RESIDUAL SEISMIC CAPACITY ESTIMATION OF RC FRAMES WITH UNREINFORCED CONCRETE BLOCK INFILL

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ABSTRACT

The objective of this study is to develop a post-earthquake seismic evaluation method for RC frames with unreinforced concrete block infill. For this purpose, full-scale, one-bay, single-story specimens are tested under cyclic loadings. In this paper, the residual seismic reduction factors are discussed analytically and experimentally to estimate the residual seismic capacity based on the observed damage class, and the damage classes of Korean typical school building, which should be properly functional as refugee centers as well as structurally safe after an earthquake, are investigated analytically under Korean design acceleration level.

1. INTRODUCTION

The objective of this study is to develop a post-earthquake seismic evaluation method for reinforced concrete (referred to as RC) frames with unreinforced concrete block (referred to as CB) infill. For this purpose, full-scale, one-bay, single-story specimens having different axial loads in columns and different opening configurations of infill are tested under cyclic loadings. During the tests, residual crack widths, which can also be found in damaged buildings, are carefully measured to estimate the residual seismic capacity from the observed damage.

In this paper, the residual seismic capacity of RC frames with CB infill is discussed analytically and experimentally, and the reduction factors are proposed to estimate the residual seismic capacity based on the observed damage class. Finally, the damage classes of Korean typical school buildings, which should be properly functional as refugee centers as well as structurally safe after an earthquake, are investigated analytically under Korean design acceleration level.

2. OUTLINE OF EXPERIMENT

Figure 1 shows a standard design of Korean school buildings in the 1980s (The Ministry of Construction and Transportation, 2002). In this paper, 2 specimens representing first and fourth story of 4 story RC school buildings are investigated. They are an infilled wall type 1 (IW1) assuming the first story and an infilled wall type 2 (IW2) assuming the fourth story. The design details of specimen IW1 are shown in Figure 2. For loading history, peak drift angles of 0.1, 0.2, 0.4, 0.67, 1.0, and 2.0% are planned. A constant axial load of 1,440kN (720kN for each column) is applied to specimen IW1 while 360kN (180kN) to specimen IW2.

Specimen IW1 has vertical and horizontal cracks in mortar between CB units and flexural cracks in RC columns at +0.1%. Shear cracks are then observed in both columns at +0.4%. Since the shear cracks rapidly open at –1.5% in the column bottom of compression side, the test is terminated. Specimen IW2 has a crack pattern in both columns and wall, which is almost the same as that of specimen IW1. Although the strength deterioration is observed at +2.0%, a rapid increase in crack width is not found. Since the shear cracks rapidly open at +3.33% in the column bottom of compression side, the test is terminated. The response of the specimens including crack patterns and their mechanism is discussed by Nakano and Choi (2005).

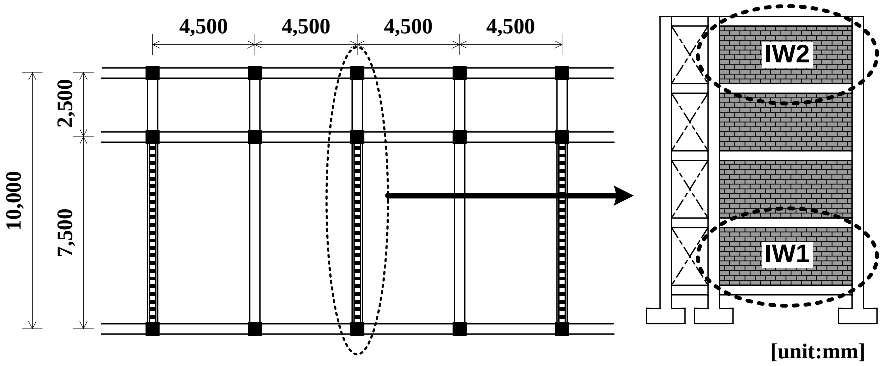

Figure 1: Standard design of Korean school buildings in the 1980s

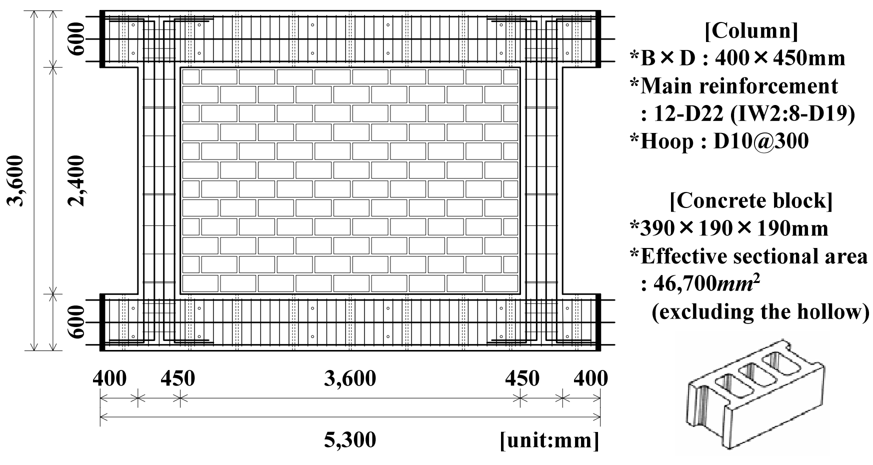

Figure 2: Details of specimen IW1

3. BASIC CONCEPT OF RESIDUAL SEISMIC CAPACITY EVALUATION

Figure 3 shows the basic concept employed in this study to evaluate the residual seismic capacity from residual crack widths observed in earthquake-damaged buildings. The seismic capacity is defined as the hysteretic energy that a structure can absorb during an earthquake, which is consistent with the basic concept found in the Japanese Standard for Seismic Evaluation of Existing RC Buildings (JBDPA, 2001 and 2005), since the procedure proposed herein to evaluate the residual seismic capacity is designed to be analogous to that of the Standard for existing (i.e., pre-earthquake damaged) buildings.

When the load-deformation relationship of a structure or members is investigated through loading tests prior to an earthquake and the response of the structure such as the peak deformation δ_p and/or the residual deformation δ_0 are given after an event, the residual seismic capacity E_r (= E_T - E_d) can be calculated by the discrepancy between initial seismic capacity E_T prior to earthquake damage and dissipated seismic capacity E_d based on the load-deformation curve as shown in Figure 3(a).

Since the peak and residual deformations of buildings are, however, usually unknown after an earthquake unless they are instrumented, other information that can be surely obtained in the damaged buildings and quantitative data that can serve as a good estimator of the peak and/or residual deformation are therefore necessary to practically evaluate the residual seismic capacity. In this study, the residual crack width W_0 that can be quantitatively measured on damaged buildings is focused to estimate the residual deformation δ_0 as shown in Figure 3(b), and their W_0-δ_0

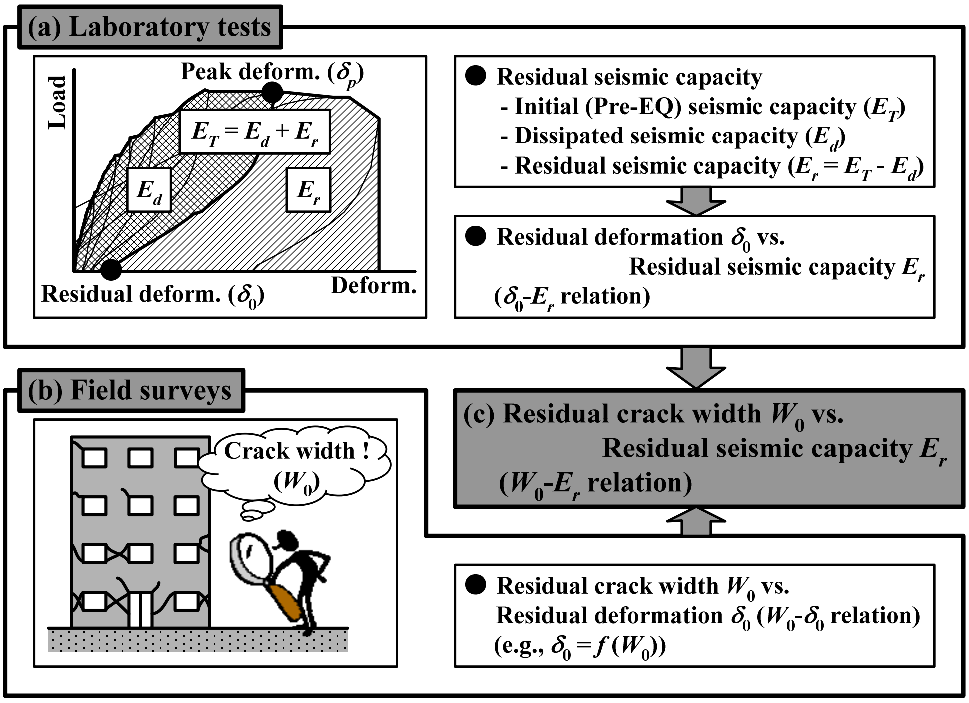

Figure 3: Basic concept of residual seismic capacity evaluation

relationships are experimentally and analytically studied. Once the W_0-δ_0 relation and the δ_0-E_r relation of typical buildings where damage is expected during an earthquake are clarified and the W_0-E_r relation is then established, the residual seismic capacity E_r of a damaged building can be evaluated through the crack width W_0 that can be measured during a damage survey.

In the following sections, the δ_0-E_r relation (see Figure 3(a)) is only investigated for RC frames with CB infill.

4. RELATIONSHIP OF RESIDUAL DEFORMATION AND RESIDUAL SEISMIC CAPACITY

4.1 Estimation of Residual Seismic Capacity by Residual Deformation

In this section, the relationship of the residual deformation (δ_0) and the residual seismic capacity (E_r) is investigated. For this purpose, the load-deformation curves obtained during the loading tests are approximated with a simplified model, and the seismic capacity reduction factor η is employed based on the model.

The load-deformation curve is first characterized by the following three basic points on the curve, the yield drift angle R_y, the maximum response drift angle R_p, and the ultimate drift angle R_u, where the drift angle is defined as the ratio of deformation to the column height (h=2,400*mm*) of specimens. In this study, R_y, R_p, and R_u are defined as shown below.

R_y : Drift angle when column longitudinal reinforcement yields
R_p : Drift angle when a structure reaches its maximum response deformation
R_u : Drift angle when the lateral load carrying capacity decreases to 80% of the peak load

Figure 4 shows the characteristic points R_y and R_u of specimens IW1 and IW2 together with damage class determined considering its definition for RC

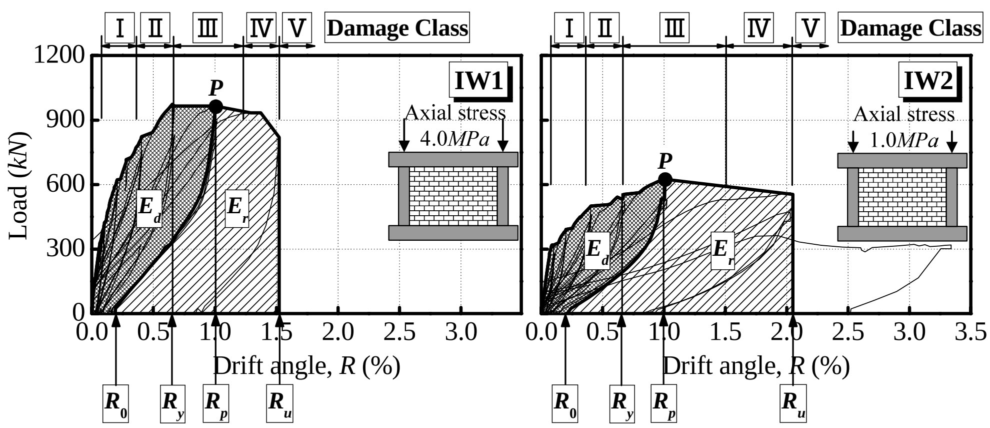

Figure 4: Load-drift angle relationship of specimens IW1 and IW2

Table 1: Damage Class Definition of RC Columns and Walls (JBDPA, 2001)

Damage class	Description of damage
I	- Visible narrow cracks on concrete surface (Crack width is less than 0.2 mm)
II	- Visible clear cracks on concrete surface (Crack width is about 0.2 -1.0 mm)
III	- Local crush of concrete cover - Remarkable wide cracks (Crack width is about 1.0 - 2.0 mm)
IV	- Remarkable crush of concrete with exposed reinforcing bars - Spalling off of concrete cover (Crack width is more than 2.0 mm)
V	- Buckling of reinforcing bars - Cracks in core concrete - Visible vertical and/or lateral deformation in columns and/or walls - Visible settlement and/or leaning of the building

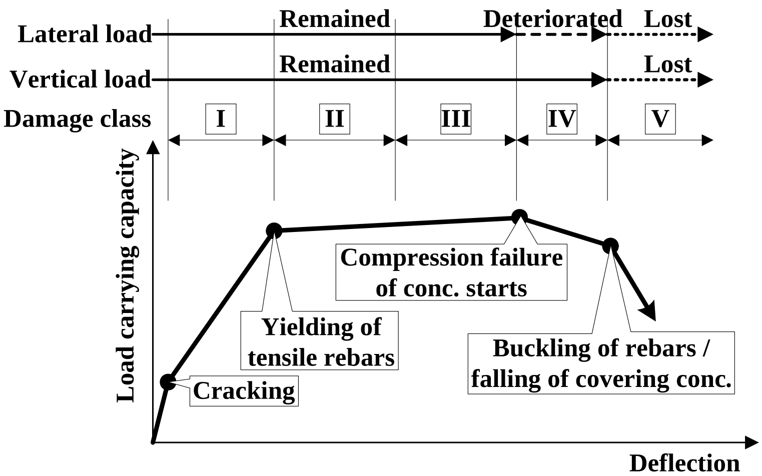

Figure 5: Schematic illustrations of damage class vs. load carrying capacity (Ductile Member, JBDPA, 2001)

members in the Guidelines for Post-Earthquake Damage Evaluation and Rehabilitation of RC Buildings in Japan (2001) shown in Table 1 and Figure 5.

The ultimate ductility factor μ of each specimen defined by R_u/R_y is approximately 2.0 and 3.0, respectively. When the structure's response has the peak drift angle R_p and the residual deformation angle R_0, the dissipated hysteretic energy E_d normalized with respect to the column height can be calculated from the area enclosed by the curve O-P-R_0. The residual energy E_r, therefore, can be calculated from the remaining area shown hatched in Figure 4. Assuming that the hysteretic energy defined above corresponds to the seismic capacity, E_r represents the residual seismic capacity.

To facilitate to apply this procedure to hysteretic loops with different strength and ductility, a seismic capacity reduction factor η defined by the ratio of the residual capacity E_r to the initial capacity E_T ($=E_d+E_r$) is then employed in this study. To find the R_0-η relationship of a structure in a more general manner, the load-deformation curve is represented with a simplified hysteretic model with assumptions (1) through (3) described below. Figure 6 shows the simplified hysteretic model.

(1) The Takeda model is employed for the basic hysteretic rule assuming (a) no hardening in post-yielding stiffness and (b) stiffness degradation factor α of 0.7 derived from the test results during unloading.

(2) The load Q_{cr} and drift angle R_{cr} at cracking point are assumed $Q_y/3$ and $R_y/15$, respectively, where Q_y and R_y are the characteristic points at yielding.

(3) The descending branch beyond the ultimate drift angle R_u linearly decreases to $(\mu+1)R_y$ onto X-axis where the ductility factor μ is defined by R_u/R_y, which is analogous with the concept found in Maeda et al. (2000).

Figure 7 shows the relationship between the seismic capacity reduction factor η and the residual drift angle R_0 for different ultimate ductilities together with the test results. As described earlier, the ductility factors of IW1 and IW2 are approximately 2.0 and 3.0, respectively, and Figure 7 shows good agreement of numerical simulations with test results.

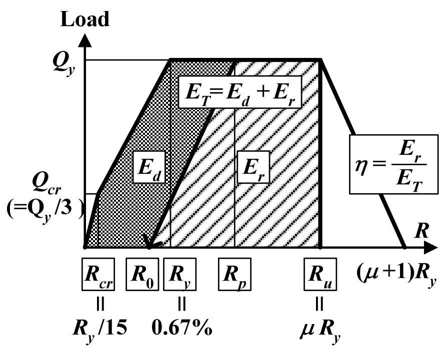

Figure 6: Simplified hysteretic model

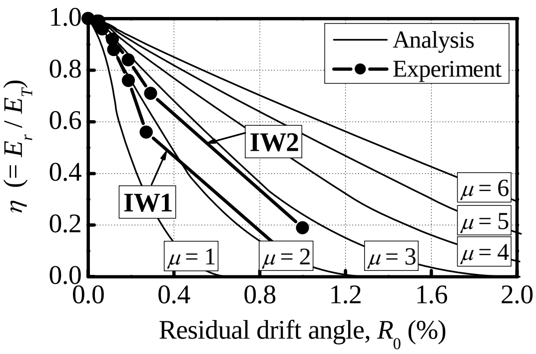

Figure 7: Relationship of R_0 and η

4.2 Estimation of Residual Seismic Capacity Corresponding to Damage Class

It should be noted that damage evaluation of buildings in the field is often made based on damage classification such as shown in Table 1 rather than direct and detailed description of measured digital data.

To facilitate to apply the relation found in Figure 7 in practice, the reduction factor η is plotted in Figure 8 with respect to the damage class I through V considering the relationship of peak drift angle and damage class shown in Figure 4, where data of specimen IW1 is used since serious damage is often found in the first story.

The results are summarized in Table 2 comparing factors specified in the Guidelines (JBDPA, 2001), where the proposed factors are determined as the average of experimental and estimated values at the boundary of two adjacent damage classes in Figure 8. Note that the factors for damage classes IV and V are assumed 0 to conservatively evaluate the results. As shown in the table, the values of η determined in this study are almost the same as those for brittle RC

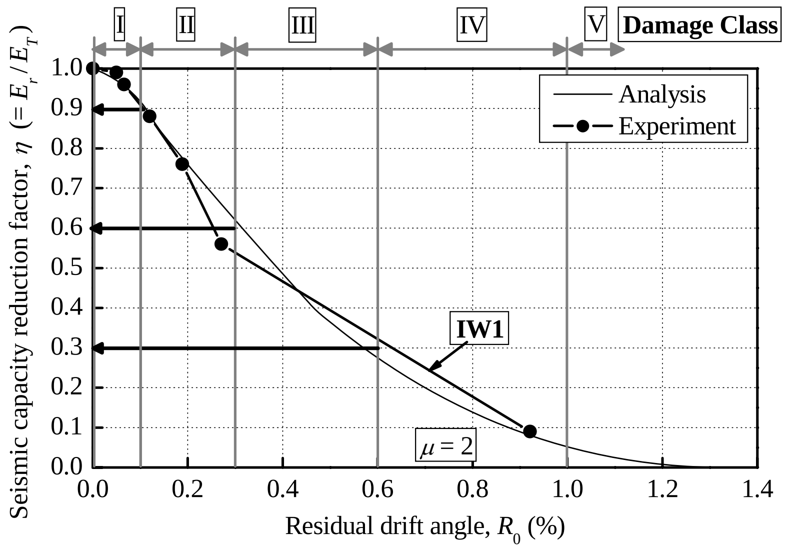

Figure 8: Seismic capacity reduction factor η vs. damage class

Table 2: Seismic capacity reduction factor η corresponding to damage class

Damage Class	Proposed in this study for RC frames with CB infill	Specified in the Guidelines (JBDPA, 2001)	
		Brittle RC column / RC wall	Ductile RC column
I	0.90	0.95	0.95
II	0.60	0.60	0.75
III	0.30	0.30	0.50
IV	0.00	0.00	0.10
V	0.00	0.00	0.00

column and wall in the Japanese Guidelines, since specimen IW1 is not ductile enough to maintain the peak load far beyond yielding.

The residual seismic capacity E_r of RC frames with CB infill can be estimated from the following procedure.

(1) Calculate the seismic capacity E_T of an original (i.e., pre-earthquake damaged) sub-assemblage or frame with CB infill.
(2) Classify its damage into one of five categories based on a damage survey.
(3) Determine the seismic capacity reduction factor η based on the damage class made in (2) above. (see Table 2)
(4) Calculate the residual seismic capacity E_r as $\eta\, E_T$.

5. DAMAGE CLASS OF KOREAN TYPICAL SCHOOL BUILDING

5.1 Ground Motion Data

In this section, the damage classes of Korean typical school buildings, which should be properly functional as refugee centers as well as structurally safe after an earthquake, are investigated analytically against future earthquakes. Since the earthquakes of maximum acceleration level determined Korean seismic design provisions have been not occurred, six artificial ground motions are used in this study. A target elastic spectrum with 5% of critical damping $S_A(T, 0.05)$ is then determined by Equation (1).

$$S_A(T,0.05)=\begin{cases}0.18+2.64T & T<0.1\sec \\ 0.44 \quad cm/\sec^2 & 0.1\sec\le T<0.52\sec \\ 0.23/T & T\ge 0.52\sec\end{cases} \qquad (1)$$

where T is the natural period of the SDOF model. The following 6 records are used to determine phase angles of ground motions: the NS component of El Centro 1940 record (referred to as ELC), NS component of Kobe 1995 record (KOB), EW component of Hachinohe 1968 record (HAC), NS component of Tohoku University 1978 record (TOH), NS component of Uljin 2004 record (ULJ) which has the highest maximum acceleration level of earthquake data measured Korean Meteorological office, and random excitation (RAN). Table 3 shows the maximum acceleration of artificial ground motion and Figure 9 shows the elastic acceleration response spectra of artificial ground motions with 5% of critical damping.

Table 3: Input ground motion

Ground Motion Record ID	Max. Ground Acceleration (cm/sec^2)
ELC	341.7
KOB	-821.0
HAC	183.0
TOH	258.0
ULJ	72.5
RAN	-

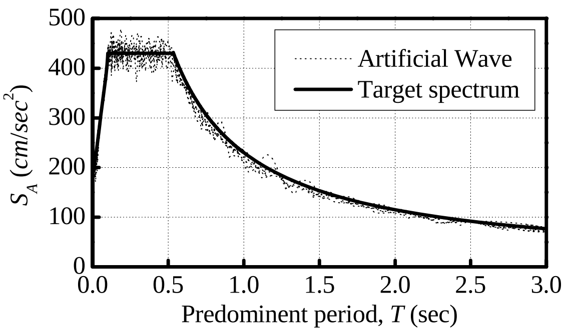

Figure 9: Elastic acceleration spectra

5.2 Damage Class Estimation of Korean Typical School Building

In this section, the damage classes of Korean typical school building based on the standard design specification in the 1980s are estimated using six artificial ground motions mentioned previous section. In this paper, 4 story frames as shown in Figure 1, where transverse direction including CB walls used as partition walls is selected since high seismic capacity is expected, are analyzed.

To simulate the inelastic behaviors of model structure and to estimate the damage classes, the Takeda hysteretic model is employed with assumptions (1) through (3) described below.

(1) The model is assumed as no hardening in post-yielding stiffness and stiffness degradation factor α of 0.7.
(2) The yield load Q_y is calculated as the sum of shear strengths of three columns and one CB infill (the average shear stresses of CB infills for

specimens IW1 assuming the first story and IW2 assuming the fourth story are approximately 0.4N/mm^2 and 0.3N/mm^2, respectively, from test results, and those for the second and the third stories are roughly assumed 0.35N/mm^2). The yield drift angle R_y is assumed 0.67% from test results. The load Q_{cr} and drift angle R_{cr} at cracking point are assumed Q_y/3 and R_y/15, respectively.

(3) The ultimate ductility factors μ of specimens IW1 and IW2 are approximately 2.0 and 3.0, respectively, and those for the second and the third stories are roughly assumed 2.5.

Figure 10 shows the inelastic behaviors of first story of model structure, where is often found serious damage, for six artificial ground motions together with the damage classes. As shown in the figure, the behaviors and damage classes are different due to phase angles of each ground motion. However, all of results exceed the maximum strength, and the results of KOB, HAC and RAN particularly exceed the ultimate drift angle of 1.35% and reach in the state of damage class V (i.e., collapse). This result means that Korean typical school buildings cannot escape more than moderate damage and do not play a role as refugee centers after the earthquake of Korean design acceleration level.

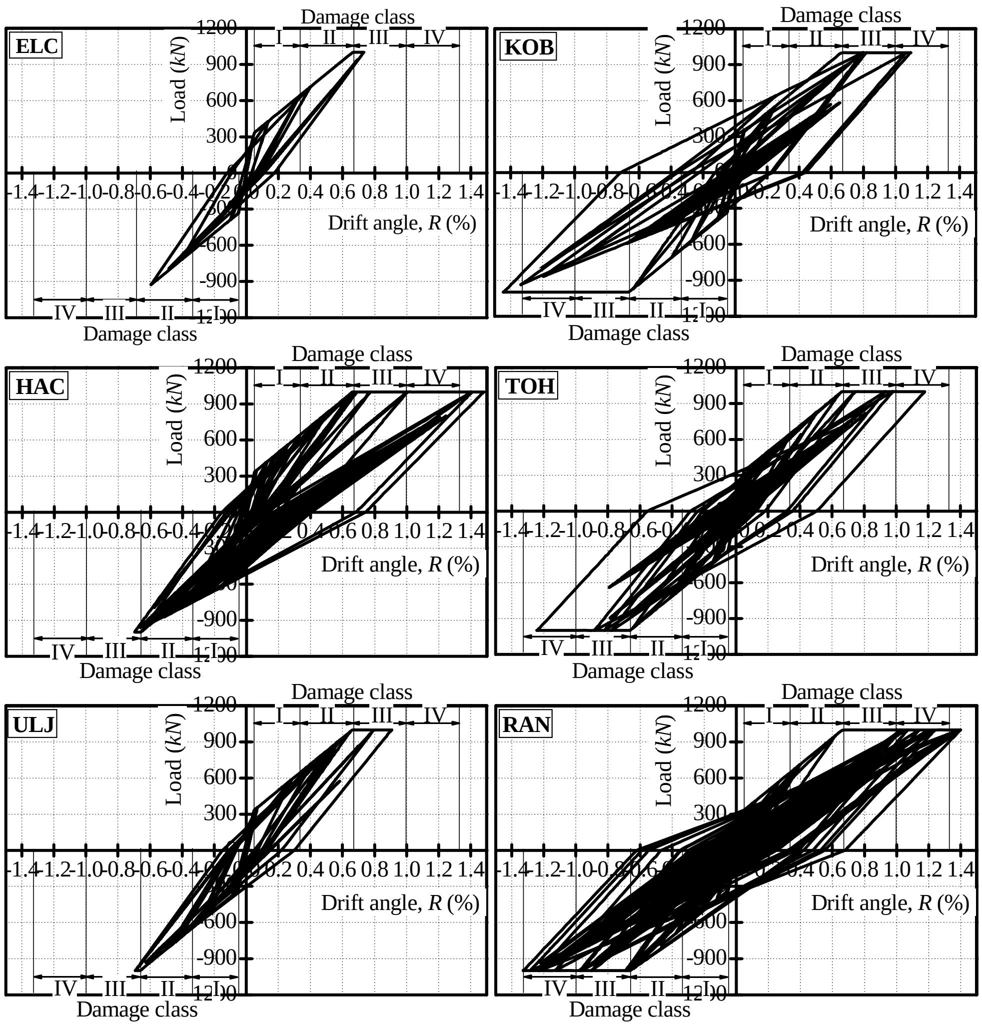

Figure 10: Inelastic behaviors and damage classes of first story

6. CONCLUSIONS

RC frames with concrete block (CB) infill representing typical school buildings in Korea are tested under cyclic loading to estimate the residual seismic capacity from residual crack widths measured on CB walls. The results can be summarized as follows.

(1) The load-deformation curves obtained during the tests are then approximated with a simplified hysteretic model, and the relationship of the residual drift angle R_0 and the residual seismic capacity reduction factor η is established based on the model. The results show good agreement with test results, which imply that the procedure proposed herein can be applied to estimate the residual seismic capacity of RC frames with CB infill having different strength and ductility.

(2) The values of η proposed in this study for RC frames with CB infill corresponding to each damage class are found almost the same as those for brittle RC column and wall specified in the Japanese Guidelines for Post-Earthquake Damage Evaluation, since the proposed values are based on data of specimen IW1, which is not ductile enough to maintain the peak load far beyond yielding.

(3) The damage classes of first story of model structure, where is often found serious damage, for six artificial ground motions exceed the maximum strength, and the results of KOB, HAC and RAN particularly exceed the ultimate drift angle of 1.35% and reach in the state of damage class V. This result means that Korean typical school buildings cannot escape more than moderate damage and do not play a role as refugee centers after the earthquake of Korean design acceleration level.

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