17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan - September 13th to 18th 2020

Dynamic Experiment of the Seismic Performance Reduction Factors of Damaged RC Column Members

H.F. Sung, (1), C.K. Chiu (2)

(1) *Ph.D., Department of Civil and Construction Engineering, National Taiwan University of Science and Technology, No.43, Keelung Rd., Sec.4, Da'an Dist., Taipei City 10607, Taiwan (R.O.C.), feynman953305@yahoo.com.tw*

(2) *Professor, Department of Civil and Construction Engineering, National Taiwan University of Science and Technology, No.43, Keelung Rd., Sec.4, Da'an Dist., Taipei City 10607, Taiwan (R.O.C.), ckchiu@mail.ntust.edu.tw*

Abstract

In order to obtain the actual reaction and the residual seismic performance of RC column members under earthquake, the dynamic experiments were conducted at the reaction wall with eight column specimens of flexural, flexural shear and shear failure modes. At first, the 3D traditional low-rise street Taiwanese building model was established by ETABS. According to the results of the nonlinear dynamic analysis of structure, the dynamic displacement histories of the selected RC column member were obtained under different damage degrees. The dynamic displacement histories were loaded into the procedure of the dynamic experiments. In the experiment, after the dynamic loading procedure has been finished, the static cycling loading was performed immediately to the damaged column specimens. Based on the experimental data, the residual seismic capacity of the RC column members can be obtained. Additionally, in order to find out the difference between the results of the dynamic experiment of this work and another related static experimental data, both of the reduction of mechanical properties were compared. According to the Japanese AIJ Guidelines, which is about the concept of damage level and the performance boundary line of column member, the relationship of the deformation and damage level is summarized based on the experimental maximum residual crack width and the damage state of the reinforced concrete. Finally, the relationship between the deformation and the reduction factor of strength, stiffness, and seismic capacity was obtained. In further work, the reduction factors can be applied to modify the nonlinear bending curve of the RC column member in pushover analysis, and the post-earthquake detailed seismic performance assessment method of the damaged RC building can be developed.

Keywords: dynamic experiment, residual seismic performance, crack width, damage level, reduction factor.

1. Introduction

After an earthquake occurs, a government generally will conduct the emergent assessment of safety for damaged buildings to avoid the secondary disaster in a limited period. For example, if the buildings are judged to be with serious damage or collapse, they should be immediately banned from use or entry to avoid casualties that continue to cause human life. In addition to the emergent assessment of safety for the damaged buildings, the post-earthquake seismic performance assessment should be conducted to determine the subsequent strategies for the damaged buildings. Therefore, for the post-earthquake assessment procedure for the damaged building, it can be roughly divided into three main stages in various countries, including the emergent assessment, the preliminary assessment of seismic performance, and detailed seismic performance assessment.

The United States, Japan, and Taiwan conduct the post-earthquake emergent assessment of safety for the damaged buildings using assessment procedures [1, 2, 3, 4]. The main purpose is to prevent people and their properties from the casualties induced by the aftershocks. The emergent assessment method mainly involves the visual inspection that must be conducted by qualified personnel, engineers or technicians. Additionally, the warning labels with various colors will be determined based on the assessment results and posted to restrict the entry or use of anyone. For any label removal or change of a building with the warning label in the post-earthquake emergent assessment of safety, a preliminary assessment of seismic performance for the building is required. When a building that is not qualified in the preliminary assessment of seismic performance, it should be conducted with a detailed assessment to determine whether the building needs retrofit or removal. In terms of the detailed assessment of seismic performance, the capacity spectrum method [5, 6] is adopted in the United States while Japan relies on third diagnoses in accordance with the technical manual [7] as the detailed assessment.

In Taiwan, National Center for Research on Earthquake Engineering (NCREE) develops "Seismic Evaluation of Reinforced Concrete Structure with Pushover Analysis" [8], which is mainly based on the capacity spectrum method [5]. However, the application of the above-detailed assessment method in practice is mostly focused on the evaluation of the existing buildings before an earthquake. It is rarely conducted to evaluate and quantify the residual seismic performance of the damaged buildings. Therefore, it is necessary to develop a seismic assessment method for obtaining residual seismic performance.

2. Motivation and literature review

After the earthquake, the overall structure or parts of the building will suffer different degrees of damage, which must be quantitatively or qualitatively described in order to effectively evaluate the residual seismic capacity to further earthquakes. In the preliminary and detailed evaluation method of seismic assessment in Taiwan, vertical members (such as columns and walls) are used as seismic evaluation targets. Therefore, the damaged members of building need to be divided into different damage levels as evaluation criteria. In addition, the Japanese JBDPA guidelines [9] clearly define the damage level according to the crack width of components and the failure of concretes and the steel bars The classification mainly refers to the defined boundary as categorization of the column member in Japanese AIJ guidelines [10]. According to the characteristics of the observed crack width, concrete stress and steel strain state, which reflected the limit in compression and tension system, the first fulfillment of the boundary feature is considered as the performance point. Thus, from the theoretical analysis or test result, this concept can be used to obtain the amount of deformation in the corresponding member under each limit category, and each limit category corresponds to the lower limit of the different damage levels in the Japanese JBDPA guidelines [9]. This work also applied this concept to obtain the relationship between the damage level and the deformation in the test result.

To evaluate the residual seismic capacity of a damaged RC column member after an earthquake, some previous studies investigated the reduction factors of various damage levels through experimentation. [11, 12, 13, 14]. In the above studies, most of them used a static cyclic-loading test to obtain the relationship between the force and displacement of a member and analyzed the variation of mechanical performance and energy dissipation of members through the hysteresis loop and envelope curve. However, for a damaged RC column member, the residual seismic capacity which is identified from the static cyclic-loading test results would be different with the dynamic test results[15, 16]. Additionally, the studies on the effects of seismic loading on RC column members are also quite limited when compared with impact and explosive loading.

Therefore, this work is to investigate the difference between the reduction factors of seismic capacity obtained from the dynamic testing and static-cyclic loading. At first, this work uses the nonlinear time-history analysis of an RC building to determine the dynamic loading for each specimen. Additionally, in order to damage a specimen to be with a specified damage level using the dynamic loading, this work refers to Chiu et al. [14] to determine the intensity of an earthquake for each specimen using the nonlinear time-history analysis. In this work, after a specimen is damaged with a specified damage level induced by the dynamic loading, the static-cyclic loading will be applied to investigate the residual seismic capacity. Finally, in addition to the experimental results, the past results and database from PEER [17] are used to conclude the reduction factors of seismic factor for the damaged RC column members.

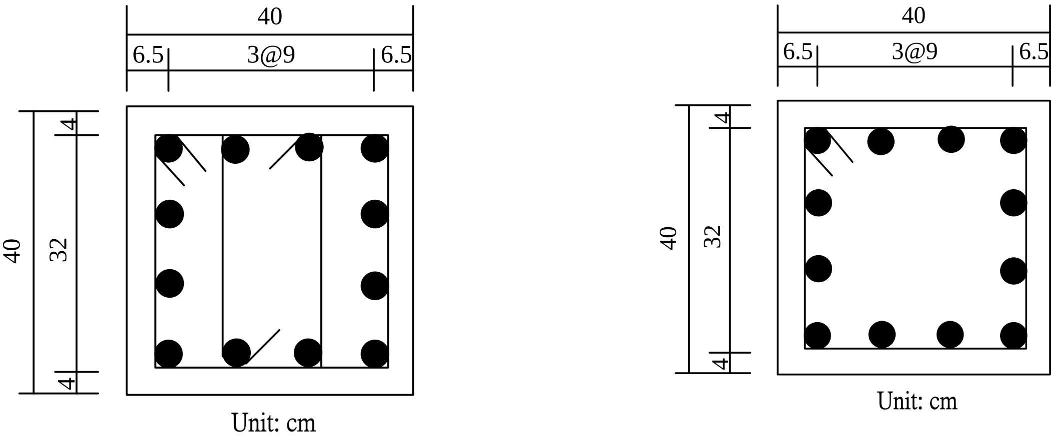
Although additional development of dynamic experimental researches have been developed, it is only carried out by changing the loading rate, which cannot fully reflect the results of the member under the real seismic force. It also was not possible to directly obtain the maximum residual crack width from most experiments, so it was not easy to use the concept of limit category in the Japanese AIJ guidelines [10] to reliably obtain the relationship between damage level and deformation of column members. Therefore, it is necessary to use different types of dynamic loading tests to verify the rationality of the static loading experimental results. In addition, most studies only use a small number of experimental results to obtain the reduction factors, which cannot fully express its applicability and rationality. Although Di Ludovico et al. [12] used a large number of database experimental results to obtain the reduction factors, the target specimens do not conform to the design specifications of Taiwan's low-rise street column members. It is necessary to extend the additional database that matches the design of objects. The study of the reduction factor is intended to be applied to the evaluation method of seismic capacity assessment of post-earthquake buildings. The reduction factors obtained by Chiu et al. [14] were applied to modify the nonlinear plastic hinge and used a case study to demonstrate the detailed evaluation method of seismic performance of post-earthquake buildings, but most studies have obtained different types of reduction factors which rarely mentioned in the practical application of seismic capacity assessment methods. It cannot reflect the practicality and purpose of reduction factors. Therefore, it is necessary to conduct additional experiments by using dynamic loading and verify the rationality of the static experimental results.

3. Eexperimetal program and result

3.1 Experiment set up

In order to understand the difference between the residual seismic capacity of the column members after dynamic and static loading, eight column specimens with the same design of Chiu [14] were used for the dynamic test (Fig. 1). The height of the specimens was 180cm, the cross-section size was 40cm × 40cm, the compressive strength of the concrete measured before the test was about 22 to 24MPa, the main bars used SD420 of D22, and the stirrups were 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, flexural-shear failure and shear failure. Table 1 presents detailed information about each specimen.

Figure 2(a) shows that the dynamic experiment set up was mainly conducted with a reaction wall, a 50-ton dynamic actuator, and an axial force system. Before the test, the surface of the specimen was painted with white cement and a grid of 15 cm × 15 cm was drawn. By using an optical measurement system (Fig. 2(b)), 34 markers were placed on the specimen to measure the deformation of specimens during the test. In addition, the displacement gauges were set on the upper and lower parts of the specimen to measure the degree of foundation displacement. 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.



(a) FF (Space= 15cm) (b) FSF (Space= 15cm), SF (Space= 30cm)

Fig. 1 –Detailed reinforcement arrangement of the specimen

(a) Specimen set-up (b) NDI Optical Measurement System

Fig. 2 –Experiment set up and the measurement system

Table 1 –Material properties of specimens

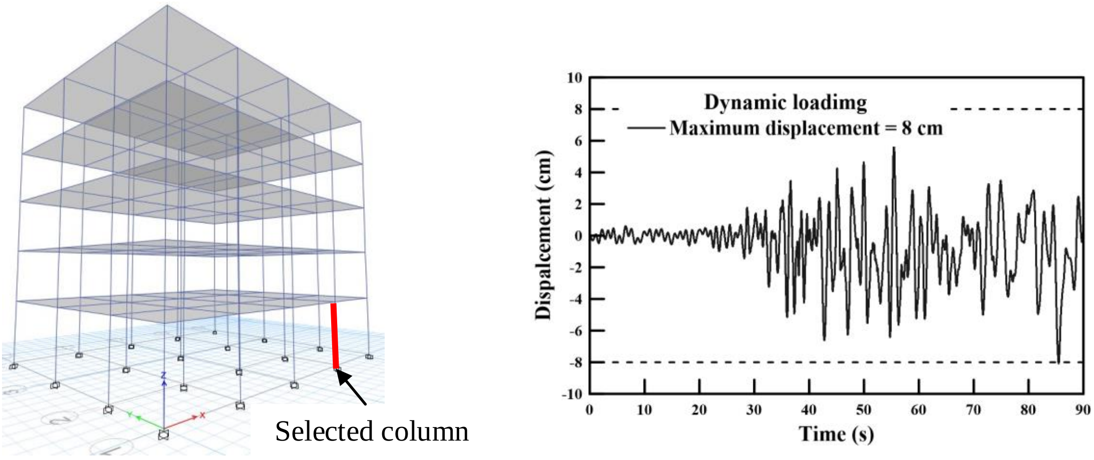
Specimen	L (cm)	f_c' (MPa)	f_y (MPa)	f_{yt} (MPa)	S (cm)	ρ_{sh} (%)	Axial Force
FF-NO1	180	21 (23.2*)	420	280	15	0.61	0.1*Agfc'*
FF-NO2	180	21 (22.6*)	420	280	15	0.61	0.1*Agfc'*
FF-NO3	180	21 (22.8*)	420	280	15	0.61	0.1*Agfc'*
FSF-NO4	180	21 (23.9*)	420	280	15	0.31	0.1*Agfc'*
FSF-NO5	180	21 (22.9*)	420	280	15	0.31	0.1*Agfc'*
FSF-NO6	180	21 (23.4*)	420	280	15	0.31	0.1*Agfc'*
SF-NO7	180	21 (24.4*)	420	280	30	0.15	0.1*Agfc'*
SF-NO8	180	21 (24.4*)	420	280	30	0.15	0.1*Agfc'*

* The measured compressive strength of concrete at the testing time.

3.2 Loading program

In this work, instead of the static cyclic loading, the dynamic loading is used to cause the damage with a specified level on a specimen. Since the dynamic loading for each specimen is conducted with the displacement control in the experiment, the displacement history of a specimen is obtained from the non-linear analysis of a selected building, i.e., a traditional low-rise street house in Taiwan. Therefore, the designed specimens are assumed to be the column members in a selected building structure. Figure 3(a) shows the selected building structure has 5 floors with a horizontal span (4 spans in total) of 17.28 m and a longitudinal span (3 spans in total) of 13.68 m. Besides the first floor is 3.6 m in height, the remaining floors are 3 m in height. The slab thickness of each floor is 12 cm. The cross-sectional size of all columns, the reinforcement and material properties in the structure are the same with the specimen design of this work.

Additionally, for the time history of an earthquake required in the structural dynamic analysis, this work selects the data recorded in Chi-Chi Earthquake [18] for the site location of the building, which is named as CHY016. For the structural dynamic analysis, the time-history data should be converted to an artificial earthquake in compatible with the code-required design response spectrum in Taiwan. In terms of the parameter setting in the structural dynamic analysis, the structural model is assumed to be with a fixed foundation. The slab is modeled using a shell element with the assumption of being a rigid floor, where a live load of 200 kgf/cm^2 is applied. The P-delta effect is not considered in the members, and the flexural and shear plastic hinges defined by NCREE [8] are applied on the beam and column members, respectively. In the nonlinear time-history analysis, this work adopts an artificial earthquake, which is compatible with the code-specified design spectrum. After the structural dynamic analysis, one of the column members in the first floor in which axial force is approximately 0.1Agfc' is selected to determine the dynamic loading of a specimen (Fig. 3(a)). We can obtain three displacement histories of the selected column with the maximum displacement of 4.0, 6.0, and 8.0 cm, respectively, by adjusting the scale of the earthquake history (Fig. 3(b)). The dynamic experiment conducted in two stages: (1) The specimens were applied dynamic displacement histories that get from simulation as the dynamic loading, and it means that the specimens have been damaged by the end of loading; (2) After dynamic loading, static cyclic loading should continue until the specimens showed damage before the result was analyzed for the residual seismic capacity of column members. In the stage of the static cyclic loading, when the specimen was damaged or the maximum strength was reduced to 60 %, the test would stop. 80 % of the maximum lateral force strength of the specimen was considered as the ultimate deformation point.

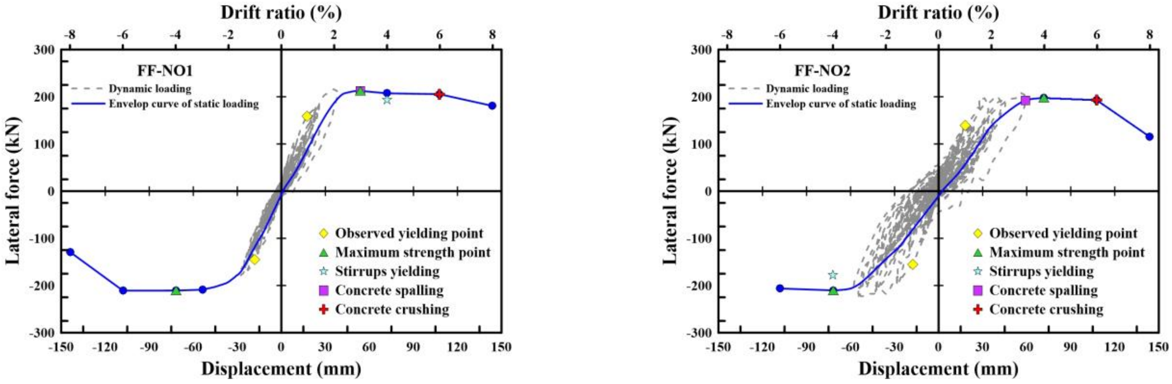


(a) 3D model of the selected building (b) Displacement histories of seleteded column

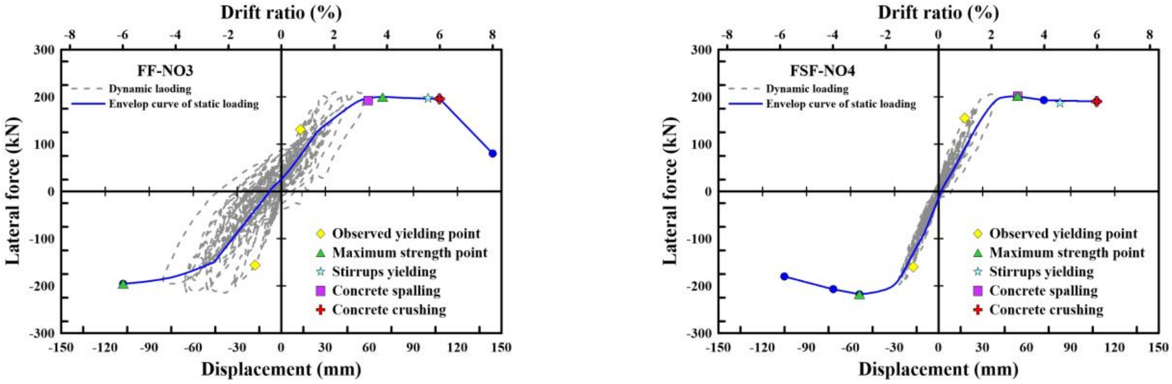
Fig. 3 –The finite element model and displacement histories of seleteded column

3.3 Test result

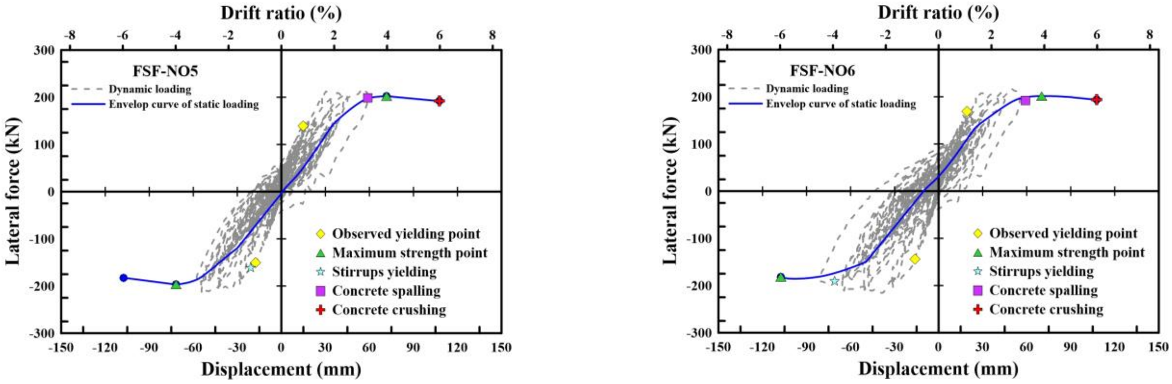
Figure 4 shows the relationship between the lateral force and deformation of each specimen in the experiment, including the dynamic and cyclic static loading. According to the strain gauges on the reinforcement and experimental data, the initial yielding point of the reinforcement, the maximum loading point, the concrete falling point and the final failure point of each specimen in the dynamic and cyclic static loading are also remarked in Figure 4.



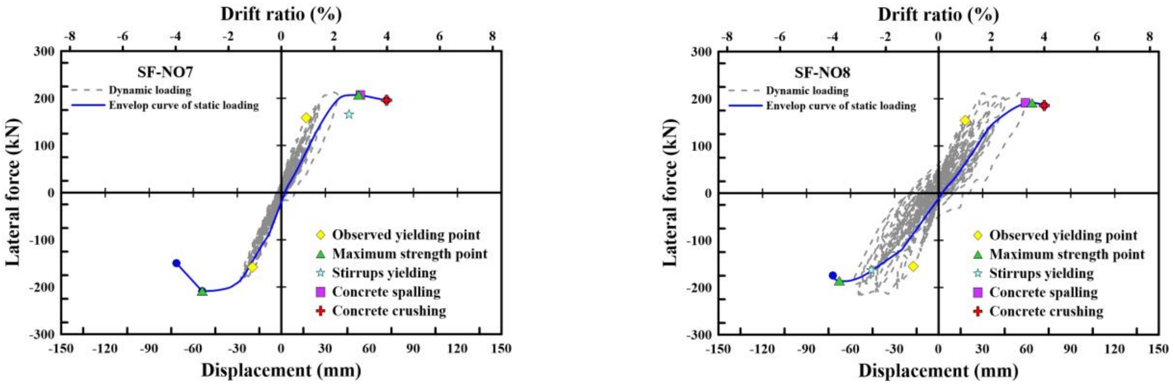
(a) FF-NO1 (b) FF-NO2



(c) FF-NO3 (d) FSF-NO4



(e) FSF-NO5 (f) FSF-NO6



(g) SF-NO7 (h) SF-NO8

Fig. 4 –Relationship of the lateral force and deformation of each specimen

4. Discussion

4.1 Damage level and drift ratio

In order to obtain the reduction factors of RC column members, we should divide the damage level first. The classification of damage level is defined by the Japanese AIJ guidelines [10]. It mainly observed the flexural and shear characteristics which included maximum residual crack width and the stress or strain of reinforcement concrete, and the first occurrence of the characteristics is considered as the performance point of the limit category. Therefore, according to the experimental results, this concept can be used to obtain the corresponding deformation in each limit category (Table 2).

Table 2 –The relationship between the damage level and the deformation of specimens

Damage level	Failure mode		
	FF(%)	FSF(%)	SF(%)
I	1.0 (1.03)	1.0 (1.00)	1.0 (0.93)
II	2.5 (2.44)	2.0 (1.99)	1.5 (1.74)
III	4.0 (3.94)	3.0 (2.91)	2.0 (1.97)
IV	6.0 (5.86)	3.5 (3.48)	-

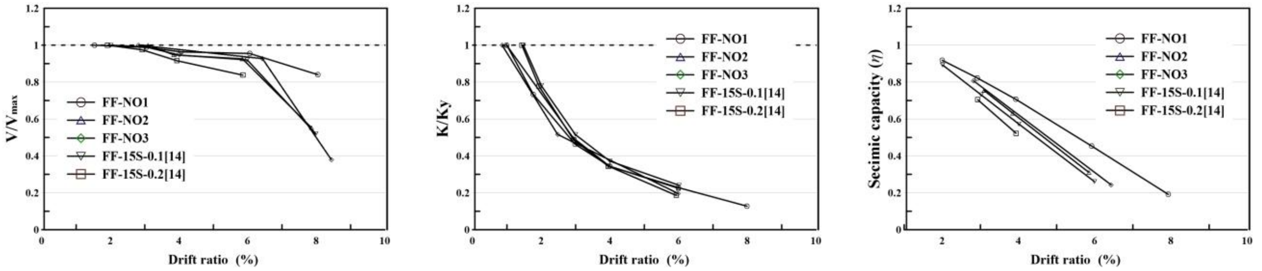
Note： The value in the parentheses represent experimental deformations.

4.2 The reduction factors of mechanical properties

In order to obtain the actual dynamic response and the residual seismic capacity of the RC column member under an earthquake, this work contrasted differently from Chiu [14] that despite similar design of specimens, we used the column member displacement history of non-linear dynamic analysis as the loading program, where static cyclic loading was conducted after the specimen was subjected to dynamic loading. The difference between dynamic and Chiu's experimental results is that Chiu focused on the residual seismic capacity of undamaged members, while dynamic experiments investigated the residual seismic capacity of damaged members after dynamic loading. Therefore, it was necessary to explore the difference of the residual seismic capacity before and after the damage, so some mechanical performances of the two experiments under static loading were compared and discussed. Since the comparing results of both experiments showed the same trends in different failure modes, only the results of flexural failure mode are listed for discussion.

Figure 5(a) plots the relationship between the deformation and positive lateral force, which is normalized by the maximum lateral force in the experiment in dynamic experiment and Chiu's experiment. Figure 5(b) plots the relationship between the deformation and the stiffness, which is normalized by the initial stiffness of the specimen. The stiffness was calculated in terms of equivalent stiffness, which was defined as the slope of the line connecting the maximum peak intensity points under the same positive and negative peak deformation. Figure 5(c) plots the relationship between the deformation and the seismic capacity reduction factor of the specimen. The calculation of the seismic capacity of reduction factor should refer to the method described in the JBDPA guideline [9]. It used the energy dissipation capability of structural members to calculate the residual seismic capacity of the damaged members, where it defined the reduction factor as a ratio of the residual energy to the initial energy dissipation capacity. All the figures show that the specimens in the two experiments had an agreement in the attenuation curve of each mechanical properties.

Because the dynamic experimental results show similar to static experimental results in mechanical performances, it verifies the rationality of results obtained from static tests. Therefore, we can obtain the relationship between the reduction factors and the drift ratio.



(a) Strength (b) Stiffness (c) Seismic capacity

Fig. 5 –Attenuation mechanical properties of flexural speciemens

5. Conclusion

The reinforced concrete structure will suffer to a degree of damage under the earthquake, and it is necessary to study the residual mechanical properties of the RC column members after dynamic loading in order to develop the post-earthquake seismic performance assessment method and obtain reduction factor under different damage levels. Thus, this work numerically simulated the building to obtain the dynamic loading program of the experiment, and carried out the dynamic experiment on the eight RC column members with three failure modes, and further discussed the reduction factor of mechanical performance.

The results show the column member which was damaged by different loading patterns has no obvious effect on its residual seismic capacity; according to the experimental results, the relationship between the deformation and the damage level in RC column members under different failure modes and the relationship between the deformation and the reduction factor of strength, stiffness, and seismic capacity was obtained. It further can be applied to the residual seismic performance assessment of damaged low-rise RC buildings. Additionally, when structural seismic performance assessment of buildings is carried out, other structural components (such as beam-column junctions and walls) will also affect the residual seismic performance of the structure after the earthquake; thus, further research is required to consider the influence of other components.

6. Reference

[1] Applied Technology Council (1989): Procedures for post-earthquake safety evaluation of buildings, ATC-20, Redwood City, CA.

[2] Applied Technology Council (2005): Field manual: Postearthquake safety evaluation of buildings, ATC 20-1, second edition. Redwood City, CA.

[3] JBDPA, Japan Building Disaster Prevention Association: The Rapid-assessment Regulations for Disaster-damaging Buildings. Available at https://www.cpami.gov.tw.

[4] CPAMI, Construction and Planning Agency Ministry of the Interior: The Rapid-assessment Regulations for Disaster-damaging Buildings. Available at https://www.cpami.gov.tw.

[5] ATC (Applied Technology Council, 1996): Seismic evaluation and retrofit of concrete buildings (ATC-40). Redwood City, California, USA.

[6] BSSC: NEHRP guidelines for the seismic rehabilitation of buildings, FEMA-273 (1997), developed by ATC for FEMA, Washington, D.C..

[7] Technology Council (2017): For seismic evaluation and seismic retrofit of existing reinforced concrete building. Japan Building Disaster Prevention Association.

[8] NCREE (National Center for Research on Earthquake Engineering of Taiwan, 2009): Seismic Evaluation of Reinforced Concrete Structure with Pushover Analysis (NCREE-09-015). Taipei, Taiwan.

[9] JBDPA (Japan Building Disaster Prevention Association, 2015): Standard for seismic evaluation of existing reinforced concrete buildings, guidelines for seismic retrofit of existing reinforced concrete buildings, and technical manual for seismic evaluation and seismic retrofit of existing reinforced concrete buildings. Tokyo, Japan.

[10] AIJ (Architecture Institute of Japan, 2004): Guidelines for performance evaluation of earthquake resistant reinforced concrete buildings (Draft). Tokyo, Japan.

[11] Poegoeh, A. C., (2012): Reduction factors of seismic capacity for earthquakedamaged reinforced concrete columns. *Master thesis,* National Taiwan University of Science and Technology.

[12] Di Ludovico, M., Polese, M., d'Aragona, M. G., Prota, A., & Manfredi, G., (2013): Aproposal for plastic hinges modification factors for damaged RC columns. *Engineering Structures*. 51, 99–112.

[13] Ito, Y., Suzuki, Y., and Maeda, M., (2015): Residual seismic performance assessment for damaged RC building considering the reduction of strength, deformation and damping ratio. *Proceeding of JCI Annual Convention*.

[14] Chiu, C. K., Sung, H. F., Chi, K. N., Hsiao, F. P., (2019): Experimental Quantification on the Residual Seismic Capacity of Damaged RC Column Members. *International Journal of Concrete Structures and Materials*. 13:17. Available at https://doi.org/10.1186/s40069-019-0338-z.

[15] Otani, S., Kanko, T., Shiohara, H., (2003): Strain rate effect on performance of reinforced concrete members. *Concrete structure in seismic regions*: FiB.

[16] Wang, D., Li, H. N., Li, G., (2013): Experimental study on dynamic mechanical properties of reinforced concrete column. *Journal of Reinforced Plastics and Composites*. 32(23) 1793–1806.

[17] PEER, Pacific Earthquake Engineering Research Center: *Structural performance database*. University of California, Berkeley. Available at http://nisee.berkeley.edu/spd/.

[18] Original seismic data of Taiwan Chi-Chi earthquake (ASCII, 1999). Available at https://scweb.cwb.gov.tw/special/special-index.htm.