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

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SUMMARY

The 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 are tested under cyclic loadings. In this paper, simplified models are proposed to estimate residual deformations from residual crack widths in columns and concrete block walls, and the residual seismic capacity corresponding to residual crack width (or damage level) is discussed analytically and experimentally. The simplified models proposed in this study can rationally reproduce the measured crack widths, and the relation of residual deformation and residual seismic capacity can be successfully explained by analytical and experimental investigations. The residual seismic capacity of concrete block wall infilled RC frames can be, therefore, directly estimated from residual crack widths in RC columns and concrete block walls observed in damaged buildings.

1. INTRODUCTION

After an earthquake, the major concerns to damaged buildings are their safety/risk to aftershocks, quantitative damage assessment to evaluate their residual seismic capacity. Post-event damage evaluation is therefore essential for quick recovery of damaged communities. Few investigations on masonry 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 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 are proposed to estimate residual deformations from residual crack widths in columns and CB walls, and the residual seismic capacity corresponding to the level of each residual deformation is discussed analytically and experimentally. The residual seismic capacity corresponding to residual crack width (or damage level) is further evaluated by the relations studied herein.

2. OUTLINE OF EXPERIMENT

2.1 Test Specimen

Figure 1 shows a standard design for Korean school buildings in the 1980s [The Ministry of Construction and Transportation, 2002]. CB walls are commonly used as partition walls or exterior walls in Korean school buildings.

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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. 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.

2.2 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. For loading history, 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). 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.

3. BASIC CONCEPT TO EVALUATE RESIDUAL SEISMIC CAPACITY

Figure 4 shows the basic concept to evaluate the residual seismic capacity from residual crack widths observed in damaged buildings after an earthquake.
If a test for members and frames is carried out under cyclic or dynamic loading in laboratory, the residual seismic capacity can be calculated by the discrepancy of initial seismic capacity and dissipated seismic capacity based on the load-deformation curve as shown in Figure 4(a) ($E_r = E_T - E_d$), and the residual seismic capacity corresponding to the level of residual deformation (δ_0-E_r relation) can be, therefore, estimated from test results.
Since only residual crack widths (W_0) are, however, observed in damaged buildings as shown in Figure 4(b), it is necessary to previously investigate the relation of residual crack width and residual deformation (W_0-δ_0 relation) in order to directly estimate the residual seismic capacity from residual crack widths (W_0-E_r relation, see Figure

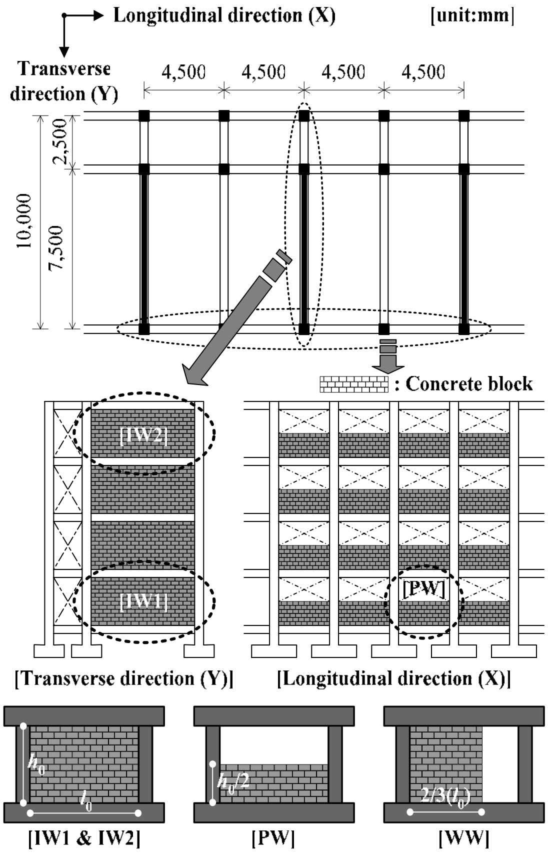


Figure 1: Standard design of Korean school buildings in the 1980s

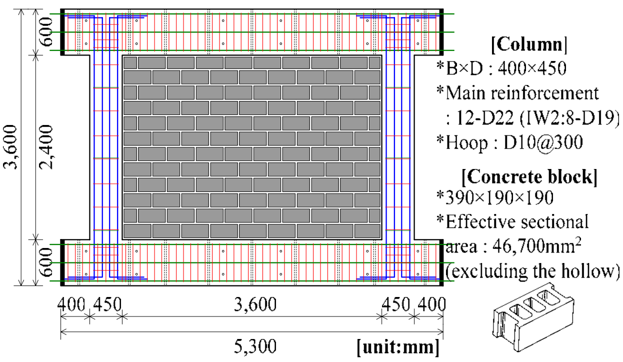


Figure 2: Detail of specimen IW1

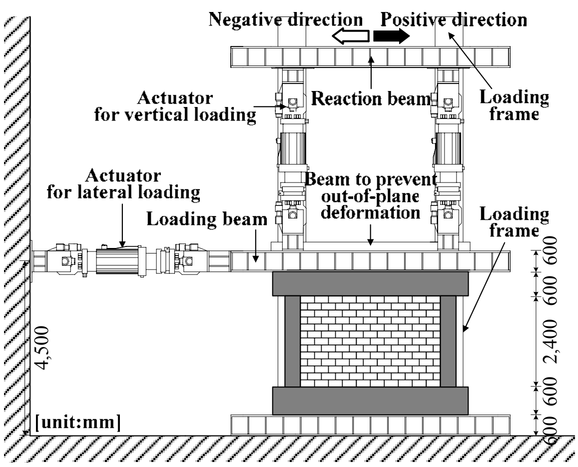


Figure 3: Test setup

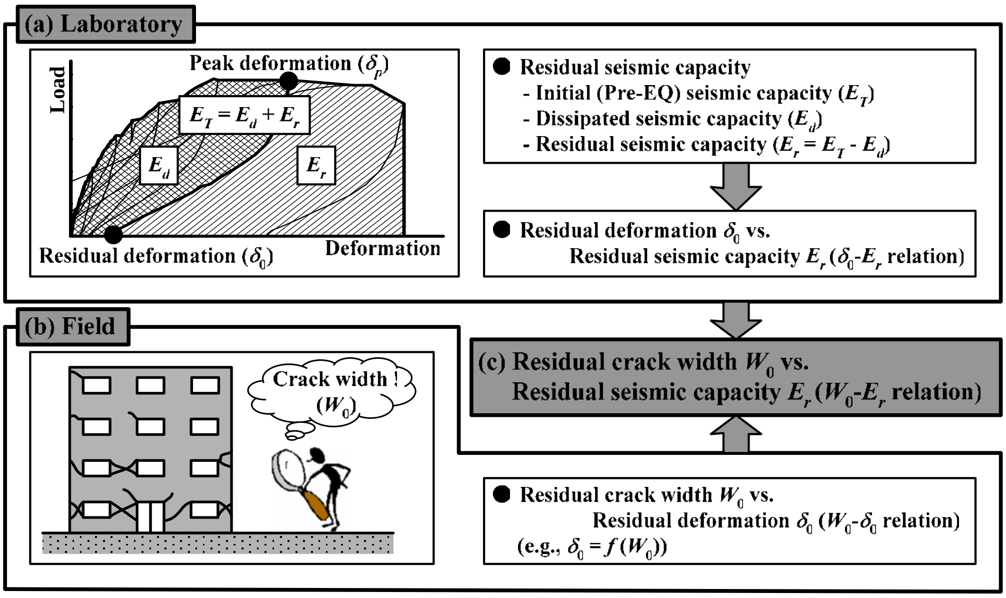


Figure 4: Basic concept to evaluate residual seismic capacity

4(c)) on the damaged buildings.
In the following sections, W_0-δ_0 relation (see Figure 4(b)) and δ_0-E_r relation (see Figure 4(a)) are investigated, respectively, to develop W_0-E_r relation (see Figure 4(c)) for CB wall infilled RC frames.

4. RELATION OF RESIDUAL CRACK WIDTH AND RESIDUAL DEFORMATION

In this section, the simplified models are proposed to investigate the relation of residual crack widths measured in RC columns and CB walls and residual deformation of frames (W_0-δ_0 relation, see Figure 4(b)).

4.1 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 5 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 5) while several cracks in the bed joints of one continued crack are measured to investigate a rotational behavior of wall (see (b) in Figure 5).

4.2 Relation of Residual Crack Width in RC Column and Residual Deformation

Based on the studies by Maeda et al. [2000], AIJ Guidelines [2004] define W_0-δ_0 relation for RC members by a simplified model. In this model, the residual deformation of RC members is evaluated by means of dividing into flexural and shear deformation as shown in Figures 6(a) and (b). In this section, the simplified model is applied to columns of CB wall infilled RC frames.

4.2.1 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 $D*R_{f0}$ as shown in Figure 6(a), since the flexural deformation of RC columns can be approximately evaluated by the rigid body rotation [Maeda et al., 2000]. The residual flexural deformation (δ_{f0}) of columns can be, therefore, 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, δ_{f0} can also be estimated using the maximum residual flexural crack width (${}_{\max}W_{f0}$) as shown in the equation.

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

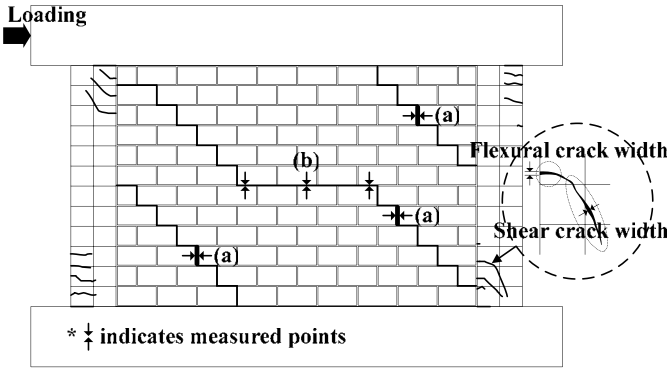
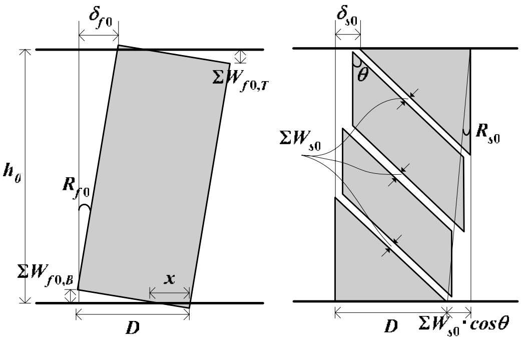


Figure 5: Schematic illustration of measured points



(a) flexural deform. (b) shear deform.

Figure 6: Simplified model of column

where,

δ_{f0}, R_{f0} : residual flexural deformation and rotation angle of column, respectively (see Figure 6(a))
$\Sigma W_{f0,T}$, $\Sigma W_{f0,B}$: total residual flexural crack width at the top and bottom of column, respectively (measured)
ΣW_{f0}, ${}_{\max}W_{f0}$: average total and maximum residual flexural crack width, respectively (measured)
D, h_0 : column depth (=450mm) and column clear height (=2,400mm), respectively
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 ($=\Sigma W_{f0} / {}_{\max}W_{f0}$)

4.2.2 *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 6(b) and equation (2).
Therefore, the residual deformation of RC columns can be calculated from the sum of residual flexural deformation (equation (1)) and residual shear deformation (equation (2)) obtained by their crack widths.

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

where,

δ_{s0}, R_{s0} : residual shear deformation and rotation angle of column (see Figure 6(b))
ΣW_{s0}, ${}_{\max}W_{s0}$: total and 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 ($=\Sigma W_{s0} / {}_{\max}W_{s0}$)

4.2.3 *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 in the positive domain are plotted for specimens IW1 and IW2 with respect to the peak drift angle in Figures 7 and 8, respectively. As shown 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 then their ratios, n_f and n_s, approximately lie in the range of 2.0.
Figure 9 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 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 deformation calculated from their crack widths (${}_{\max}W_{f0}$ and ${}_{\max}W_{s0}$) generally compare well with the measured results, and the simplified model in Figure 6 successfully explains W_0-δ_0 relation for RC columns. This result implies that the residual deformation of frames can be approximately estimated from maximum residual flexural and shear crack widths observed in RC columns.

4.3 Relation of Residual Crack Width in CB Wall and Residual Deformation

As mentioned above, W_0-δ_0 relation for RC members has been studied by some researchers including Maeda et al. [2000]. Nevertheless, few researches on W_0-δ_0 relation 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.

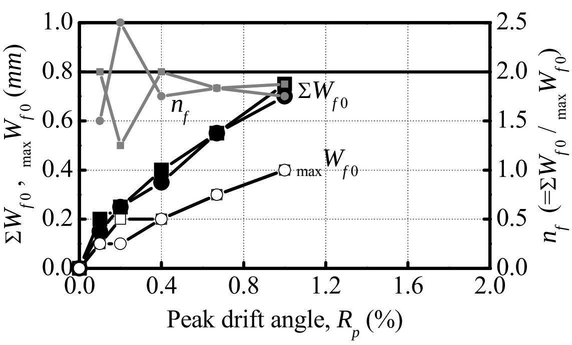


Figure 7: ΣW_{f0}, $_{max}W_{f0}$, and n_f

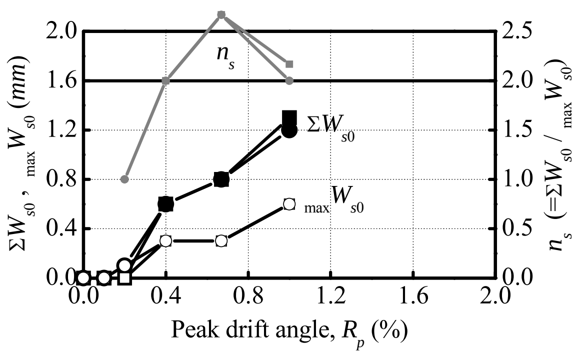


Figure 8: ΣW_{s0}, $_{max}W_{s0}$, and n_s

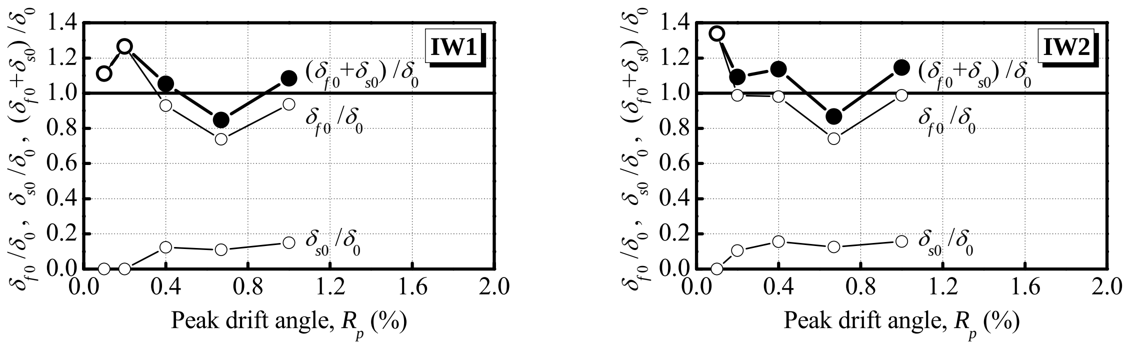


Figure 9: δ_{f0}/δ_0, δ_{s0}/δ_0, and $(\delta_{f0}+\delta_{s0})/\delta_0$

4.3.1 Residual crack width in CB wall

The residual deformation (δ_0), total and maximum residual crack widths ($\Sigma_{max}W_0$ and $_{max}W_0$) in CB wall, and their ratios, [$\Sigma_{max}W_0/\delta_0$] and [$_{max}W_0/\delta_0$], are plotted for specimens IW1 and IW2 with respect to the peak drift angle in Figure 10. In this figure, $_{max}W_0$ is defined as the maximum residual crack width, as shown (a) in Figure 5, 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 [$\Sigma_{max}W_0/\delta_0$] approximately lies in the range of 0.2 to 0.3. The reason can be found in the following section.

4.3.2 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 11(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 11(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

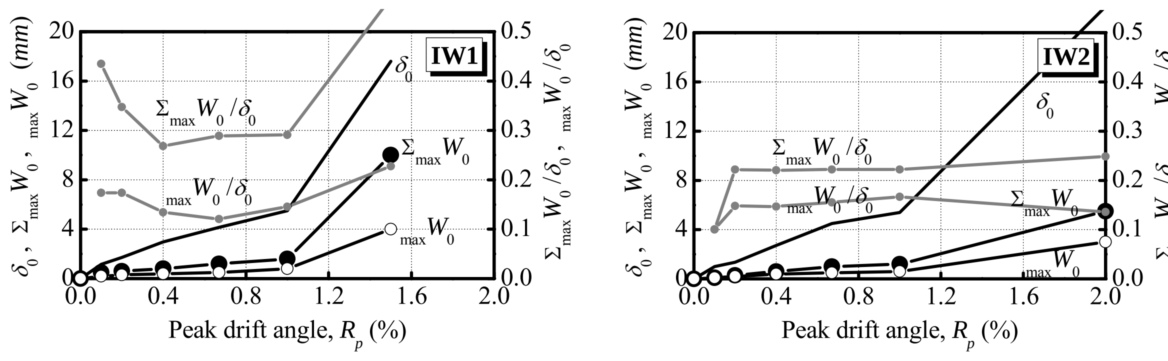


Figure 10: δ_0, $\Sigma_{max}W_0$, $_{max}W_0$, $\Sigma_{max}W_0/\delta_0$, and $_{max}W_0/\delta_0$

major cracks due to residual flexural deformation are expected.

The residual shear deformation distribution along its height in each column, however, is not obviously identical as shown in Figure 11(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. 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 11(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 ($\Sigma_{\max} W_0$).

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 11 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 (3) and (4) [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 (5).

$$ {}_t\delta_{f0} = {}_tR_{f0} \cdot h_0 = \frac{\Sigma_t W_{f0,T} + \Sigma_t W_{f0,B}}{2 \cdot (D-x)} \cdot h_0 , \quad {}_c\delta_{f0} = {}_cR_{f0} \cdot h_0 = \frac{\Sigma_c W_{f0,T} + \Sigma_c W_{f0,B}}{2 \cdot (D-x)} \cdot h_0 \tag{3), (4} $$

$$ \Sigma_{\max} W_{f0} = \left(\frac{\Sigma_c W_{f0,B} - \Sigma_t W_{f0,B}}{D-x} \right) \cdot \frac{h_0}{2} \tag{5} $$

where,

${}_t\delta_{f0}$, ${}_c\delta_{f0}$: residual flexural deformation of tension and compression side column, respectively (see Figure 11(a))
${}_tR_{f0}$, ${}_cR_{f0}$: residual flexural rotation angle of tension and compression side column, respectively (see Figure 11(a))
$\Sigma_t W_{f0,T}$, $\Sigma_t W_{f0,B}$: 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

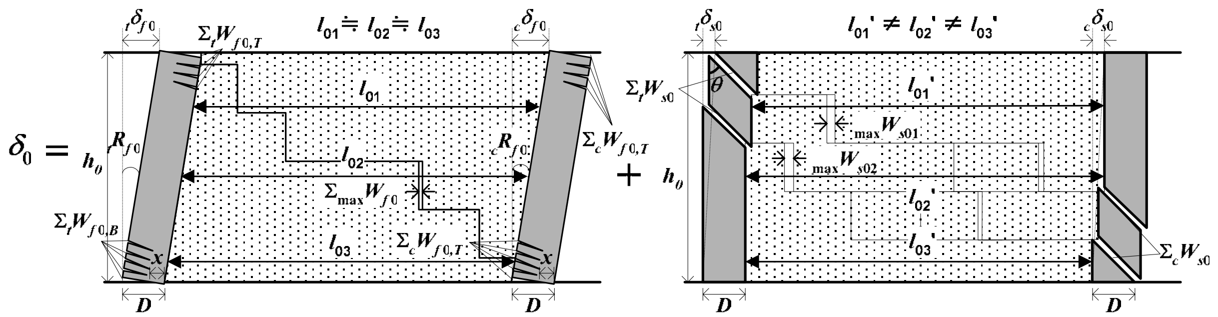
(3) Crack width due to shear deformation

The residual shear deformations, ${}_t\delta_{s0}$ 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 (6) and (7) [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 (8).

Therefore, the total residual crack width in CB wall, $\Sigma_{\max} W_0$, can be calculated by the sum of crack widths defined in equations (5) and (8).

$$ {}_t\delta_{s0} = \Sigma_t W_{s0} \cdot \cos\theta , \quad {}_c\delta_{s0} = \Sigma_c W_{s0} \cdot \cos\theta \tag{6), (7} $$

$$ \Sigma_{\max} W_{s0} = \frac{{}_c\delta_{s0} + {}_t\delta_{s0}}{2} \left(= \frac{(\Sigma_c W_{s0} + \Sigma_t W_{s0}) \cdot \cos\theta}{2} \right) \tag{8} $$



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

Figure 11: Simplified model of column and CB wall

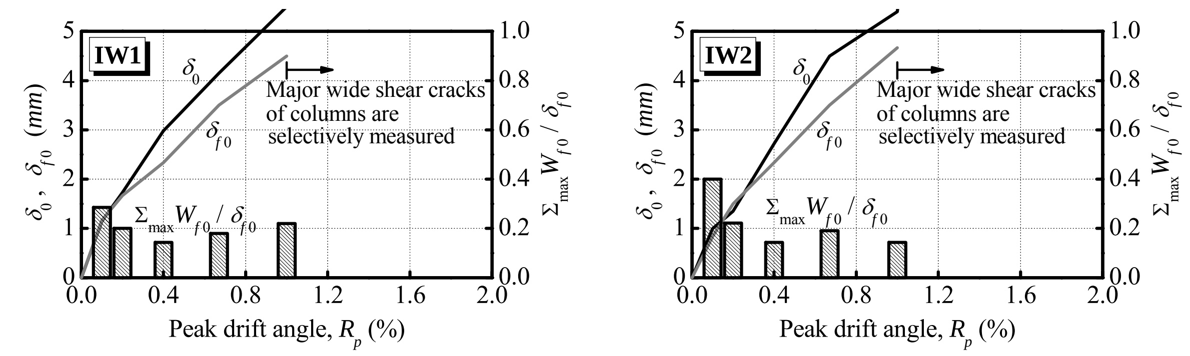


Figure 12: δ_0, δ_{f0}, and $\Sigma_{max} W_{f0} / \delta_{f0}$

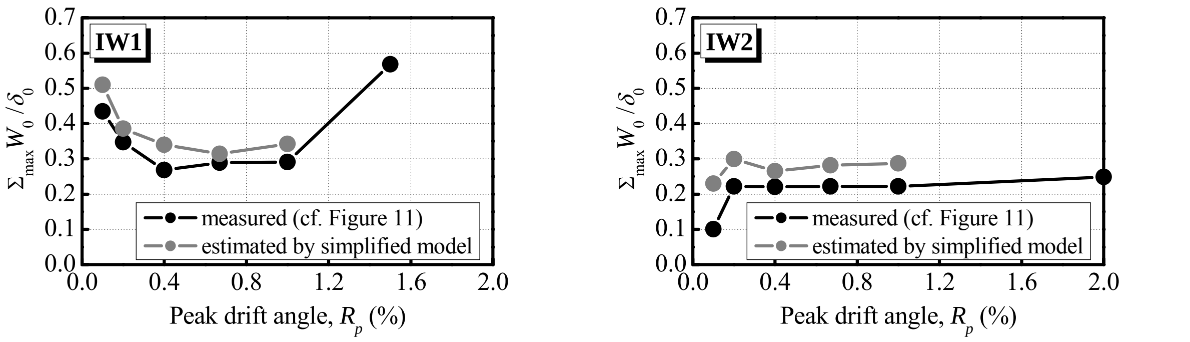


Figure 13: $\Sigma_{max} W_0 / \delta_0$

where,

$_t\delta_{s0}$, $_c\delta_{s0}$: residual shear deformation of tension and compression side column, respectively (see Figure 11(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

Figure 12 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 (3) and (4). 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 results shown in Figure 10. 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 13 shows the estimated crack widths in CB wall at unloaded stages obtained from the sum of crack widths defined in equations (5) and (8) 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 11 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 [$\Sigma_{max} W_0 / \delta_0$].

5. RELATION OF RESIDUAL DEFORMATION AND RESIDUAL SEISMIC CAPACITY

In previous section, W_0-δ_0 relations (see Figure 4(b)) for RC columns and CB walls are estimated by simplified models. In this section, δ_0-E_r relation (see Figure 4(a)) is analytically and experimentally investigated

The residual seismic capacity corresponding to the level of each residual rotation angle (R_0-E_r relation) can be experimentally estimated from the load-rotation angle relations of specimens IW1 and IW2 as shown in Figure 14. 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 specimens IW1 and IW2 then is approximately 2.0 and 3.0, respectively.

To analytically estimate the R_0-E_r relation, the typical hysteretic characteristic for CB wall infilled RC frames is proposed as shown in Figure 15 based on test results of specimens IW1 and IW2 in Figure 14. 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 $(\mu+1)R_y$.
(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 Figure 15.

Figure 16 shows the analytical results for the seismic capacity reduction factor η corresponding to the level of each residual rotation angle R_0 together with the experimental results, where the analytical results are plotted according to the ultimate ductility factor μ=1-6. As shown in the figure, both results are roughly consistent with 2.0 and 3.0 of the ultimate ductility factor μ, respectively and the relation of residual rotation angle R_0 and seismic capacity reduction factor η (R_0-η relation) can be successfully explained by analytical and experimental investigations.

6. ESTIMATION OF RESIDUAL SEISMIC CAPACITY

In this section, the relation of residual crack width and residual seismic capacity for CB wall infilled RC frames is investigated 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.

6.1 Estimation of Residual Seismic Capacity by Residual Crack Width

Both W_0-δ_0 relation (see Figure 4(b)) and δ_0-E_r relation (or R_0-η relation, see Figure 4(a)) discussed in the previous sections are used to directly evaluate the residual seismic capacity of CB wall infilled RC frames from the residual crack widths measured in RC columns and CB walls.

Assuming that $R_{f0} = 0.8R_0$, $R_{s0} = 0.2R_0$ (see Figure 9), $n_f = n_s = 2$ (see Figures 7 and 8), $x = 0.2D$, $\theta = 45°$, $D = 450mm$, and $h_0 = 2{,}400mm$, the relation of maximum residual flexural and shear crack widths (${}_{max}W_{f0}$ and ${}_{max}W_{s0}$) in RC columns and residual rotation angle (R_0) of frames is obtained from equations (1) and (2). Figures 17(a) and (b) show the relation of calculated maximum residual flexural and shear crack widths (${}_{max}W_{f0}$ and ${}_{max}W_{s0}$) in RC columns and seismic capacity reduction factor (η) together with measured results.

The relation of maximum residual crack width (${}_{max}W_0$) in CB walls and residual rotation angle (R_0) of frames can

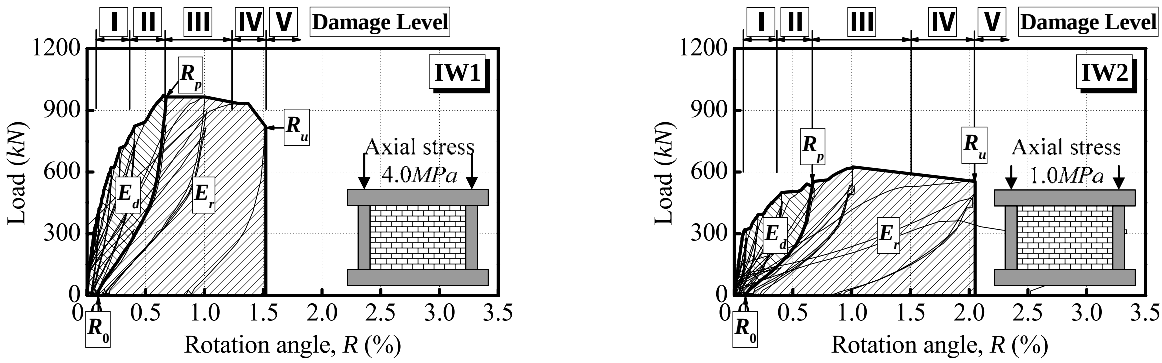


Figure 14: Load-rotation angle relations of specimens IW1 and IW2

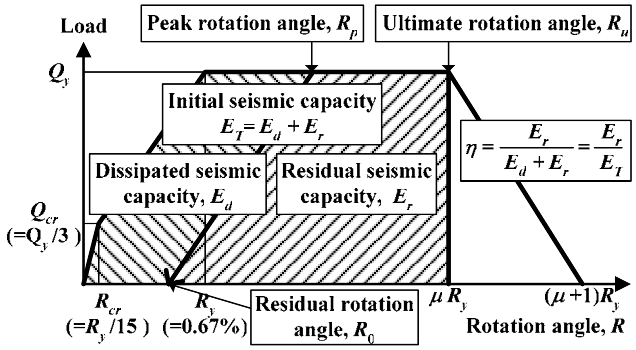


Figure 15: Model of hysteretic characteristic

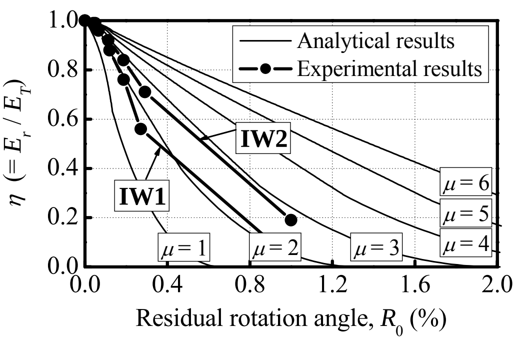
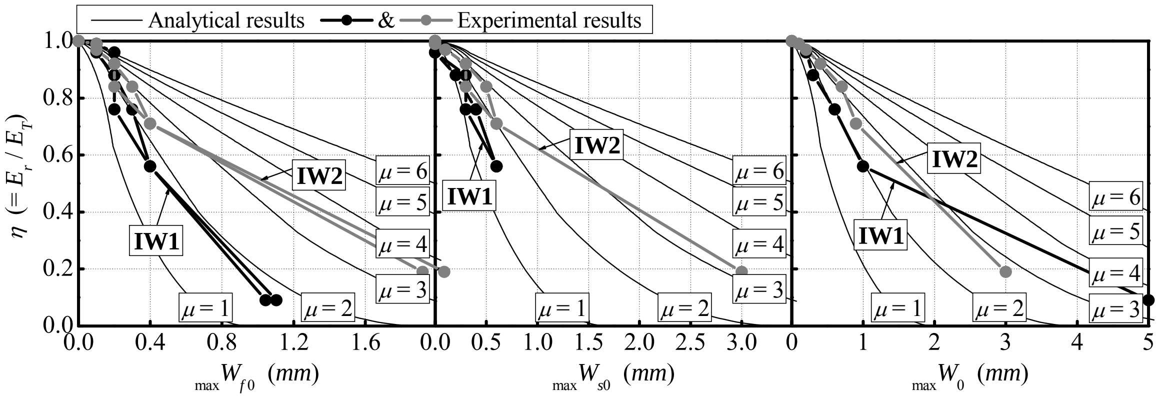


Figure 16: η -R_0 relations



(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 17: Relation of residual crack width and seismic capacity reduction factor

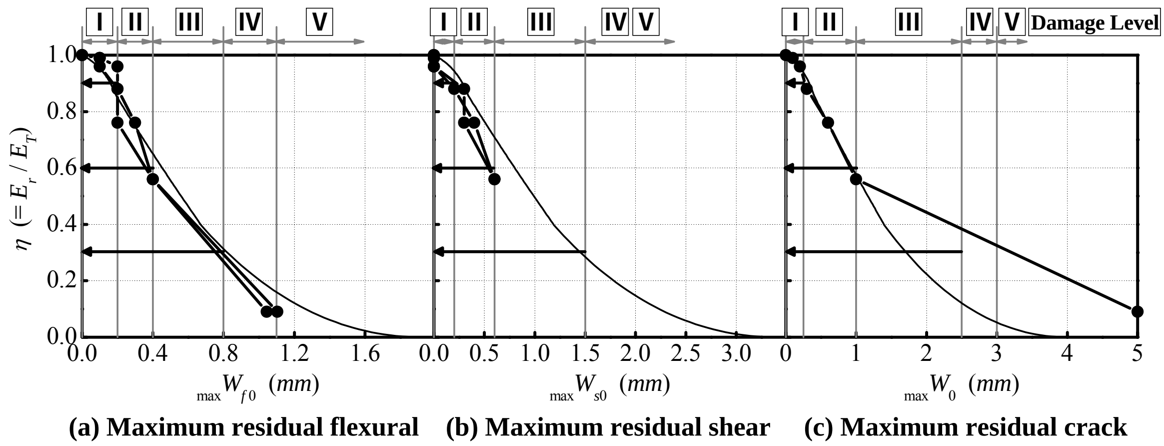
be obtained from the ratio [${}_{max}W_0/\delta_0$] which approximately lies in the range of 0.125 (0.1 to 0.15) as shown in Figure 10. Figures 17(c) shows ${}_{max}W_0$-η relation for CB walls together with measured results.

As shown in Figures 17(a) through (c), the analytical results approximately compare well with the experimental results at 2.0 and 3.0 of the ultimate ductility factor μ, respectively and the W_0-η relation is successfully explained for CB wall infilled RC frames. This result implies that residual seismic capacity for CB wall infilled RC frames can be directly estimated from residual crack widths in RC columns and CB walls observed in those damaged buildings.

6.2 Estimation of Residual Seismic Capacity Corresponding to Damage Level

In this section, the residual seismic capacity corresponding to each damage level for CB wall infilled RC frames is estimated using the load-deformation relation of specimen IW1 assuming a first story where the largest damage is expected 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 14, the damage levels are classified to five stages in the following manner; Damage levels I and II are represented as the stages of crack developing point through maximum strength point, damage level III as the stage to crushing of cover concrete, damage level IV as the stage to bucking of main bars, and final damage level V follows damage level IV.

Figures 20(a) through (c) show the seismic capacity reduction factor (η) corresponding to each damage level for CB wall infilled RC frames, where the value of η is determined as the lowest average value of experimental and analytical results in each damage level. Table 1 shows the values of η corresponding to each damage level for CB wall infilled RC frames determined in this study together with those values in Japanese guidelines [JBDPA, 2001]. As shown in the table, the values of η determined in this study are almost same as those values 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 rational result that the values of η in this study are consistent well with those in Japanese guidelines.



(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 18: Seismic capacity reduction factor corresponding to each damage level

Table 1: Seismic capacity reduction factor corresponding to damage level

Damage Level	Guidelines for Post-Earthquake Damage Evaluation and Rehabilitation [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

7. CONCLUSIONS

Concrete block (CB) wall 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 simplified models are proposed to investigate the relationship between residual crack widths measured in RC columns and CB walls and residual deformation of frames. For RC columns, the sum of residual flexural and shear deformations obtained from their crack widths generally compare well with the measured residual deformation. For CB walls, the measured ratio [$\Sigma_{max}W_0$ /δ_0] for specimens IW1 and IW2 approximately lies in the range of 0.2 to 0.3. Although the ratio [$\Sigma_{max}W_0$/δ_0] is much smaller than 1.0, the simplified model considering residual flexural and shear deformation distribution of columns proposed in this study can rationally reproduce the measured results and successfully explains the crack development mechanism of CB wall. These results imply that the residual deformation of frames can be approximately estimated from residual crack widths in CB walls as well as in RC columns observed in those damaged buildings.

(2) The relationship between residual deformation and residual seismic capacity is analytically and experimentally investigated based on the test results and the proposed hysteretic characteristic. Both results are approximately consistent with 2.0 and 3.0 of the ultimate ductility factor μ, respectively and the relationship between residual deformation and residual seismic capacity is successfully explained by analytical and experimental investigations.

(3) The relationship between residual crack widths in RC columns and CB walls and residual seismic capacity represented by seismic capacity reduction factor (W_0-η relation) is analytically and experimentally investigated using W_0-δ_0 and δ_0-η relations. The analytical results approximately compare well with the experimental results at 2.0 and 3.0 of the ultimate ductility factor μ, respectively and the W_0-η relation is successfully explained for CB wall infilled RC frames. This result implies that residual seismic capacity for CB wall infilled RC frames can be directly estimated from residual crack widths in RC columns and CB walls observed in those damaged buildings.

(4) The seismic residual reduction factors corresponding to each damage level determined in this study are almost same as those values 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 rational result that the values of η determined in this study are consistent well with those in Japanese guidelines.

8. REFERENCES

Maeda, M., Bunno M. and Nagata M. (2000), A Study on the Damage Level Estimation of RC Buildings based on Residual Seismic Capacity of Members, *Proceedings of the Japan Concrete Institute*, Vol.22, No.3, 1447-1452

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