Study on the Earthquake Damage Evaluation Procedure for RC and Confined Masonry Buildings

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SUMMARY:
Data collection is important in earthquake reconnaissance, and damage data that was not collected or archived properly might cause errors in the subsequent research. For instance, different damage evaluation procedures are used to describe the damage state of buildings in different earthquakes, causing difficulties and misunderstandings when sharing the data.
This paper aims at establishing an earthquake damage evaluation procedure that is objective and easy to use for low-rise RC and confined masonry buildings. Several current damage evaluation standards are reviewed and summarized to determine the evaluation factors. The relationships between evaluation factors and damage conditions are discussed by applying the presented procedure to three in-situ test specimens. The ability of the procedure to distinguish medium damage states of the procedure was also verified by using the data of 10 school buildings damaged during recent moderate earthquakes. Twelve professionals with different backgrounds were asked to evaluate the damage state of the buildings with both their subjective judgement and the procedure proposed in this work. It was found that the damage state determined by the presented procedure showed less variation and more conservative results than the subjective judgements.

Keywords: Earthquake damage, Data collection, Damage evaluation

1. INTRODUCTION

Past experience is a good teacher for people who face repeating disasters, such as earthquakes and floods. One of the best-known early examples of this is the Learning from Earthquakes (LFE) Program implemented by the Earthquake Engineering Research Institute (EERI) that started in 1973 (http://www.eeri.org/site/lfe-introduction). This program has shown that making observations and keeping records of the damage and effects following a disaster are critical to managing emergency response activities in the short term, and improving the understanding of natural hazards in the long term.

Damage data has been widely used in earthquake-related research, such as seismic assessment, loss estimation, and establishment of vulnerability function. The ATC-13 report (ATC, 1985) presented a methodology for estimating earthquake damage/losses by using existing damage data from California. However, it is usually difficult to apply the damage data out of the region where it was originally collected. The difficulty comes not only from the difference in structural characteristics of the building culture in different areas, but also from the difference in the descriptions and definitions of damage used. Damage can be defined qualitatively or quantitatively, and determined subjectively by the researcher. Qualitative damage states can be simply expressed as damaged/collapsed or subdivided into several discrete levels (Whitman et al. 1973; EERI, 1996; Dolce et al. 2006), while a quantitative damage index might be defined as the cost/number/range of repair/replacement for an individual building, or the percentage for a category of buildings (Scawthorn et al. 1981; Miyakoshi et al. 1997; Nagato and Kawase, 2004). A workshop hosted by EERI on the collection and management of earthquake data (EERI, 2003) identified the need to improve data collection, access, organization, and use. Creating a data dictionary so that different professions can use the same language to describe the same concept is one of the major issues when collecting such data, as is defining guidelines for the collection process.

In an earlier work, the authors established a databank for school buildings damaged during the Chi-Chi earthquake, and undertaken a study of the motion-damage relationship by using this (Tu et al. 2009). A typical five-level qualitative standard, including slight, light, moderate, severe damage and collapse, was used to define the damage state of each building from the databank. However, it was found that the damage states of some buildings were questionable, since they were determined by subjective judgements. The relationship between the damage state and the seismic capacity of a building was also unclear in the data, causing uncertainties when it was used for comparison with analytical models. Therefore, this research aims at establishing a new earthquake damage evaluation procedure for low-rise RC and confined masonry buildings. The procedure presented in this work is expected to redefine the damage states with objective and clear language, thus reducing the errors caused by subjective judgements.

2. ESTABLISHMENT OF THE DAMAGE EVALUATION PROCEDURE

2.1. Review of the Existing Damage Evaluation Standards

Before the establishment of the new procedure, several existing damage evaluation standards for RC and confined masonry buildings were reviewed and compared, with the aim of finding the similarities and differences among them. Those parts accepted by most researchers became the basis of the new procedure. The procedures reviewed were as follows:

A. The post-earthquake damage evaluation standard for RC buildings by the Japan Building Disaster Prevention Association (1991) (five levels).

B. The damage evaluation standard for confined masonry buildings by Astroza et al. (Gent Franch et al. 2008) that was used after the 1985 Central Chile earthquake (six levels).

C. The damage evaluation standard that was used after the 1999 Chi-Chi earthquake by the Architecture and Building Research Institute, Ministry of the Interior of Taiwan (Hsiao et al. 1999) (five levels).

D. The damage evaluation standard for low-rise RC school buildings by Jean et al. (2008) (five levels).

E. The damage evaluation standards for masonry and RC buildings by Anagnostopoulos et al. (2008) (four levels).

F. The post-earthquake emergent risk evaluation standard for damaged buildings by the Construction and Planning Agency, Ministry of the Interior of Taiwan (http://www.cpami.gov.tw/) (three levels).

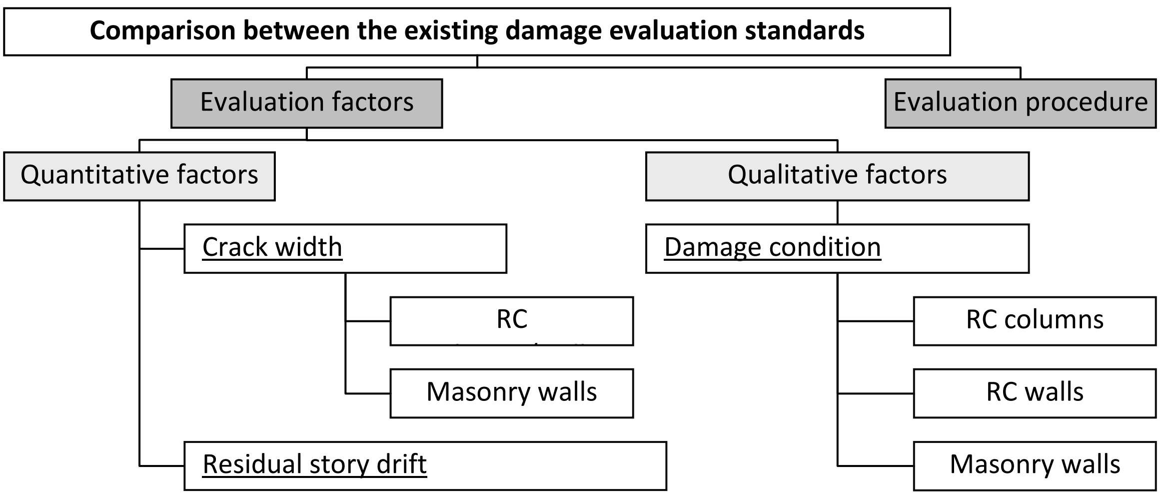


Figure 1. Framework of the comparison among the existing damage evaluation standards

Figure 1 shows the framework of the comparison among the various standards. The damage evaluation is usually composed of two parts: the factors that describe the damage and the procedure that weighs them and then determines the global damage state. Most damage evaluation standards use qualitative descriptions to define the damage states. In some standards, as shown in Table 1, quantitative factors, such as crack width or residual story drift, are also used. The values of quantitative factors and the choice of qualitative factors used in the various standards were compared, and details of this comparison can be found in the master's thesis of Ao (2010). The major results of the comparison are outlined below.

Table 1. Numbers of damage states and the use of quantitative factors in the existing damage evaluation standards

Standards		A	B	C	D	E	F
Number of damage states		5	6	5	5	4	3
Quantitative factors	Crack width	O	X	X	O	O	O
	Residual story drift	O	X	O	O	X	O

2.1.1. Evaluation Factors

I. Quantitative factors:

1. Crack width: The crack width is related to the tensile stress of the reinforcement in the RC members. A wide crack generally represents the yielding of the reinforcement across it. In most of the standards, a crack width < 1mm indicates light damage, that between 1mm and 2mm indicates moderate damage, and > 2mm indicates severe damage states for RC columns and walls. Some of the standards evaluate flexural and shear cracks separately, in which a greater width is allowable for former than the latter in the same damage state. For masonry walls, the crack width is 2 to 3mm larger than that for RC members in the same damage state.
2. Residual story drift: This factor is only used in the Japanese and Taiwanese standards reviewed. In most standards, the residual story drift < 1% indicates light damage and 1% to 3% indicates moderate damage state. A building with residual story drift > 3% is usually classified as severely damaged.

Table 2. Relationships between qualitative factors and damage states

		Factors \ Damage states	None / Slight	Light	Moderate	Severe	Total / Collapse
RC Columns	Cracking	Fine cracks	■	■			
		Visible cracks		■	■	■	
		Flexural cracks	■	■			
		Shear cracks		■	■		
		Wide cracks			■	■	
	Concrete	Spalling		■	■		
		Serious spalling				■	■
		Crush				■	■
	Reinforcement	Exposure			■	■	
		Buckling or fracture				■	■
RC Walls	Cracking	Flexural cracks	■	■			
		Shear cracks		■	■		
	Concrete	Spalling		■	■	■	
		Crush				■	■
	Reinforcement	Exposure			■	■	
		Buckling or fracture				■	■
	Others	Failure of the boundary column					■
Masonry Walls	Cracking	Flexural cracks		■			
		Shear cracks		■	■		
	Others	Damage of the boundary columns			■		
Others		Visible inclination				■	■
		Partial or total collapse					■

II. Qualitative factors:

Table 2 shows the qualitative factors that are commonly used in the existing standards and their relationships with the damage states. The number of damage states is not identical in every standard, as shown in Table 1, although five levels are the most frequently used, including in the EERI procedure (1996) that is not reviewed here. The vertical members (RC columns/walls and masonry walls) are usually the major objects for evaluation, perhaps due to their importance in vertical and horizontal load bearing. Vertical members are also easier to observe, compared to beams that are usually hidden in ceilings. For each type of member, the factors were sorted by the damage content, and the results are summarized as follows:

1. The cracking appears early in the damage states. Slight or only flexural cracking is allowed in light damage states, and sometimes this is even considered as no damage. Shear cracking usually appears later than flexural cracking, and any obviously visible or wide cracks are usually referred to as moderate and severe damage.
2. Concrete spalling starts to appear in the light damage state. Large areas of concrete spalling that cause the exposure of reinforcement indicates severe damage. However, the exposure of reinforcement starts to appear in the moderate damage state, since it might also be observed in widened cracks.
3. The appearance of the crushing of core concrete, the buckling or fracturing of reinforcement, or the partial collapse of slabs that indicate the loss of vertical capacity, usually represent severe damage or collapse, as does the visible inclination that means large residual story drift.

2.1.2. Evaluation Procedure

The evaluation procedures of the reviewed standards can be divided into two major types:

1. Overall evaluation: The evaluation is based on the overall damage condition of the whole building or the most severely damaged part. This procedure is used in standards B, C, and D, listed above. While this approach has the advantages of simplicity and speed, the evaluation results tend to be subjective and conservative.
2. Detailed evaluation: The evaluation usually contains two steps. First, the damage conditions of individual members or factors are determined. Then the overall damage state is calculated considering the effect of each member or factor by applying a weighting coefficient. This procedure is used in standards A, E, and F. It is expected to be more objective and accurate than the overall evaluation, since quantitative factors are frequently used in this procedure. However, the determination of quantitative factors and weighting coefficient is still subjective, and it is also time-consuming and complicated.

2.2. The Presented Damage Evaluation Procedure

Based on the preceding review of the various evaluation methods,a new damage evaluation procedure is developed, as shown in this subsection. In order to combine the advantages of the two evaluation procedures mentioned above, the new procedure was designed to be a detailed evaluation that is only applied to the most severely damaged members. The evaluation factors and procedure are integrated into a single form that can be printed on an A4-size paper, as shown in Table 3. The evaluation factors are divided into the various main elements, including non-structural elements, RC beams/columns, masonry walls, and RC walls, and described using clear and concise language. The inspectors just need to check the boxes with regard to the observed damage conditions, and then follow the divisions marked by the shaded area to determine the overall damage state. The overall damage state is then determined by the severest damage condition observed. The damage state is basically divided into five levels, as in most other standards, but the fifth/highest state was subdivided into total damage (level V) and collapse (level V+) to distinguish buildings that are about to collapse and have already collapsed.

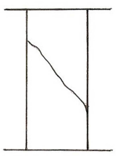
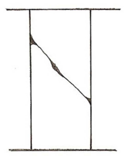
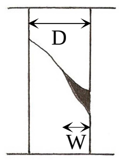
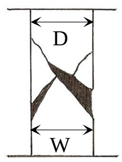
The determination of the evaluation factors and their relationships with the damage states in the proposed procedure basically follow the logic of the standards reviewed earlier, with some changes. Damage to non-structural elements was only evaluated in slight, light, and moderate damage states. The structural factors combined quantitative part and qualitative part. However, the standards for crack width were modified so that they corresponded to the other factors in the same damage states.

For example, a crack width between 1mm to 2mm indicates moderate damage in the above review, but this is obviously a conservative assessment compared to damage in which steel reinforcements are exposed. An appendix that provides definitions and examples of some of the factors, such as flexural/shear cracking and secondary/structural walls, is also attached to the form. In addition, the appendix provides detailed descriptions and illustrations for the qualitative factors, such as the concrete spalling, as shown in Table 4.

Table 3. The damage evaluation form

Non- structural elements	Overall assessment	Need of simple		Lightly damaged	Moderately damaged	Severely damaged	
Non- structural elements	1. Fall of ceiling	☐ No	☐Yes			Note: Damage of non-structural elements only apply to the overall damage states I, II, and III	
Non- structural elements	2. Fall of tile	☐ No	☐ Yes				
Non- structural elements	3. Parapet damaged	☐ No		☐ Yes			
Non- structural elements	4. Joints between buildings	☐ No damage / old cracks		☐ Damaged / widened	☐ Visible gap		
Non- structural elements	5. Fixed window glass damaged	☐ No		☐ Yes			
Non- structural elements	6. Doorframe deformed	☐ No			☐ Yes		
Structural elements – RC Beams / Columns	1. Flexural crack	☐ None / fine (d<0.3mm)	☐ d =0.3~5mm	☐ d=5-10 mm	☐ d>10 mm		☐ Partial or total collapse
Structural elements – RC Beams / Columns	2. Shear crack	☐ None / fine (d<0.3mm)	☐ d =0.3~3mm	☐ d=3-10 mm	☐ d>10 mm		
Structural elements – RC Beams / Columns	3. Concrete spalling	☐ None	☐ Light	☐ Moderate	☐ Severe		
Structural elements – RC Beams / Columns	4. Steel exposure	☐ No		☐ Yes			
Structural elements – RC Beams / Columns	5. Core crushing / steel buckling	☐ No			☐ Yes		
Structural elements – RC Beams / Columns	a. Percentage of column with (5.)				☐ < 1/3	☐ > 1/3	
Structural elements – RC Beams / Columns	6. Top slab	☐ Not damaged			☐ Drift	☐ Light settlement	
Structural elements – Walls – ☐ Masonry Walls	1. Secondary wall cracking	☐ None / fine (d<1mm)	☐d = 1~20mm	☐ d >20mm			☐ Partial or total collapse
Structural elements – Walls – ☐ Masonry Walls	2. Structural wall						
Structural elements – Walls – ☐ Masonry Walls	a. Shear crack	☐ None / fine (d<1mm)	☐ d = 1-10mm	☐ d > 10 mm	☐ Perforated		
Structural elements – Walls – ☐ Masonry Walls	b. Surface spalling	☐ None	☐ Light	☐ Moderate	☐ Severe		
Structural elements – Walls – ☐ Masonry Walls	c. Brick crushing	☐ None	☐ Light	☐ Moderate	☐ Severe		
Structural elements – Walls – ☐ Masonry Walls	d. Shear crack on boundary column	☐ No		☐ Yes (no steel exposure)	☐ Yes (with steel exposure)		
Structural elements – Walls – ☐ Masonry Walls	e. Dislocation / sliding	☐ None		☐ Light	☐ Significant, but no collapse		
Structural elements – Walls – ☐ RC Walls	1. Secondary wall cracking	☐ None / hairline	☐ d <= 5mm	☐ d > 5mm	☐ Perforated		☐ Partial or total collapse
Structural elements – Walls – ☐ RC Walls	2. Structural wall						
Structural elements – Walls – ☐ RC Walls	a. Cracks at opening corners	☐ None / hairline	☐ Yes				
Structural elements – Walls – ☐ RC Walls	b. Cracks on shear walls	☐ No	☐ Yes				
Structural elements – Walls – ☐ RC Walls	i. Flexural crack	☐ None	☐ d<=3mm	☐ d=3~5 mm	☐ d > 5 mm	☐ Perforated	
Structural elements – Walls – ☐ RC Walls	ii. Shear crack	☐ None	☐ d<=3mm	☐ d=3~5 mm	☐ d > 5 mm	☐ Perforated	
Structural elements – Walls – ☐ RC Walls	c. Concrete spalling	☐ None	☐ Light	☐ Moderate	☐ Severe		
Structural elements – Walls – ☐ RC Walls	d. Steel exposure	☐ No		☐ Yes			
Structural elements – Walls – ☐ RC Walls	e. Concrete crushing	☐ No			☐ Yes		
Structural elements – Walls – ☐ RC Walls	f. Top slab	☐ No damage			☐ Drift	☐ Light settlement	
Residual story drift		☐ Invisible		☐ <1%	☐ 1%-3%	☐ >3%	
Overall Damage State		☐ Slight	☐ Light	☐ Moderate	☐ Severe	☐ Total	☐ Collapse
		I	II	III	IV	V	V+
Overall assessment for use		■(GREEN) Safe for use	■(YELLOW) The building must not be used before the non-structural damage is repaired.	■(YELLOW) The building must not be used before a detailed inspection is performed.	■(RED) Safety measures must be taken immediately. Aftershocks might cause further damage.	■(RED) Entry is prohibited. The building is danger and might collapse in aftershocks.	■(RED) Partial or total collapse of the building.
Action to take for the structure		No need for repair	Repair or retrofit	Retrofit	Retrofit or demolish (determined after detailed assessment)	Should be demolished	

Table 4. The definitions of the degree of concrete spalling

Degree	None	Light	Moderate	Severe
Illustration				
Description	Only the peeling off of tiles or coating material is observed.	Slight spalling of the concrete cover along the cracks.	Small area of spalling of the concrete cover along the cracks. W≦1/2D (*)	Large area of spalling of the concrete cover. W≧1/2D

*: D = the total width of the member; W = the total width of the area of spalling

3. COMPARISON WITH IN-SITU TEST SPECIMENS

The presented evaluation procedure was applied to three specimens of in-situ push-over tests for school buildings by the National Center for Research on Earthquake Engineering (NCREE), including Kouhu elementary school (Jaung et al. 2008), Reipu elementary school (Chung et al. 2007), and Guanmiao elementary school (Chiou et al. 2008). The purpose of the comparison was to study the relationships between the evaluation factors and the capacity curves of the specimens and to check if the factors refer to the same damage states appear close to each other in the experimental damage progress. However, the crack width was not checked in the comparison. Because the crack width in the in-situ tests was observed when the specimens were under loading, it should be wider than the post-earthquake crack width, and thus was not applicable. Moreover, all the specimens were confined masonry buildings, and thus the factors related to RC walls were not checked.

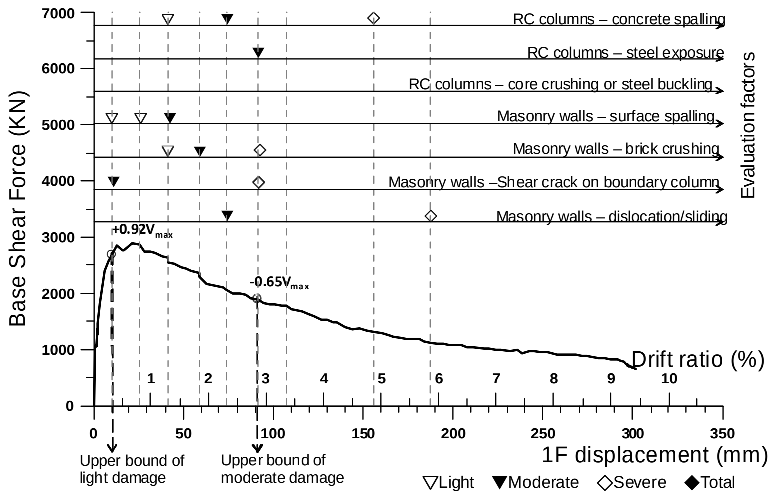
Figure 2 shows the relationships between the evaluation factors and the capacity curves of the in-situ specimens. For each evaluation factor, marks that represent different damage states (light/moderate/ severe/total) were placed along the drift/displacement axes whenever a damage level in the evaluation form was reached. The figures were supposed to be capable of determining the positions of the overall damage states, as the dotted lines show. For example, the first mark that represents severe damage appeared at the drift ratio of 2.86% in the Kouhu elementary school specimen (Figure 2(a)), meaning that the specimen moved from moderate damage to severe damage at this drift. However, since the crack width factors were not included in the evaluation, the determined damage state should be conservative. In other words, the determined damage states might appear earlier if the crack width was evaluated. Therefore, the dotted lines actually represent the possible upper bound of the damage states.

Except for one mark in the Kouhu specimen, the marks that represent the same damage states are close to each other in Figure 2, and their distributions are reasonable. However, the positions of the damage states were found to be later than expected. Table 5 shows the base shear corresponding to the boundaries of damage states. The positive and negative values mean that they appeared before and after the maximum base shear, respectively. This indicates that the boundary between light and moderate damage states approximately corresponds to the maximum base shear. However, as mentioned above, this result might be conservative, since the crack width was not included in the evaluation.

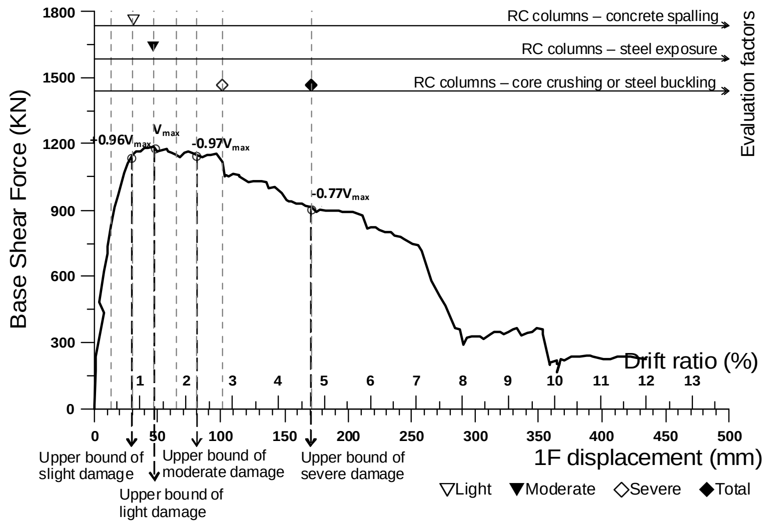
Table 5. The base shear corresponding to damage states

Specimen \ Damage states	Upper bound of slight damage	Upper bound of light damage	Upper bound of moderate damage	Upper bound of severe damage
Kouhu elem. school	—	$+0.92\ V_{max}$	$-0.65\ V_{max}$	—
Reipu elem. school	$+0.96\ V_{max}$	V_{max}	$-0.97\ V_{max}$	$-0.77\ V_{max}$
Guanmiao elem. school	$-0.98\ V_{max}$	$-0.95\ V_{max}$	$-0.90\ V_{max}$	$-0.63\ V_{max}$

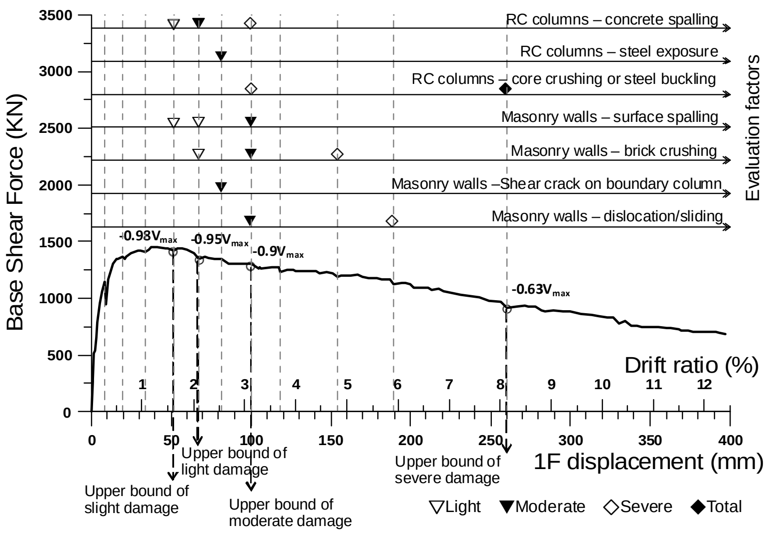
V_{max}: Maximum base shear



(a) Kouhu elementary school



(b) Reipu elementary school

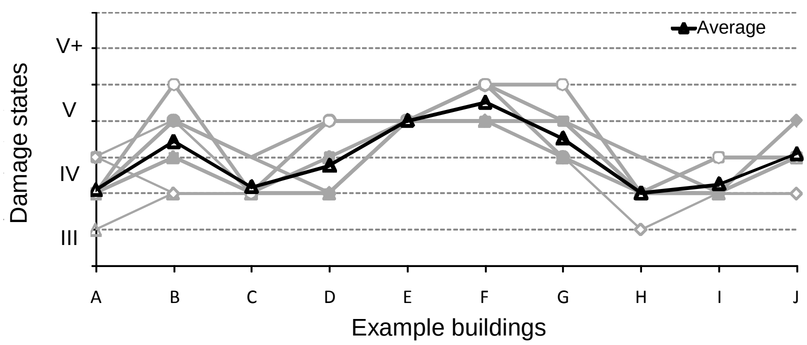


(c) Guanmiao elementary school

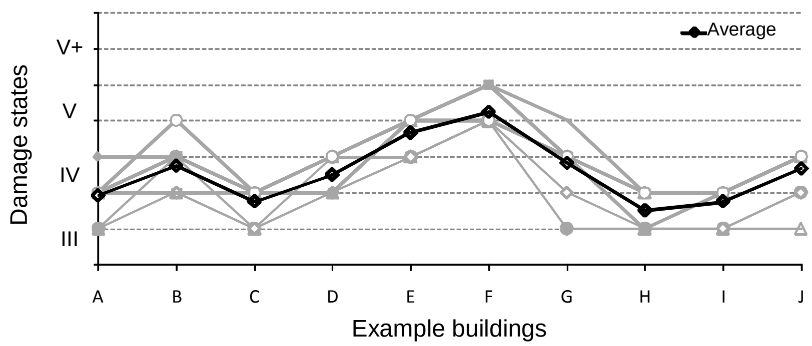
Figure 2. Relationships between the evaluation factors and the capacity curves of the in-situ specimens

4. VERIFICATION WITH SCHOOL BUILDINGS DAMAGED DURING MODERATE EARTHQUAKES

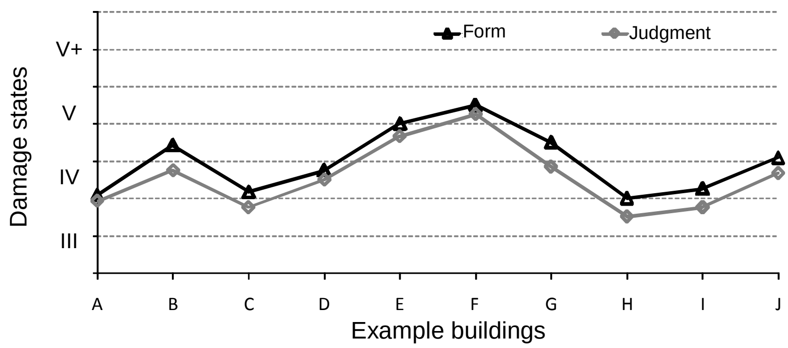
The damage states of buildings with the two extreme conditions are the easiest to determine: none/slight damage and total damage/collapse. The determination of light, moderate and severe damage states is usually subject to debate, since the boundaries in-between are ambiguous in typical quantitative evaluation standards. Therefore, the capability of the procedure to distinguish medium damage states was verified. Ten school buildings damaged in recent moderate earthquakes in Taiwan were chosen as the examples for evaluation. Twelve architectural and structural engineering professionals, including three architects, three structural engineers, and six researchers, were asked to evaluate the examples using pictures of damage.



(a) The form-determined damage states



(b) The subjectively judged damage states



(c) The comparison between average form-determined and average subjectively judged damage states

Figure 3. The comparison between form-determined and subjectively judged damage states

The evaluators were asked to complete the evaluation forms developed in this work, although the shaded areas marking the division of overall damage states in were removed. The evaluators were asked to check the boxes of the factors that corresponded to their observations, and to determine the overall damage state based on their subjective judgement. After the forms were retrieved, another overall damage state was determined in accordance with the checked factors following the proposed procedure. Figure 3 shows a comparison between the form-determined damage states and the subjectively assessed ones.

The grey lines in Figures 3(a) and 3(b) show the individual results, and the black lines represent the average. There are obvious individual differences in both form-determined and subjectively judged damage states, but the former were more concentrated on one damage state than the latter. The individual differences in form-determined results indicate that there might still have been some misinterpretation of the evaluation factors or the damage pictures. The averages of the two results were very close, and the form-determined one was slightly stricter, as shown in Figure 3(c). Although the verification was made from a limited number of examples and evaluators, the results suggest that the procedure presented in this work is at least as efficient as subjective judgements in distinguishing the medium damage states. More detailed results and discussion can be found in the master's thesis of Ao (2010).

5. CONCLUSIONS

A new earthquake damage evaluation procedure is presented in this paper. On the basis of a review of the existing standards, the procedure was designed to be a simple evaluation form. By using this method, the overall damage state can be determined in a few minutes by checking the evaluation factors corresponding to the observed damage. In order to reduce the errors from subjective judgements, the evaluation factors were expressed by quantitative values and clear, concise qualitative language.

The procedure was applied to three specimens of in-situ push-over tests for school buildings to study the relationships between evaluation factors and the capacity curves of the structures. The distributions of evaluation factors were found to be reasonable. However, the corresponding positions of the damage states on the capacity curves were later than expected. The capability of distinguishing the medium damage states of the procedure was also verified by using the data from 10 school buildings damaged during recent moderate earthquakes. Twelve professionals with different backgrounds were asked to complete the evaluation form and subjectively evaluate the damage states of the example buildings. The averages of the form-determined and subjectively judged results were found to be very close, and the form-determined one was more conservative. This suggests that the procedure presented in this work is both effective and efficient.

It should be noted that the proposed procedure is only applicable to RC and confined masonry buildings. In addition, because the verification was undertaken with limited samples, future research regarding damage assessment for buildings with RC walls and verification with a larger number of samples are being planned by the researcher.

AKCNOWLEDGEMENT

The authors gratefully acknowledge the National Science Council of Taiwan for supporting this research through grant no. NSC 98 - 2221 - E - 006 - 201.

REFERENCES

Anagnostopoulos, S. and Moretti, M. (2008), Post-earthquake emergency assessment of building damage, safety and usability-Part1: Technical issues, *Soil Dynamics and Earthquake Engineering*, **28:3**, 223-232.

Ao, L. C. (2010), Improvement of Earthquake Damage Evaluation Procedure for RC and Confined Masonry Buildings, Master thesis, Department of Architecture, National Cheng Kung University, Tainan, Taiwan.

ATC (1985), Earthquake Damage Evaluation Data for California, ATC-13 Report, Applied Technology Council, Redwood City, California.

Chiou, Y. C., Hwang, S. J., and Tsai, K. C. (2008), Proceedings of the Conference on In-situ Pushover Test of RC School Buildings with Seismic Retrofitting in Guanmiao, NCREE Research Report, NCREE-08-001,

National Center for Research on Earthquake Engineering, Taipei. (in Chinese)
Chung, L. L., Wu, L. Y., Yang, Y. S., Huang, Y. C., Lien, K. H., Chien, W. Y., Yeh, Y. K., Hwang, S. J., Hsiao, F. P., and Chiou, T. C. (2007), In Situ Monotonic Pushover Test on Retrofit of School Buildings by Adding Composite Columns to Partition Brick Walls, NCREE Research Report, NCREE-07-058, National Center for Research on Earthquake Engineering, Taipei. (in Chinese)
Dolce M., Kappos A., Masi A., Penelis G., Vona M. (2006), Vulnerability Assessment and Earthquake Damage Scenarios of the Building Stock of Potenza (Southern Italy) Using Italian and Greek Methodologies, *Engineering Structures*, **Vol. 28**, 357–371.
EERI (1996), Post Earthquake Investigation Field Guide, Earthquake Engineering Research Institute, Oakland, California.
EERI (2003), Collection and Management of Earthquake Data: Defining Issues for An Action Plan, Earthquake Engineering Research Institute, Oakland, California.
Gent Franch, K. A., Giuliano Morbelli, G. M., Astroza Inostroza, M. A., Gori, R. E. (2008), A Seismic Vulnerability Index for Confined Masonry Shear Wall Buildings and a Relationship with the Damage, *Engineering Structures*, **30:10**, 2605-2612.
Hsiao, C. P., Yeh, H. H., Sheu, M. S., Tsai, K. C., and Ding, Y. Q. (1999), General Report on Damage in Chi-Chi Earthquake – Damage Investigation for Building Structures, NCREE Research Report, NCREE-99-054, National Center for Research on Earthquake Engineering, Taipei. (in Chinese)
Japan Building Disaster Prevention Association (1991), Damage Evaluation Standard and Technical Instructions for Retrofit of Buildings Damaged by Earthquake (RC buildings), Japan Building Disaster Prevention Association, Tokyo. (in Japanese)
Jean, W. Y., Lien, K. H., Chang, Y. W., Chung, L. L., and Hwang, S. J. (2008), The Fragility of Low-rise RC School Buildings in Taiwan, *The 9th National Conference on Structure Engineering*, Kaohsiung, Taiwan, Aug. 22-24, no. L-0289. (in Chinese)
Jaung, W. C., Chiou, T. C., Hsiao, F. P., Tu, Y. H., Chien, W. Y., Yeh, Y. K., Chung, L. L., and Hwang, S. J. (2008), In-situ Pushover Test of School Building Structure in Kao-hu Elementary School, NCREE Research Report, NCREE-08-044, National Center for Research on Earthquake Engineering, Taipei. (in Chinese)
Miyakoshi, J., Hayashi, Y., Watanabe, K., and Tamura, K. (1997), Seismic performance Evaluation of Buildings from Building Damage of the 1995 Hyogo-Ken-Nanbu Earthquake, *Journal of Structural Engineering, Architectural Institute of Japan*, **Vol. 34B**, 269-276. (in Japanese)
Nagato, K. and Kawase, H. (2004), Damage Evaluation Models of Reinforced Concrete Buildings Based on the Damage Statistics and Simulated Strong Motions during the 1995 Hyogo-Ken Nanbu Earthquake, *Earthquake Engineering and Structural Dynamics*, **Vol. 33**, 755–774.
Scawthorn, C., Iemura, H., and Yamada, Y. (1981), Seismic Damage Estimation for Low-and Mid-Rise Buildings in Japan, *Journal of Earthquake Engineering and Structural Dynamics*, **Vol. 9**, 93-115.
Tu, Y. H., Yeh, P. L., Liu, T. W., and Jean, W. Y. (2009), Seismic Damage Evaluation for Low-Rise RC School Buildings in Taiwan, *The 2009 Structure Congress*, Austin, U.S., April 30-May 2, 1347-1356.
Whitman, R. V., Hong, S., and Reed, J. W. (1973), Damage Statistics for High-Rise Buildings in the Vicinity of the San Fernando Earthquake, Massachusetts Institute of Technology Department of Civil Engineering Research Report R73-24, Cambridge, Massachusetts.