual shear crack width of each column as shown in equations (7) and (8) (AIJ 2004). The total residual crack width in CB wall due to different residual shear deformation distribution between tension and compression side column can be estimated using the average total residual shear crack width as shown in equation (9).

$$ {}_t\delta_{s0} = \Sigma_t W_{s0} \cdot \cos\theta \tag{7} $$

$$ {}_c\delta_{s0} = \Sigma_c W_{s0} \cdot \cos\theta \tag{8} $$

$$ \Sigma_{\max} W_{s0} = \frac{{}_c\delta_{s0} + {}_t\delta_{s0}}{2} \left(= \frac{(\Sigma_c W_{s0} + \Sigma_t W_{s0}) \cdot \cos\theta}{2} \right) \tag{9} $$

where,

${}_t\delta_{s0}$, ${}_c\delta_{s0}$: residual shear deformation of tension and compression side column, respectively (see Figure 15(b))

$\Sigma_t W_{s0}$, $\Sigma_c W_{s0}$: total residual shear crack width of tension and compression side column, respectively (measured)

$\Sigma_{\max} W_{s0}$: total residual crack width in CB wall due to the shear deformation distribution

(4) Total crack width in CB wall

As shown in equation (10), the total residual crack width in CB wall, $\Sigma_{\max} W_0$, can be calculated using crack widths defined in equations (6) and (9).

$$ \Sigma_{\max} W_0 = \Sigma_{\max} W_{f0} + \Sigma_{\max} W_{s0} = \left(\frac{\Sigma_c W_{f0,B} - \Sigma_t W_{f0,B}}{D - x} \right) \cdot \frac{h_0}{2} + \frac{(\Sigma_c W_{s0} + \Sigma_t W_{s0}) \cdot \cos\theta}{2} \tag{10} $$

Figure 16 shows the residual deformation δ_0 and δ_{f0} with respect to the peak drift angle, where δ_{f0} is assumed to be the average of ${}_t\delta_{f0}$ and ${}_c\delta_{f0}$ at unloaded stages derived from equations (4) and (5). Since major wide cracks are selectively measured after 1.0% drift, δ_{f0} is plotted up to 1.0%. As mentioned above, δ_{f0} mainly contributes to the overall residual deformation δ_0. It is also interesting to point out that the ratio of residual crack widths $\Sigma_{\max} W_{f0}$ to δ_{f0} is relatively small, which is consistent with the

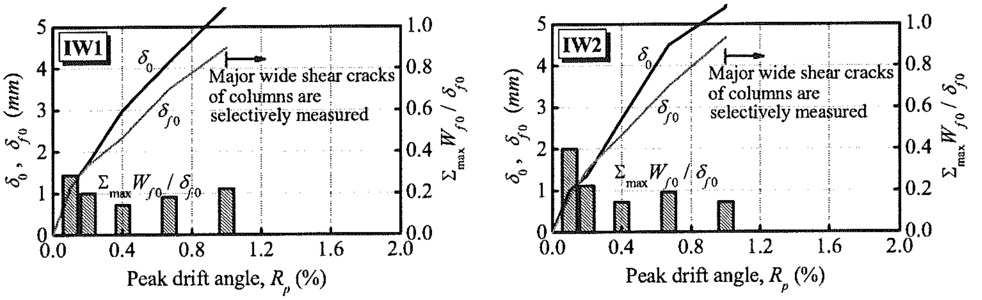


Figure 16. δ_0, δ_{f0}, and $[\Sigma_{\max} W_{f0} / \delta_{f0}]$ vs. peak drift angle R_p

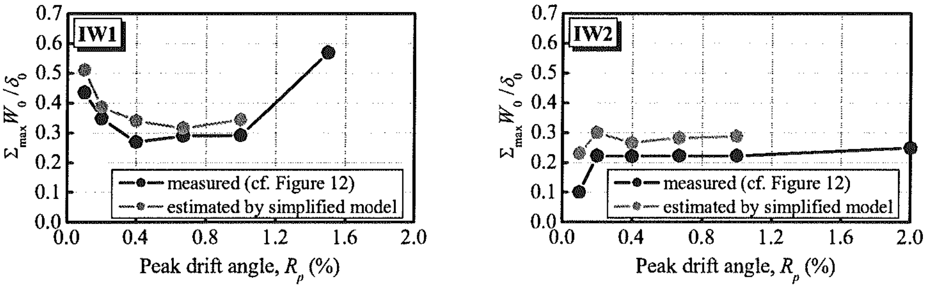


Figure 17. $[\Sigma_{max}W_0/\delta_0]$ vs. peak drift angle R_p (in positive loading)

results shown in Figure 12. This is mainly because the flexural deformation distribution along their height of two boundary columns does not differ much (i.e., $l_{01} \approx l_{02} \approx l_{03}$) and therefore leads to minor cracks in head joints.

Figure 17 shows the estimated crack widths in CB wall at unloaded stages obtained from equation (10) together with measured results. The estimated results slightly overestimate the measured results since all cracks developed in CB wall are not perfectly measured during tests. The estimated results, however, generally compare well with the measured results and the proposed model shown in Figure 15 successfully explains the crack development mechanism of CB wall studied herein. This result implies that the residual deformation (δ_0) of frames as well as RC members can be estimated from residual crack widths ($\Sigma_{max}W_0$) observed in CB wall based on the ratio $[\Sigma_{max}W_0/\delta_0]$. The residual seismic capacity, therefore, could be evaluated through previously estimated δ_0 if the typical hysteretic characteristics of CB wall infilled frame are given.

RELATION OF RESIDUAL DEFORMATION AND RESIDUAL SEISMIC CAPACITY

In previous section, the relationship between residual crack widths (W_0) carefully measured in columns and CB walls and residual deformation (δ_0) of frames (see Figure 5(b)) is evaluated by simplified models. In this section, the relationship between residual deformation (δ_0) and residual seismic capacity (E_r) (see Figure 5(a)) is analytically and experimentally investigated to directly estimate the residual seismic capacity of CB wall infilled RC frames from the residual crack widths measured in RC columns and CB walls (see Figure 5(c)).

Figure 18 shows the load-rotation angle relations of specimens IW1 and IW2. The residual seismic capacity (E_r) corresponding to the level of each residual rotation angle (R_0) can be experimentally estimated from the test results as shown in Figure 18. The ultimate rotation angle R_u is assumed the rotation angle when the maximum load deteriorates to its 80%, and the ultimate ductility factor μ of

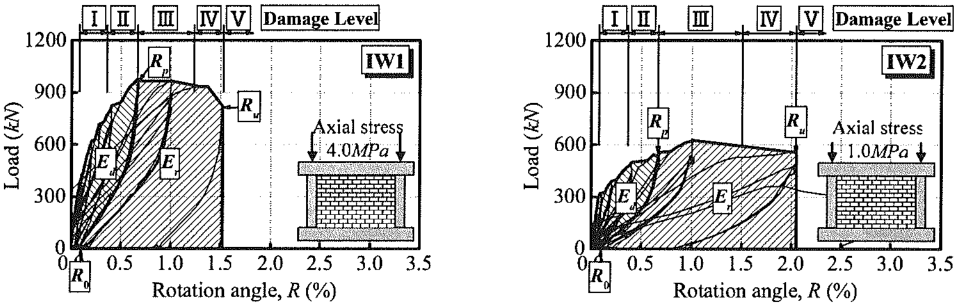


Figure 18. Load-rotation angle relations of specimens IW1 and IW2

specimens IW1 and IW2 then is approximately 2.0 and 3.0, respectively.

To analytically estimate such relationship, the typical hysteretic characteristic for CB wall infilled RC frames is proposed as shown in Figure 19 based on test results of specimens IW1 and IW2 of Figure 18. The proposed hysteretic characteristic is defined as:

(1) The proposed hysteretic characteristic is represented by Takeda model.
(2) The yield load and rotation angle at yield point is represented by Q_y and R_y, respectively.
(3) The cracking load Q_{cr} and rotation angle at cracking point R_{cr} are assumed herein to $Q_y/3$ and $R_y/15$, respectively.
(4) The deformation capacity of frames varies with the ultimate ductility factor μ.
(5) After the ultimate rotation angle R_u develop, the strength deteriorates toward $(\mu+1)R_u$.
(6) The stiffness degradation factor α at unloaded stages is determined as 0.7 from test results.

In this study, the seismic capacity reduction factor η representing residual seismic capacity is defined as the ratio of residual seismic capacity (E_r) to initial seismic capacity (E_T) as shown in equation (11).

$$\eta = \frac{E_r}{E_d + E_r} = \frac{E_r}{E_T} \tag{11}$$

where,

η : seismic capacity reduction factor representing residual seismic capacity
E_T : initial (pre-earthquake) seismic capacity (see Figures 18 and 19)
E_d : dissipated seismic capacity (see Figures 18 and 19)
E_r : residual seismic capacity (see Figures 18 and 19)

Figure 20 shows the analytical results for the seismic capacity reduction factor η corresponding to the level of each residual rotation angle (R_0) obtained from proposed model of Figure 19 together with the experimental results obtained from test results of Figure 18, where the analytical results are plotted according to the ultimate ductility factor μ = 1 - 6. As shown in Figure 20, both results are approximately consistent with 2.0 and 3.0 of the ultimate ductility factor μ, respectively, and the relationship between residual deformation δ_0 and seismic capacity reduction factor η is analytically and experimentally clarified.

ESTIMATION OF RESIDUAL SEISMIC CAPACITY

In this section, the residual seismic capacity of CB wall infilled RC frames is directly estimated from the residual crack widths measured in RC columns and CB walls using the results clarified in the previous sections, and the residual seismic capacity corresponding to each damage level is proposed based on the Japanese guidelines and test results.

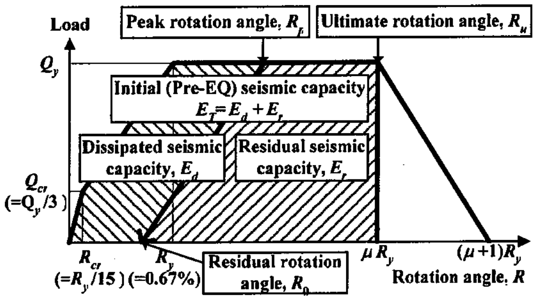


Figure 19. Model of hysteretic characteristic

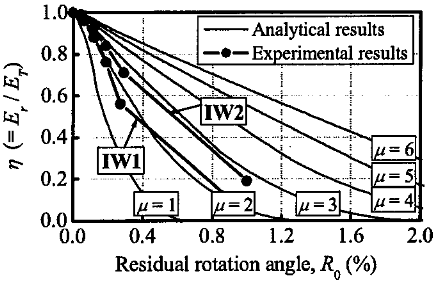


Figure 20. η -R_0 relations

Estimation of Residual Seismic Capacity by Residual Crack Width

Both the relationship between residual crack widths (W_0) and residual deformation (δ_0) (see Figure 5(b)) and that of residual deformation (δ_0) and residual seismic capacity represented by seismic capacity reduction factor (η) (see Figure 5(a)) discussed in the previous sections are used to directly estimate the residual seismic capacity of CB wall infilled RC frames from the residual crack width measured in RC columns and CB walls.

Assuming that $R_{f0}=0.8R_0$, $R_{s0}=0.2R_0$ (see Figure 10), $n_f=n_s=2$ (see Figures 8 and 9), $x=0.2D$, $\theta=45°$, $D=450mm$, and $h_0=2400mm$, the relationship between maximum residual flexural and shear crack widths (${}_{\max}W_{f0}$ and ${}_{\max}W_{s0}$) in RC columns and residual rotation angle (R_0) can be obtained as shown in equation (12) and (13) from equations (1) and (2). Figures 21(a) and (b) show the relationship between calculated maximum residual flexural and shear crack widths (${}_{\max}W_{f0}$ and ${}_{\max}W_{s0}$) in RC columns derived from equations (12) and (13) and seismic capacity reduction factor (η) together with measured results.

$$ {}_{\max}W_{f0} = 144 \cdot R_0 = 0.06 \cdot \delta_0 \tag{12} $$

$$ {}_{\max}W_{s0} = 340 \cdot R_0 = 0.14 \cdot \delta_0 \tag{13} $$

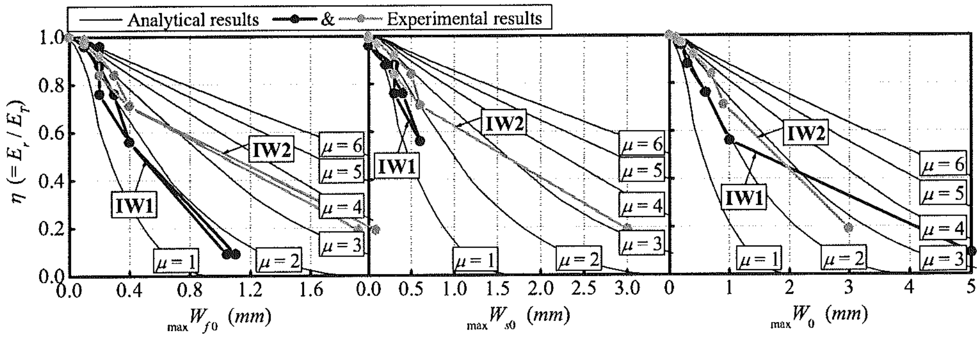
The relationship between maximum residual crack width (${}_{\max}W_0$) in CB walls and residual rotation angle (R_0) can be obtained as shown in equation (14) using the ratio [${}_{\max}W_0/\delta_0$] which approximately lies in the range of 0.125 (0.1 to 0.15) as shown in Figure 12. Figures 21(c) shows the relationship between calculated maximum residual crack width (${}_{\max}W_0$) in CB walls derived from equation (14) and seismic capacity reduction factor (η) together with measured results.

$$ {}_{\max}W_0 = 300 \cdot R_0 = 0.125 \cdot \delta_0 \tag{14} $$

As shown in Figures 21(a) through (c), both results are approximately consistent with 2.0 and 3.0 of the ultimate ductility factor μ, respectively, and the relationship between residual crack widths (W_0) in RC columns and CB walls and seismic capacity reduction factor (η) is analytically and experimentally clarified. This result implies that residual seismic capacity of CB wall infilled RC frames can be estimated from residual crack widths in RC columns and CB walls observed in damaged buildings.

Estimation of Residual Seismic Capacity Corresponding to Damage Level

In this section, the residual seismic capacity represented by seismic capacity reduction factor (η) corresponding to each damage level for CB wall infilled RC frames is estimated using the load-



(a) Maximum residual flexural crack width in both columns (b) Maximum residual shear crack width in both columns (c) Maximum residual crack width in CB walls

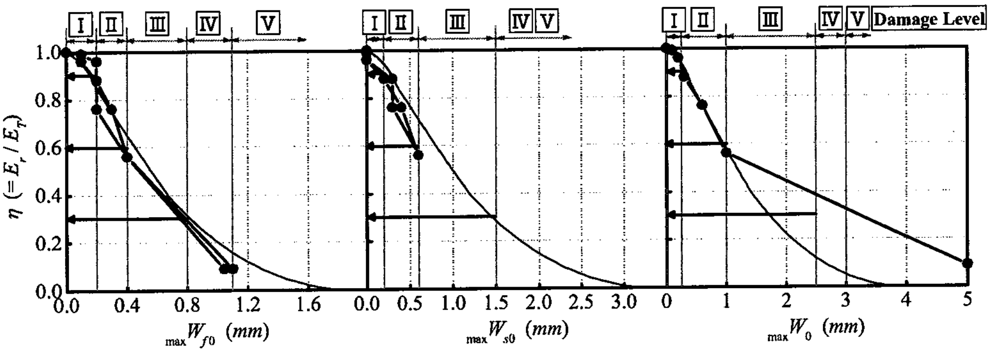
Figure 21. Relation of residual crack width and seismic capacity reduction factor

deformation relation of specimen IW1 assuming a first story where damage is expected to be the largest under an earthquake. The damage levels are identified based on the Guidelines for post-earthquake damage evaluation and rehabilitation (JBDPA 2001) and the failure pattern of specimen IW1. As shown in Figure 18, the damage levels are classified to five stages in the following manner; damage levels Ⅰ and Ⅱ are represented from crack developing point to maximum strength point, damage level Ⅲ as until crushing of cover concrete, damage level Ⅳ as until bucking of main bars, and final damage level Ⅴ follows damage level Ⅳ.

Figures 22(a) through (c) show the seismic capacity reduction factor (η) corresponding to each damage level for CB wall infilled RC frames, where the seismic capacity reduction factor (η) is determined as the lowest average value of experimental and analytical results in each damage level. Table 1 shows the seismic capacity reduction factors (η) corresponding to each damage level for CB wall infilled RC frames together with those factors determined in Japanese guidelines (JBDPA 2001). As can be found the table, the value of η at damage level Ⅳ is approximately assumed to be zero, since the strength deterioration of frame occur in damage level Ⅳ. The seismic residual reduction factors (η) determined in this study are almost same as those of RC walls with/without RC columns and shear RC column in Japanese guidelines. Since specimen IW1 is not to long maintain the maximum strength and finally fails in shear due to shear force acting on the column bottom of the compression side, it is rationally expectable result that the values of η determined in this study are consistent well with those of RC walls with/without RC columns and shear RC column in Japanese guidelines.

Table 1. Seismic capacity reduction factor corresponding to damage level

Damage Level	JBDPA (2001)					This study
	Flexural RC column	Shear RC column	RC Walls with no boundary RC column	RC Walls with one boundary RC column	RC Walls with two boundary RC columns	CB walls with two boundary RC columns
Ⅰ	0.95	0.95	0.95	0.95	0.95	0.90
Ⅱ	0.75	0.60	0.60	0.60	0.60	0.60
Ⅲ	0.50	0.30	0.30	0.30	0.30	0.30
Ⅳ	0.10	0.00	0.00	0.00	0.00	0.00
Ⅴ	0.00	0.00	0.00	0.00	0.00	0.00



(a) Maximum residual flexural crack width in both columns (b) Maximum residual shear crack width in both columns (c) Maximum residual crack width in CB walls

Figure 22. Seismic capacity reduction factor corresponding to each damage level

CONCLUSIONS

Concrete block (CB) infilled RC frames for school buildings in Korea are tested under cyclic loading to estimate the residual seismic capacity of those frames from residual crack widths measured in RC columns and CB walls. The results can be summarized as follows.

(1) The relationship between residual crack widths in RC columns and residual deformation is discussed by simplified model. The sum of residual flexural and shear deformations obtained from their crack widths generally compare well with the measured results, and the simplified model successfully explains the relationship between residual crack width and residual deformation for RC columns. This result implies that the residual deformation of frames can be roughly estimated from maximum residual flexural and shear crack widths observed in damaged RC columns.

(2) The simplified model for CB wall is proposed to investigate the crack development mechanism. The measured ratio $[\Sigma_{\max} W_0 / \delta_0]$ for specimens IW1 and IW2 approximately lies in the range of 0.2 to 0.3. Although the ratio $[\Sigma_{\max} W_0 / \delta_0]$ is much smaller than 1.0, the simplified model considering residual flexural and shear deformation distribution of columns can rationally reproduce the measured results and successfully explains the crack development mechanism of CB wall. This result implies that residual deformation of frames as well as RC members can be estimated from residual crack widths observed in CB wall based on the ratio $[\Sigma_{\max} W_0 / \delta_0]$.

(3) The relationship between residual deformation and residual seismic capacity is analytically and experimentally investigated. Both results are approximately consistent with 2.0 and 3.0 of the ultimate ductility factor μ, respectively, and the relationship is successfully explained.

(4) The relationship between residual crack widths in RC columns and CB walls and seismic capacity reduction factor is analytically and experimentally clarified using both relations (W_0-δ_0 and δ_0-η). This result implies that residual seismic capacity of CB wall infilled RC frames can be estimated from residual crack widths in RC columns and CB walls observed in damaged buildings.

(5) The seismic residual reduction factors corresponding to each damage level determined in this study are almost same as those of RC walls with/without RC columns and shear RC column in Japanese guidelines. Since specimen IW1 is not to long maintain the maximum strength and finally fails in shear due to shear force acting on the column bottom of the compression side, it is rationally expectable result that the values of η determined in this study are consistent well with those of RC walls with/without RC columns and shear RC column in Japanese guidelines.

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