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ORIGINAL ARTICLE

Study on the Reduction Factor of Damaged RC Column Members

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***Abstract*:** To quantify the post-earthquake residual seismic capacity of reinforced concrete (RC) column members, experimental data for 6 column specimens with flexural, flexural-shear and shear failure modes are used to derive residual seismic capacity of damaged RC column members for specified damage states in this work. Besides of the experiment data, some related researches are also investigated to suggest the reduction factors of strength, stiffness and energy dissipation capacity for damaged RC column members, respectively. According to the damage states of RC columns, their corresponding seismic reduction factors are suggested herein. Taking an RC column with the flexural-shear failure for an example, its reduction factors of strength, stiffness and energy dissipation capacity are 0.5, 0.6 and 0.1, respectively. This work also proposes the seismic performance assessment method for the residual seismic performance of earthquake-damaged RC buildings. In the case study, this work selects one actual earthquake-damaged school building to demonstrate the post-earthquake assessment of seismic performance for a damaged RC building.

Keywords: reinforced concrete, building, residual seismic performance, crack width, reduction factor.

1. Introduction

On the basis of investigations made after several major earthquakes occurred in Taiwan, e.g., Ruei-Li earthquake (July 17, 1998), Chi-Chi earthquake (September 21, 1999), and Chia-Yi earthquake (October 22, 1999), a number of low-rise buildings suffered damages of various degrees. Especially in Chi-Chi earthquake, nearly half of the school buildings, which are almost categorized into low-rise reinforced concrete (RC) buildings (building height is lower than 15 m), in the central area of Taiwan collapsed or were damaged seriously. Even in Taipei City, which is about 150 km far away from the epicenter, there were 67 school buildings damaged in Chi-Chi earthquake. Additionally, school buildings are usually required to act as emergency shelters soon after a disastrous earthquake event. Therefore, a post-earthquake emergent assessment procedure for decision-making for earthquake-damaged buildings is needed.

Many seismic assessment methods for buildings have been developed in recent years (ATC, 1996; FEMA, 1998 and 2000); however, those methods seldom mention re-evaluating the seismic residual of

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earthquake-damaged buildings. Di Ludovico et al. (2013) proposed the experiment-based expressions of modification factors for stiffness, strength and displacement capacity as a function of the rotational ductility demand. Additionally, the proposed expressions can be introduced to modify the moment-rotation plastic hinges of RC columns in the buildings of Mediterranean regions with design characteristics non-conforming to present-day seismic provisions. However, how to apply the modification factors to stiffness, strength and displacement capacity in the seismic performance assessment is not mentioned clearly in the paper. The guidelines developed by JBDPA (2001 and 2015) for evaluating the residual seismic performance of earthquake-damaged buildings can be used to determine the damage class of a building; however, the procedure is only suitable for the preliminary seismic performance assessment. Restated, a preliminary seismic performance assessment does not provide sufficient data for engineers or users to make decisions on earthquake-damaged buildings. Additionally, for the detailed seismic performance assessment of low-rise RC building structures in Taiwan, engineers need to use the nonlinear static analysis method, which is different from the method proposed in the JBDPA guidelines (2001 and 2015). Therefore, a post-earthquake detailed assessment method of seismic performance is needed to evaluate the residual seismic performance of an earthquake-damaged RC building for the post-earthquake maintenance strategy.

In the JBDPA guidelines (2001 and 2015), the reduction factors are suggested using limited experimental data. For the practical use in Taiwan, these reduction factors should be verified using more reliable experimental data. This work uses experimental data for 6 column specimens with various failure modes to derive reduction factors of seismic capacity for specified damage states described in the JBDPA guidelines (2001 and 2015) (Table 1). While the reduction factors of seismic capacity are defined using the residual capacity of energy dissipation under cyclic loading, the reduction factors of strength and stiffness are conducted for each RC column specimen. This work also proposes a method that can be used to define nonlinear plastic hinges for damaged RC column members according their damage states and corresponding reduction factors of seismic capacity. Additionally, on the basis of the seismic performance assessment method developed by the NCREE (2009), a post-earthquake detailed assessment method of seismic performance is developed in this work.

Table1 definition of damage levels of structural members. (JBDPA, 2001)

Damage level	Description of damage
I	Visible narrow cracks on concrete surfaces. Crack widths are less than 0.2 mm.
II	Visible cracks on concrete surface. Crack widths in the range 0.2 mm - 1 mm.
III	Localized crushing of concrete cover. Noticeable wide cracks. Crack widths in the range 1 - 2 mm.
IV	Crushing of concrete with exposed reinforcing bars. Spalling off of cover concrete. Crack widths are greater than 2 mm.
V	Buckling of reinforcing bars. Cracks in core concrete. Visible vertical deformation in columns, walls, or both. Visible settlement, tilting of the building, or both.

2. Quantification of Seismic Damage to RC Column Members

2.1 Definition of Reduction Factors of Seismic Capacity

Figure 1 defines the reduction factor η in terms of the dissipated energy E_d and the residual energy dissipation capacity E_r. Table 2 presents the reduction factors of seismic capacity related to various RC vertical components that are provided in the Japanese guidelines (JBDPA, 2001 and 2015). For a column member with the flexural-shear failure, JBDPA (2015) added its corresponding reduction factors of seismic capacity excluded in JBDPA (2001).

2.2 Reduction Factors of Seismic Capacity of Damaged RC Columns

In place of the reduction factors that are defined in terms of the energy dissipation capacity, Ito et al. (2015) proposed reduction factors of the strength, deformation, and damping ratio of damaged RC column members for evaluating post-earthquake residual seismic performance. The reduction factors of strength were obtained directly from experimental results. For each selected specimen, Ito et al. (2015) used the damage index model of Park and Ang (1985) to estimate the equivalent ultimate deformation capacity; then, the reduction factors of deformation were calculated from the equivalent ultimate deformation capacity. To evaluate the reduction factor of the damping ratio, Ito et al. (2015) used the equivalent damping ratio to quantify the energy dissipation capacity of damaged RC column members, which was studied using the hysteretic energy under cyclic loading. In the post-earthquake assessment of seismic performance of Ito et al. (2015), their nonlinear statistical analysis considered reduction factors of the strength (η_s), deformation (η_d) and damping ratio (η_h) of flexural and shear members (Table 3).

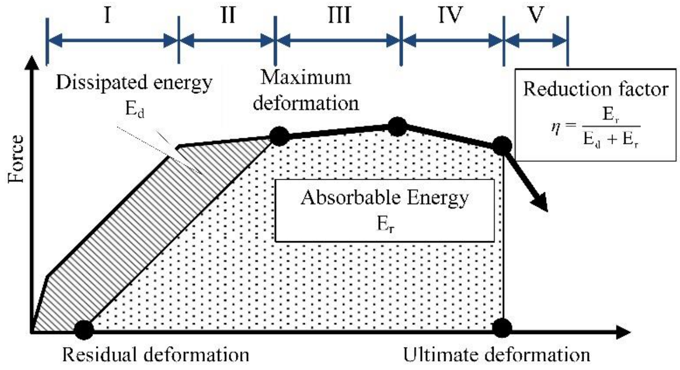


Figure1 energy dissipation capacity of damaged structural members. (JBDPA, 2001)

Poegoeh (2012) utilized experimental data about full-size RC column specimens with various failure modes to study the accuracy of the seismic reduction factors that were suggested by the JBDPA (2001). Poegoeh (2012) acquired experimental data for 16 columns from the NCREE and Japan Society of Civil Engineers (JSCE). Reduction factors of seismic capacity of RC column specimens with various failure modes were analyzed; their failure modes were flexural failure, flexural-shear failure, and shear failure.

Table2 seismic reduction factors suggested by the references (JBDPA, 2001 and 2015)

Damage level	RC column		
	Shear	Flexural-shear	Flexure
I	0.95	0.95	0.95
II	0.6	0.7	0.75
III	0.3	0.4	0.5
IV	0	0.1	0.2
V	0	0	0

According to the descriptions of damage levels of each RC column specimen (Table 1), the maximum residual crack widths were used to classify damage levels to estimate their corresponding reduction factors of seismic capacity. The shear failure of columns adversely affects the safety of any structure. Therefore, residual factors for RC columns with shear failure should be evaluated conservatively. Poegoeh (2012) suggested reduction factors of seismic capacity for damaged RC columns with various failure modes including the flexural-shear mode, which are presented in Table 4.

However, some of the specimens used in Poegoeh (2012) were designed with high-strength materials, including concrete and steel. Moreover, since the maximum residual crack widths were not obtained directly from experimental results, the relationship between the maximum residual crack widths and the reduction factors was not reliably obtained. Therefore, this work considers full-size RC column specimens to confirm reduction factors of strength, stiffness and energy dissipation capacity. The specimens in this work are designed based on column members that are typically used in low-rise RC buildings in Taiwan.

Table3 reduction factors of strength, deformation and damping ratio. (Ito et al. 2015)

Damage level	Flexural member		
	η_s	η_d	η_h
I	1	1	0.95
II	1	0.95	0.8
III	1	0.85	0.75
IV	0.6	0.75	0.7
V	0	0	0
Damage level	**Shear member**		
	η_s	η_d	η_h
I	1	1	0.9
II	1	0.85	0.7
III	1	0.75	0.6
IV	0.4	0.7	0.5
V	0	0	0

3. Experimental Set-up and Results

3.1 Experimental Set-up

The column specimens with single curvature herein are 1800 mm long and their cross-sections are 400 mm × 400 mm, as shown in Fig. 2. Figure 3 shows the loading system for the column specimens with single curvature in this work. Since the experimental set-up cannot let the applied axial loading constant in the experiment, the experimental results cannot be used to investigate the effect of the axial loading on the reduction factors. For the target building of this work is set to be the low-rise RC buildings, the variation of the axial loading of a column member under earthquake is not significant and constant under earthquake. Therefore, the reduction factors obtained from the experimental set-up in this work can still be used for the low-rise RC buildings. The main bars are SD420 of D22, while the stirrups are SD280 of D10. These specimens have the same tensile reinforcement ratio. Three stirrup ratios are utilized to study the seismic reduction factors of the column specimens with various failure modes, which are flexural failure (FF), flexural-shear failure (FSF) and shear failure (SF). Two arrangements of the reinforcements in the specimen section is designed and used in this work, as shown in Fig. 3. The measured compressive strength of concrete is approximately 30 – 37 MPa. Table 5 presents detailed information about each specimen.

Table4 suggested reduction factors of seismic capacity for damaged RC columns.

Damage Level	Flexural failure	Flex.-shear failure	Shear failure
I	0.9	0.9	0.9
II	0.7	0.6	0.6
III	0.5	0.3	0.3
IV	0.1	0.1	0
V	0	0	0

Table5 detailed information of each specimen

Specimen	f_c' (MPa)	S (mm)	ρ_{sh} (%)	Axial Force
FF-15S	37.0	150	0.61	$0.1Agfc'$
	33.1	150	0.61	$0.2Agfc'$
FSF-15S	34.6	150	0.31	$0.1Agfc'$
	30.8	150	0.31	$0.2Agfc'$
SF-30S	34.1	300	0.15	$0.1Agfc'$
	33.2	300	0.15	$0.2Agfc'$

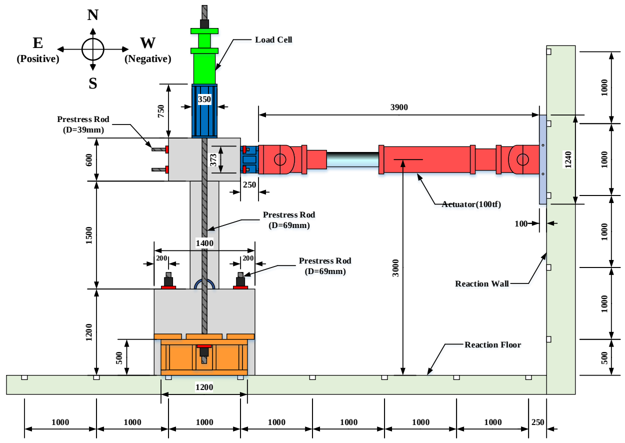
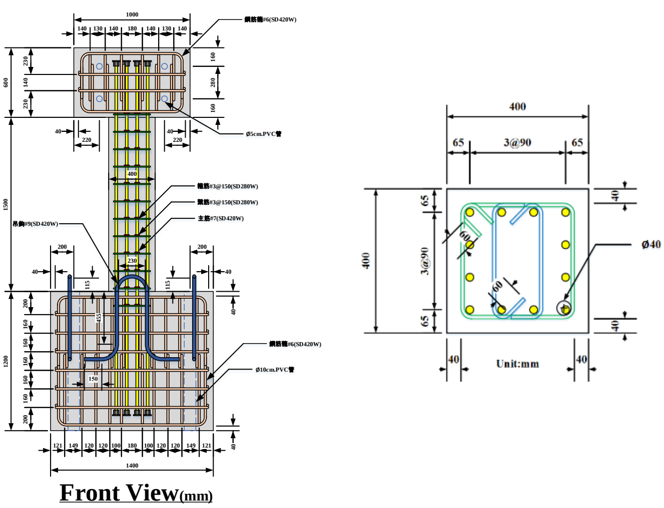


Figure3 applied loading system for the cantilever beam specimens in this work.

To measure crack development, each specimen is brushed with white cement paint and 100 × 100 mm grid lines are drawn on it before testing. The stirrup position is indicated on each specimen. The crack widths are measured under a microscope with a measurement resolution of 0.01 mm. The maximum crack width at a specified peak deformation and the residual crack width with the applied loading set back to zero at each measurement point are recorded in the experiment. The methods for measuring cracks of various types in various positions are as follows (Fig. 4)

(1) Flexural crack: cracking occurs where the bending moment stress of a cross section is at its maximum.

(2) Shear crack: cracking occurs where the shear stress of a cross section is at its maximum. The width at the intersection between the shear crack and the stirrup, which includes the shear crack width and the width parallel to the stirrup, is measured.



(a) FF-15S (Front View) (b) FF-15S

Figure2 detailed reinforcement arrangement of the specimen of FF-15S.

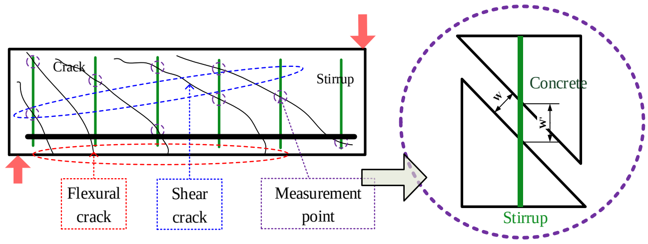


Figure4 measuring cracks of various types at various positions in a specimen

3.2 Experimental results

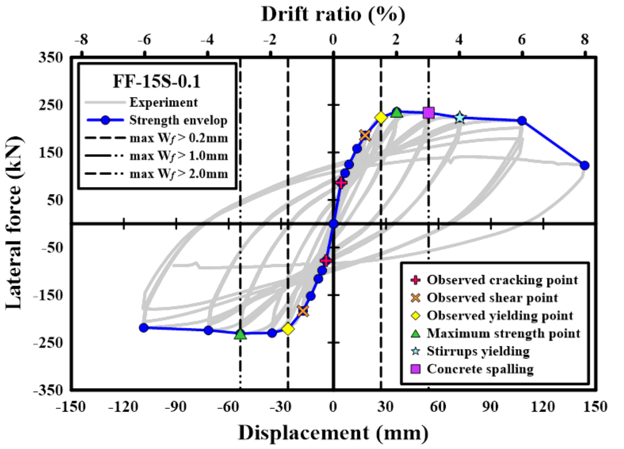
Figure 5 plots the relationship between the lateral force and deformation of each specimen obtained using the applied loading system in Sec. 3.1. To study the damage state, when a specimen is set back to zero deformation from a specified peak drift ratio, the residual crack width is obtained. Additionally, the envelop line of the hysteretic loop for each specimen is used to determine the ultimate deformation point corresponding to the lateral force equal to 0.8Vmax.

By visual inspection and applying strain gauges to the reinforcement, peak drift ratios at the initial crack points, at the initial yielding points of the main bars and the stirrup, at maximum loading points, at the compressive concrete spalling points and in the final step for each specimen under cycling loading are obtained and listed in Table 6. Figure 6 shows the damage situation of each specimen in the final step.

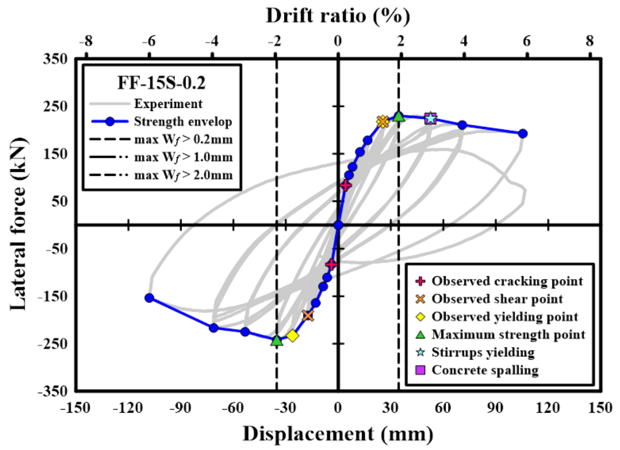
4. Reduction Factors of Mechanical Properties of Seismic Capacity

Based on the definition of the damage levels of structural members in Table 1, the maximum residual crack width and damage state that were observed in the experiment can be used to determine the damage level of each specimen. The strength of the specimens clearly decreases at damage level IV. In this work, the lateral force of 0.8Vmax in the envelope line of hysteretic hoops for a specimen is used to determine the ultimate deformation point as a dividing point between damage levels IV and V. Based on experimental results, this section examines the reduction factors of strength, stiffness and energy dissipation capacity.

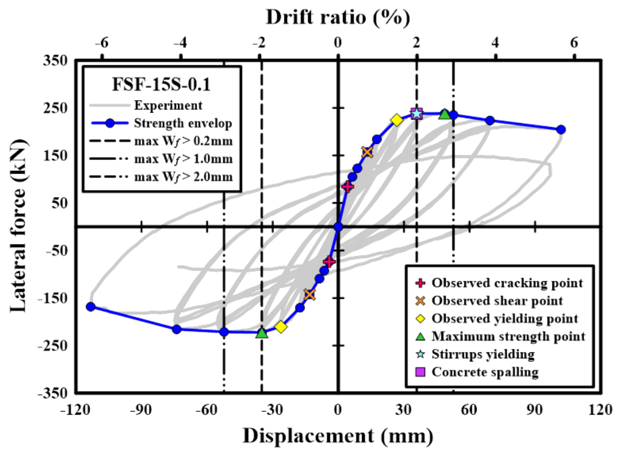
Actually, it is not easy to distinguish the flexural failure mode from the flexural-shear failure mode based on the testing results. Generally, for the flexural-shear failure mode of a specimen, when the applied force researches the shear strength, it can be found that many severe shear cracks occur in the specimen. Additionally, these cracks dominate the deformation capacity of the specimen. This work also investigates the yielding point of the stirrup in a specimen under the cyclic loading. It can be found that the deformation corresponding to the yielding point of the stirrup is around 3.0 – 4.0 % for the specimens with the flexural failure mode while the yielding point of the stirrup is around 1.5 – 2.0 % for the specimens with the flexural-shear and shear failure modes. Therefore, on the basis of the shear crack development and the stress development of the stirrup, this work defines the failure mode for each specimen.



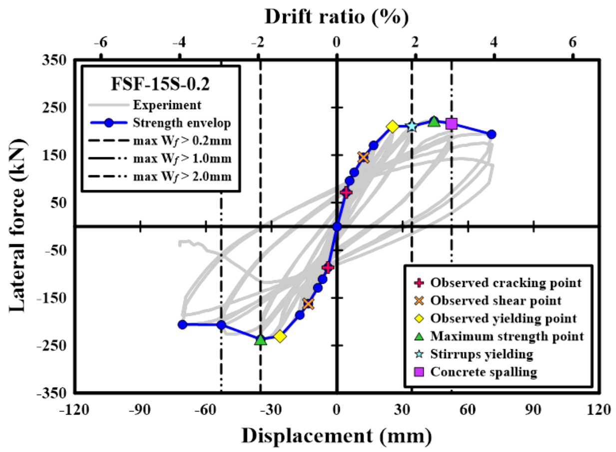
(a) FF-15S-0.1



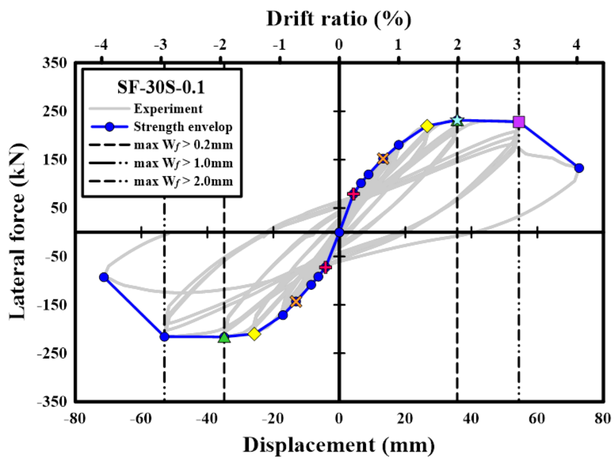
(b) FF-15S-0.2



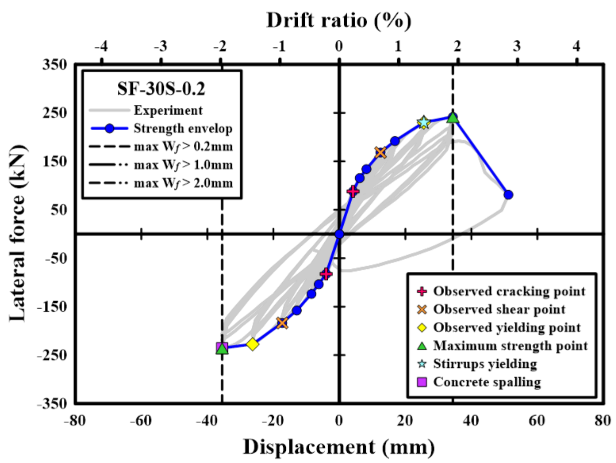
(c) FSF-15S-0.1



(d) FSF-15S-0.2



(e) SF-30S-0.1



(f) SF-30S-0.2

Figure5 relationship of the lateral force and deformation of each specimen in this work

4.1 Reduction Factor of Energy Dissipation Capacity

Applying the definition of damage levels of structural members in Table 1, the experimental results herein are utilized to quantify the reduction factors of energy dissipation capacity for RC column members, as described in Sec.2.1. Figure 7 plots the relationship between the maximum residual flexural crack width and reduction factor of energy dissipation capacity for specimens with flexural and flexural-shear failure modes in the experiment. Figure 7 also plots the reduction factors of energy dissipation capacity at various damage levels and the reduction factors at the damage levels of I, II, III are estimated using the regression lines. Additionally, the reduction factors at the damage level IV are calculated using the dividing point between damage levels of IV and V, which is defined as the ultimate deformation point (Table 7).

Table6 performance points of each specimen under cyclic loading.

Specimen	Initial yielding	max.-loading	concrete spalls	Final step
FF-15S-0.1	1.5%	2%	-3%	8%
FF-15S-0.2	1.5%	2%	-2%	6%
FSF-15S-0.1	1.5%	3%	-2%	6%
FSF-15S-0.2	1.5%	-2%	3%	4%
SF-30S-0.1	1.5%	2%	-2%	-4%
SF-30S-0.2	1.5%	2%	-2%	3%

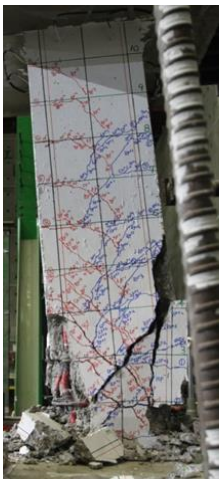
Table 8 lists the suggested reduction factors of energy dissipation capacity η_E for each damage level for an RC column member with various failure modes. For the specimen with the shear failure mode, rather than the maximum residual crack width, the damage state is used to determine the damage level. As suggested in the Japanese guideline (JBDPA, 2015), the residual capacity of energy dissipation is assumed to be zero for damage levels IV and V. Since only a few specimens are utilized herein to examine the residual capacity of energy dissipation, this work takes conservative reduction factors for RC column members considering the experimental reduction factors and those suggested by the Japanese guideline.

Table7 dividing points between the damage levels IV and V.

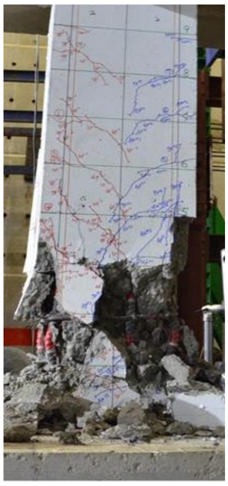
Failure mode	Specimen	Drift ratio (%)
Flexural failure	FF-15S-0.1	5.99
		6.03
	FF-15S-0.2	5.86
		6.00
Flexural-shear failure	FSF-15S-0.1	5.66
		6.29
	FSF-15S-0.2	3.93
		3.93
	SF-30S-0.1	3.02
		2.94
Shear failure	SF-30S-0.2	-

4.2 Reduction Factor of Strength

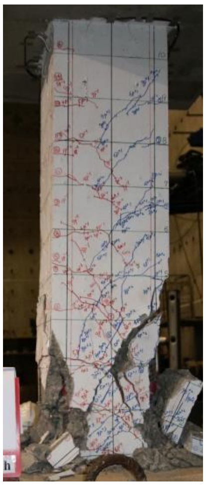
Figure 8 plots the relationship between the maximum residual crack width and lateral force, which is normalized by the maximum lateral force in the experiment. The strength of specimens with flexural and flexural-shear failure modes at damage levels I, II and III can be assumed not to be reduced based on Fig. 8 then, the reduction factors of strength at damage levels I, II, and III can be set to 1.0. Additionally, the reduction factors at the damage level IV are calculated using the dividing point between damage levels of IV and V, i.e, ultimate deformation point. Table 9 lists the suggested reduction factors of strengthη_v at each damage level for an RC column member with various failure modes. The damage state of the specimen with shear failure is used to determine its damage level. Since the maximum lateral force is at the dividing point between damage levels III and IV, the strength falls



(a) FF-15S-0.1
Concrete spalls severely

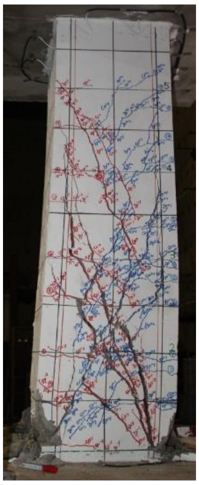


(b) FF-15S-0.2
Concrete spalls severely



(c) FSF-15S-0.1
Serious damage near the bottom end

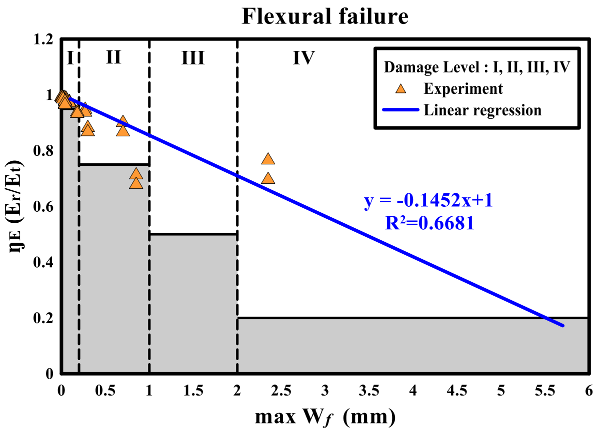
(d) FSF-15S-0.2
Serious damage near the bottom end



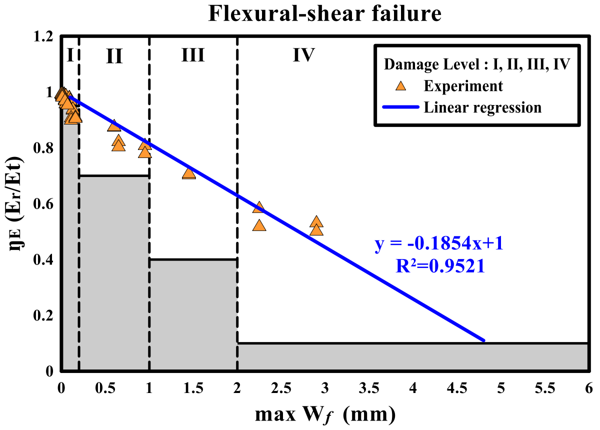
(e) SF-30S-0.1
Serious shear cracking

(f) SF-30S-0.2
Serious damage

Figure 6 the final step for each specimen



(a) Flexural failure mode



(b) Flexural-shear failure mode

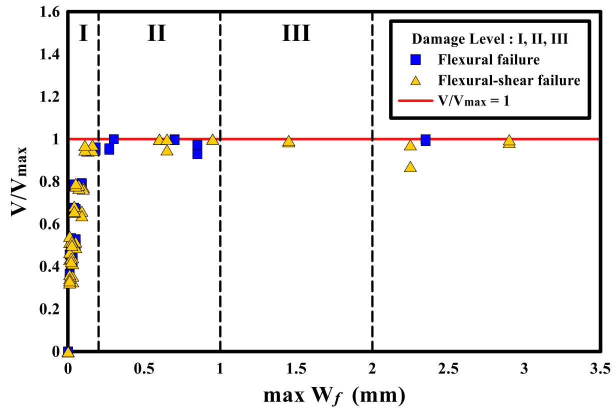
Figure7 experimental reduction factors of energy dissipation capacity for the specimens with the flexural and flexural-shear failure modes.

Table8 suggested reduction factors of energy dissipation capacity for RC column members

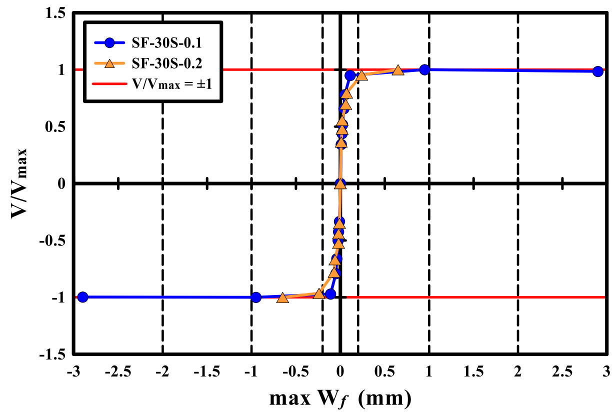
Damage Level	Suggested values		
	Flexural failure	Flexural-shear failure	Shear failure
I	0.95	0.95	0.95
II	0.75 (0.85)	0.7 (0.8)	0.6 (0.85)
III	0.5 (0.7)	0.4 (0.6)	0.3 (0.5)
IV	0.1	0.1	0
V	0	0	0

Note : The value in the parentheses represent experimental reduction factors.

seriously in damage states IV and V. The residual strength in damage states of IV and V is assumed to be zero. As same with the residual capacity of energy dissipation capacity, this work takes conservative reduction factors of strength for RC column members considering the experimental reduction factors and those suggested by the Japanese guideline.



(a) Specimens with the flexural and flexural-shear failure modes.



(b) Specimen with the shear failure mode.

Figure8 relationship between the reduction factor of strength and maximum residual flexural crack width.

4.2 Reduction Factor of Stiffness

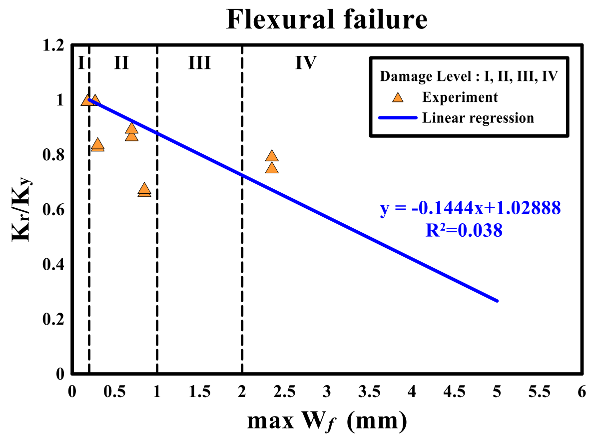
For the specimens with the flexural and flexural-shear failure modes, Figure 9 shows the relationship between the maximum residual crack width and residual stiffness (reloading stiffness in the experiment), which is normalized by the original yielding stiffness. According to the definition of damage levels of structural members listed in Table 1, this work uses the experimental results to investigate the reduction factors of stiffness for RC column members. Obviously, in the damage level I, since the specimens are still in the elastic range, the stiffness values are larger than the original yielding stiffness. Therefore, the residual stiffness can be assumed same with the original yielding stiffness (The reduction factor of stiffness is 1.0). Figure 9 shows the experimental reduction factors of stiffness under various damage levels and the reduction factors at the damage levels of I, II, III are estimated using the regression lines. Additionally, the reduction factors at the damage level IV are calculated using the dividing point between damage levels of IV and V, i.e, ultimate deformation point.

Table9 suggested reduction factors of strength for RC column members

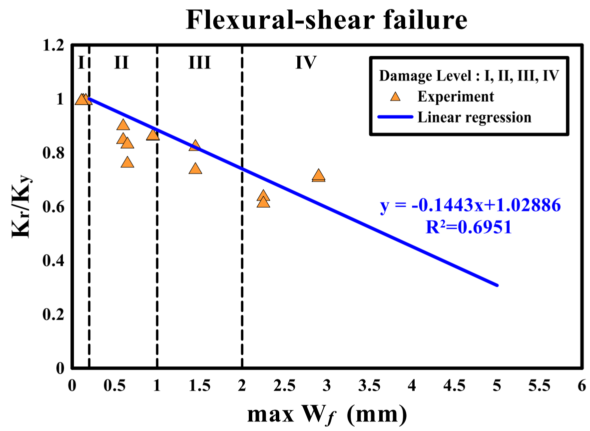
Damage Level	Suggested values		
	Flexural failure	Flexural-shear failure	Shear failure
I	1	1	1
II	1	1	1
III	1	1	1
IV	0.6	0.6 (0.75)	0
V	0	0	0

Note : The value in the parentheses represent experimental reduction factors.

For the specimen with the shear failure mode (SF-30S-0.2), instead of the maximum residual crack width, the damage state is used to determine the damage level. Since the maximum lateral force is the dividing point between the damage levels III and IV, the decrease of the stiffness occurs in the damage states of IV and V obviously. Additionally, in the damage states of IV and V, the stiffness is assumed to be zero. Therefore, this work suggests the reduction factors of stiffness η_K for each damage level, as listed in Table 10.



(a) Flexural failure mode



(b) Flexural-shear failure mode

Figure9 reduction factors of stiffness related to various damage levels for the specimens

Table10 suggested reduction factors of stiffness for RC column members.

Damage Level	Suggested values		
	Flexural failure	Flexural-shear failure	Shear failure
I	1	1	1
II	0.8	0.8	0.8
III	0.7	0.7	0.7
IV	0.5	0.5	0
V	0	0	0

5. Case Study

This work uses the failure model of a column to define the nonlinear plastic hinges of the column (NCREE, 2009). Figure 10 shows the finite element model built in the ETABS (CSI., 2008) for an RC school building selected for a case study. Their detailed information can be found in the reference (NCREE, 2012). The damage level of each vertical component of these building was determined according to visual inspections of these buildings and damage classifications (Table 1). For the selected building, damaged components were on the first floor (Fig. 11). Four columns were damaged most with flaking concrete covers and no crashing on their concrete cores; therefore, they were classified as damage level IV (Fig. 12 (a)). Additionally, Figure 12 (b) shows a column with flaking tile and brick, which was classified as damage level III.

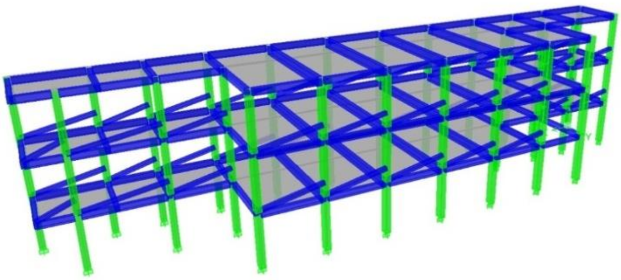


Figure10 the finite element model of the selected RC school building.

According to the literature (NCREE, 2009), infill walls are an efficient way to upgrade the seismic performance of an RC building. In Taiwan, low-rise RC buildings often lack infill walls in the longitudinal direction, which is generally parallel with the corridors. Because of the lack of infill walls, low-rise RC buildings have lower seismic performance in the longitudinal direction than the other direction. Therefore, this case study only assessed the seismic performance of the longitudinal direction for the selected buildings. Figure 13 shows the detailed columns for the pushover analysis.

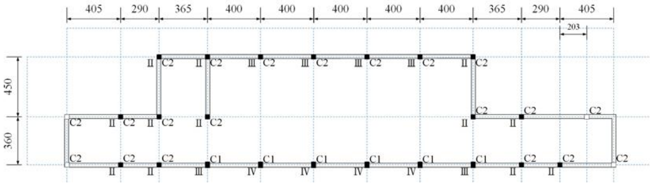
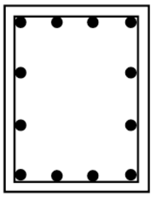
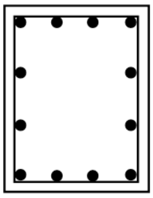
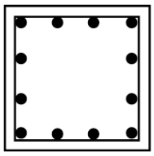


Figure11 damaged column members in the first floor.

(a) Damage Level IV (b) Damage Level III

Figure12 damage levels of damaged column members.

	C1	C2	C3
Cross Section			
Main Bar	12-#8	12-#8	12-#8
Hoop Bar (mm)	#3@300	#3@250	#3@250
B × D (mm)	350 × 450	350 × 450	350 × 350

Note:
Average compression strength of concrete is 15.0 MPa.
Yielding strength of reinforcing steel is 280 MPa.

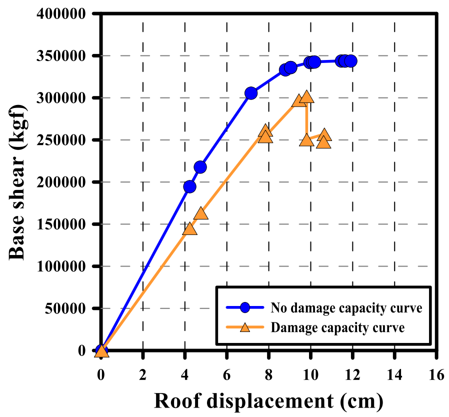
Figure13 detailed information needed in the pushover analysis.

Table11 residual performance of seismic capacity

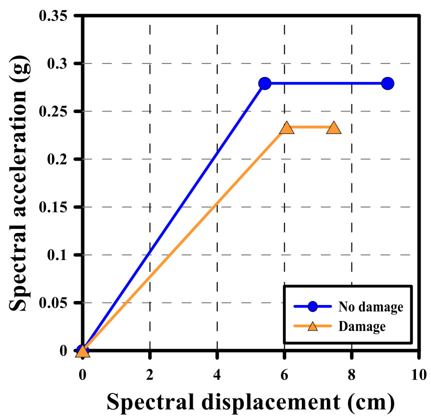
Mechanical properties	Before	After	Reduction ratio
Strength (kgf)	343851	302061	87.9%
Stiffness (kgf/cm)	42724	33417	74.7%
Performance-based ground acceleration (g), A_p	0.199	0.145*	72.7%
Code-required ground acceleration (g) (MOI, 2005), A_T			0.308

6. Conclusions

This work provided reduction factors of seismic capacity for RC columns with various failure modes based on experimental data and the past researches. For an RC column member with seismic damage, besides of the energy dissipation capacity, the residual strength and residual stiffness can be quantified using the suggested reduction factors in



(a) Capacity curve



(b) Capacity spectrum

Figure14 seismic performance of the selected building obtained using the pushover analysis.

this work. According to the damage states of RC columns and their corresponding reduction factors suggested herein, this work proposes the seismic performance assessment method for the residual seismic performance of earthquake-damaged low-rise RC buildings.

This work selected one building damaged in the earthquake to demonstrate the post-earthquake assessment of seismic performance. In the future, when many buildings are damaged by a large earthquake, a post-earthquake emergent decision-making procedure for damaged low-rise RC buildings can be conducted using the proposed residual seismic performance assessment method to determine the strategies for the damaged buildings. However, this work only suggests the reduction factor of damaged column components. Other structural components (such as beam-column joints and walls) will also affect the post-earthquake residual seismic performance of structures in the pushover analysis, and it requires further researches to consider the effects of other components.

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