CURRENT SEISMIC RETROFITTING PROGRAMS OF SCHOOL AND RESIDENTIAL BUILDINGS IN TAIWAN

S. J. Hwang[(1)], L. L. Chung[(2)], T. C. Chiou[(3)], P. C. Chen[(4)]

[(1)] *Director General, National Center for Research on Earthquake Engineering, sjhwang@ncree.narl.org.tw*
[(2)] *Deputy Director General, National Center for Research on Earthquake Engineering, chung@ncree.narl.org.tw*
[(3)] *Associate Researcher, National Center for Research on Earthquake Engineering, tcchiou@ncree.narl.org.tw*
[(4)] *Project Technician, National Center for Research on Earthquake Engineering, pinchi@ncree.narl.org.tw*

Abstract

Prior to the introduction of modern seismic codes in the late 1990s for Taiwan, many reinforced concrete buildings were designed without adequate detailing and reinforcement for seismic protection. For these vulnerable buildings, enhancements to the seismic capacities through retrofitting are urgently needed. The objective of this paper is to report the current seismic retrofitting programs of Taiwan. One is the school retrofitting program issued by the Ministry of Education 12 years ago. There are 3,783 elementary and high schools in Taiwan, and the total number of buildings may be as high as approximately twenty seven thousands. Without careful planning, the budget could easily be exceeded due to the large number of buildings. Adopting an effective strategy using economical technologies and systematic prioritization is essential for this school retrofitting project to be successful. The government of Taiwan has launched a project to upgrade the seismic performance of school buildings, and a total of $138 billion Taiwan dollars was budgeted from 2009 to 2022. This school retrofitting program have upgraded the seismic capacities of approximately 8,500 school buildings in Taiwan.

The other is the seismic retrofitting program for residential buildings by phases issued by the Ministry of Interior Affairs. Reinforced concrete buildings account for 75% of the total floor area in Taiwan. More than three quarters of these existing concrete buildings were constructed before 1999. Because of the less seismic demand and the inadequate seismic detailing, these older reinforced concrete buildings are prone to severe earthquake damage and even collapse. Worst of all is the deficiency of the soft first story due to the residential and commercial mixed usage. This retrofitting program by phases, started from 2018, is aimed to remove the seismic deficiency of the soft first story as a first priority for the residential buildings. The strategy, technology and progress of these seismic programs are introduced in this paper.

Keywords: reinforced concrete; residential building; school building; seismic retrofitting; soft first story

1. Introduction

Reinforced concrete buildings account for 75% of the total floor area in Taiwan. More than three quarters of these existing concrete buildings were constructed before 1999. Because of the less seismic demand and the inadequate seismic detailing, these older reinforced concrete buildings are prone to severe earthquake damage and even collapse. Recent reconnaissance reports revealed that the school buildings with cantilever corridors and the residential buildings with the soft first stories are the particularly vulnerable structures in Taiwan. Therefore, enhancements to the seismic capacities of these buildings through retrofitting are urgently required.

The school retrofitting program issued by the Ministry of Education started from 2009 and continued to 2020. This program is fully developed and yields substantial results. Firstly the strategy, technology and progress of this seismic project for school buildings in Taiwan are reported. The seismic retrofitting program for residential buildings by phases issued by the Ministry of Interior Affairs just started from 2018. This program is in the early stage. Then the objective, special features and problems of this seismic project for residential buildings in Taiwan are discussed in this paper.

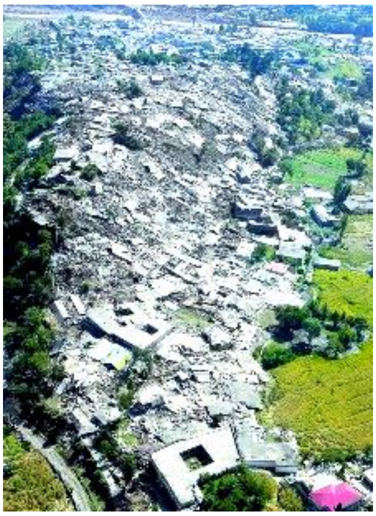
2. Program for upgrading seismic capacity of school buildings

School buildings are public constructions which are densely utilized. The number of casualties that can be caused by a collapse due to an earthquake is unimaginable. Consider the 7.6 Richter scaled earthquake that took place in Pakistan on October 8, 2005 at 8:50 a.m. (Fig. 1). This earthquake occurred during class time, and the collapse of the school buildings resulted in the death of 19,000 students. Among the 87,000 deaths in this earthquake, a staggering twenty two percent were students. Pakistan lost a generation of young people in this earthquake, a huge loss that can never be recovered. A similar tragedy also occurred during the Chinese Wen-Chuan earthquake in May of 2008 (Fig. 2), and it is essential that we learn from these experiences and ensure that a similar tragedy does not happen again.

The 921 Chi-Chi earthquake demonstrated that the safety level of school buildings in Taiwan was of great concern. During this earthquake, more than half of the school buildings in Nantou County were either partially or fully destroyed (Fig. 3). Therefore, it is without a doubt that the seismic capacity of the school buildings in Taiwan should be a cause for concern, and that the seismic capacity of the school buildings needs to be urgently improved through retrofitting. However, there are 3,783 public elementary, junior, and senior high schools (including vocational schools) in Taiwan and over 27,000 school buildings. Such a large number of buildings would easily exhaust the available funds if no economically effective method existed, and completing the project within budget would be hard to achieve.

Due to the importance of the safety of the school buildings, the government allocated a budget of TD$138 billions (1USD≒30TD) to upgrade, from 2009 to 2022, the seismic capacity of public elementary, junior and senior high school buildings. The National Center for Research on Earthquake Engineering (NCREE), entrusted by the Ministry of Education, established a Project Office for Seismic Upgrading of School Buildings to provide technical and administrative assistance to the project. In terms of technical assistance, NCREE provided methods for the school buildings' seismic evaluation and retrofitting. In terms of administrative assistance, the Project Office established operation specifications, gave seminars, popularized good retrofitted examples, and established a data bank.

The following sessions firstly report the strategy for implementing the school buildings' seismic capacity and retrofitting plan, and the proposal for the various stages of the plan. Next, this paper discusses the characteristics of the seismic evaluation and retrofitting techniques, and their verification by using related experiments. Finally, through analysis of available data, the progress of the plan, qualities and characteristics of the project, the status of funds expenditure, and the effectiveness of the rehabilitation are reported.



Date: Oct. 8, 2005, 08:50
Richter Scale: 7.6

Fig. 1 – Pakistan 2005 Kashmir EQ

Date: May 12, 2008, 14:18
Richter Scale: 7.8

Fig. 2 – Chinese 2008 Wen-Chuan EQ

Date: Sep 21, 1999, 01:47
Richter Scale: 7.3

Fig. 3 – Taiwan 1999 Chi-Chi EQ

Fig. 4 shows the strategy for upgrading the seismic capacity of school buildings in Taiwan [1]. The strategy is divided into four stages, i.e., census, preliminary evaluation, detailed evaluation, and retrofitting design and construction. The stages of census, preliminary evaluation, and detailed evaluation are useful for determining the retrofitting priority of each building. These procedures identify school buildings with inadequate seismic capacity, and by using seismic performance indices, the retrofitting priority for each building is determined. The detailed evaluation and retrofitting design would then undergo reviews to ensure the quality of the analysis and the design, and the retrofitting construction would be inspected by engineers to ensure the quality of construction. The results for each stage are submitted into the Taiwan School Buildings' Seismic Performance Data Bank. By analyzing this data, it is possible to understand the progress of the project, the quality and specific characteristics of the operations, and to provide information for references in decision making. All the stages for upgrading seismic performance of school buildings are described separately in the sections below.

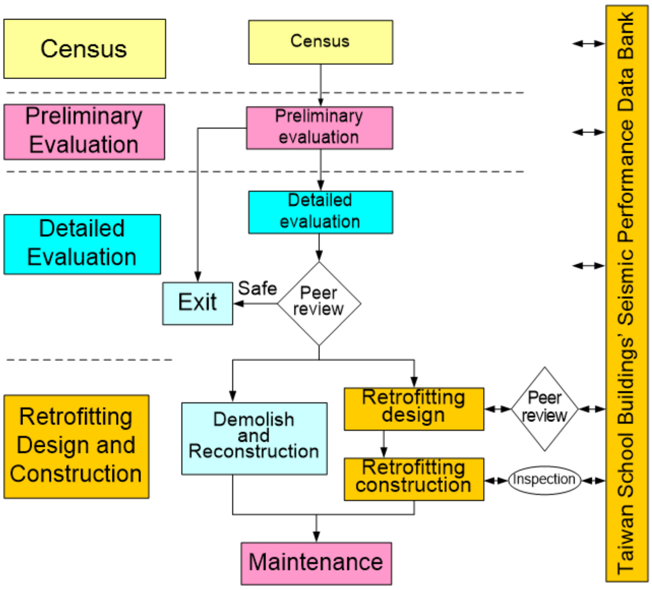


Fig. 4 – Strategy of seismic upgrading of school buildings in Taiwan

2.1 Census

The establishment of a data bank to record results from seismic evaluation and retrofitting of all school buildings in Taiwan is helpful in improving the quality of the plan and the schools' safety administration of campuses.

For this purpose, the Project Office for Seismic Upgrading of School Buildings started gathering basic information about seismic capacity for all elementary and high school buildings. Undergraduate civil and construction engineering students from several universities carried out this census of school buildings as their practical work experience during winter and summer vacations. In 2011 the census was completed. It collected a total number of buildings as high as approximately twenty seven thousands.

2.2 Preliminary evaluation

The technique used in preliminary evaluation of school buildings is shown below:

$$\frac{Strength}{Demand} = \frac{\tau_c A_c + \tau_{rcw} A_{rcw} + \tau_{bw} A_{bw}}{a_g \times w \times \sum A_f} \tag{1}$$

where A_c is the total cross-sectional area of RC columns on the first floor, τ_c is the average lateral strength per unit cross-sectional area of the RC column. A_{rcw} is the total cross-sectional area of RC walls along corridor on the first floor, τ_{rcw} is the average lateral strength per unit cross-sectional area of the RC wall, A_{bw} is the total cross-sectional area of the brick walls along corridor on the first floor, τ_{bw} is the average lateral strength per unit cross-sectional area of the brick wall, a_g is the seismic design ground acceleration, w is the unit mass per floor area, and ΣA_f is the summation of floor area above the second floor.

The preliminary evaluation of school buildings was conducted by professionals in structural engineering. A table for preliminary evaluation [2] was made according to Eq. (1). The evaluation standard was based on the geometrical dimensions of the vertical structural components and their average lateral strength, and was performed by professionals on site at the selected school buildings. They did not have to find the material strength, and did not have to look for the original design plans. Half a day was allocated for preliminary evaluation of each school building with a fee of TD$6,000. The results of the preliminary evaluation had to be submitted to the NCREE website, which are then used for further monitoring and adjustment of the project. The goal of the preliminary evaluation was to further identify school buildings with seismic capacity concerns and to assign priorities for the selected buildings to go through the detailed evaluation stage.

2.3 Detailed evaluation

NCREE suggested that the detailed evaluation of the seismic capacity of school buildings should be carried out using the method of performance based design [3, 4], i.e., first conduct the nonlinear lateral pushover analysis to find the capacity curve of the school building, and then carry out the spectrum analysis to obtain the performance curve of the school building. By selecting the performance point, the associated peak ground acceleration can be determined, as shown in Fig. 5. For most school buildings, the goal is to ensure the safety of students and teachers if the buildings should suffer medium level of damage by being subjected to the design earthquake with 475-year return period. For buildings used as emergency shelters, the goal is to provide useful shelter if the buildings should suffer slight damage subjected to the design earthquake with 475-year return period. Based on the aforementioned goals, the selection of the performance point in the detailed evaluation of the seismic capacity should refer to the school building handbook [3, 4].

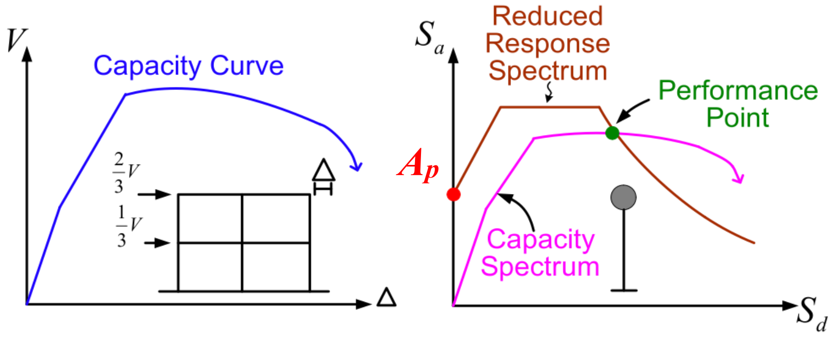
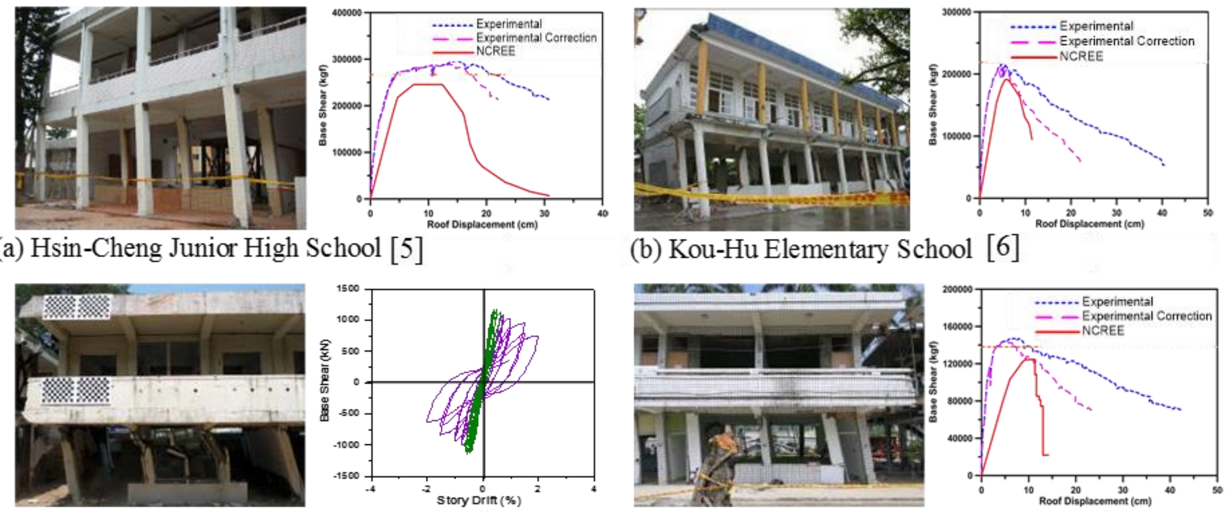


Fig. 5 – Detailed evaluation for seismic capacity

The lateral pushover analysis suggested by NCREE [3] was verified by experiments onsite. The experiments were performed on targeted school buildings which had already been assigned to be demolished. A uni-directional static lateral pushover test, pseudo dynamic test, and cyclic loading test were conducted during the winter and summer vacation period [5-11]. These experiments were conducted on Taiwan's existing school buildings and the results were quite reliable. Fig. 6 shows the in-situ experimental verification of NCREE's lateral pushover analysis. The two main points of verification were the accuracy of the damage mode predicted by the analysis model, and the accuracy of predicted capacity curve due to lateral force. The result of the lateral pushover analysis by NCREE showed that, after the school buildings were subjected to lateral forces, the building frame underwent a shearing type behavior. The damage was due to failure of the vertical columns on the first floor [5-7, 10], which was the same as that observed in the in-situ tests (Fig. 6). In addition, the rigidity, strength, and ductility were found to be conservative compared to the values measured onsite in NCREE's predicted building capacity curve due to lateral force (Fig. 6).



(a) Hsin-Cheng Junior High School [5] (b) Kou-Hu Elementary School [6]

(c) Ruei-Pu Elementary School [7] (d) Guan-Miao Elementary School [10]

Fig. 6 – Experimental verification of pushover analysis by in-situ school tests

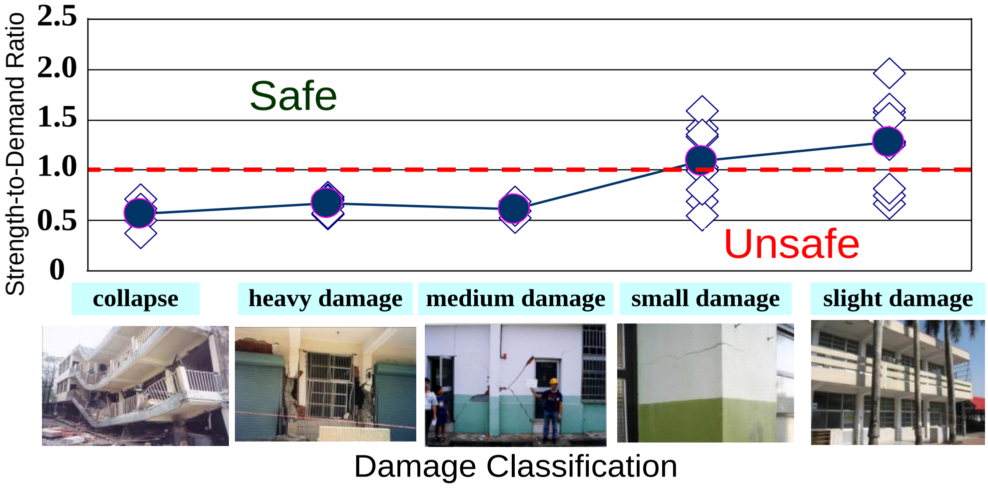


Fig. 7 – Verification of evaluation method by 921 seismic damage data bank of school buildings

The spectrum analysis and criteria for the selection of performance points suggested by NCREE were verified by using data from the 921 seismic damage data bank of Nantou's school buildings [12]. These data included the blueprints of the school buildings' structural design, records of the ground acceleration at the 921 seismic site, and records of seismic damages. Through understanding the structural characteristics of the school buildings, the intensity of the earthquake, and the extent of the damages, a comparative study and verification could be conducted on the selection of the performance point, and the accuracy of the spectrum analysis. Fig. 7 shows the contents of Nantou's 921 seismic damage data bank [13], in which the five levels of damages were identified as collapse, heavy damage, medium damage, small damage, and slight damage. The levels were determined from photographs of the damaged buildings and records of interviews. The strength-to-demand ratio was determined by the peak ground acceleration obtained by NCREE's detailed evaluation divided by the design ground acceleration at the site. It can be seen from Fig. 7 that the strength-to-demand ratio determined from NCREE's analysis had a positive relationship with the levels of 921 seismic damages. Based on the strength-to-demand ratio, the method of NCREE seismic capacity evaluation required that all damaged buildings classified as collapse, heavy damage, and medium damage in Fig. 7 should undergo retrofitting. However, in the predicted behavior of buildings with small and slight damage shown in Fig. 7, the NCREE considers them safe according the average values. It can be seen from Fig. 7 that NCREE's method of seismic capacity detailed evaluation (lateral pushover analysis, spectrum analysis, and selection of performance points, etc.) could effectively determine the seismic capacity safety level of each building, and is also more conservative.

2.4 Retrofitting design

From the reconnaissance of the 921 damaged school buildings, typical school buildings of Taiwan were mostly damaged by the failure of vertical structural members on the first floor, and led to the collapse of the buildings along the direction of the corridor (Fig. 3). Therefore, increasing the number of vertical structural members, or improving the strength and ductility of existing columns are effective methods of retrofitting. Fig. 8 illustrates several traditional methods of retrofitting applied to the buildings [6, 8, 10, 11], some of which were already explained in the school building handbook [3, 4].

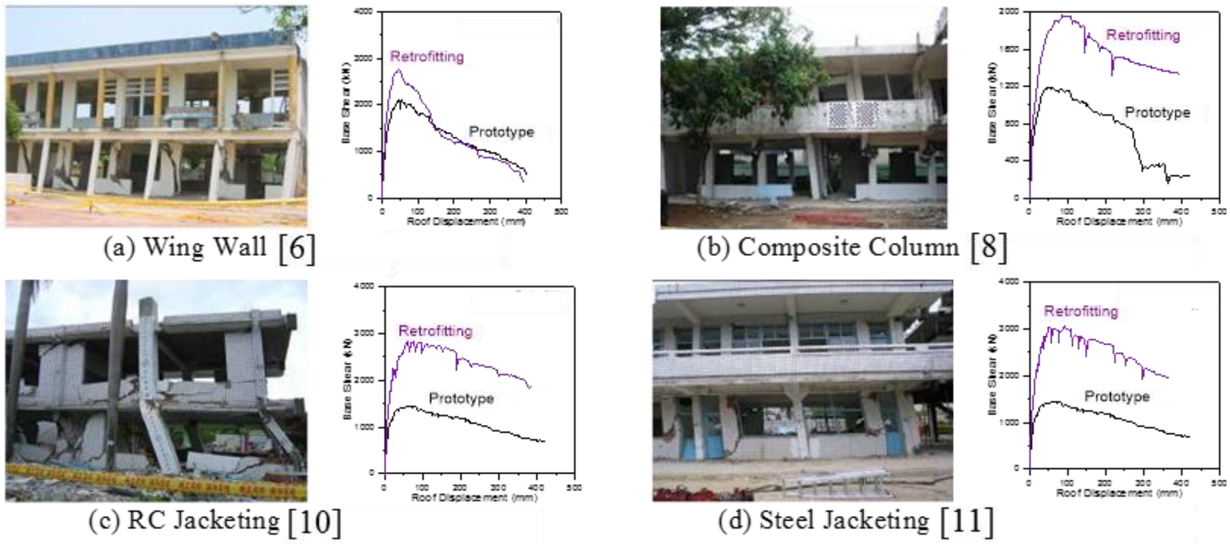


Fig. 8 – Experimental verification of retrofitting measures by in-situ school tests

Both detailed evaluation of seismic capacity and the design of retrofitting should go through the review process. The reviews are conducted at the beginning and at the completion of the job. The review at the beginning of the job is conducted so that members of the review committee, the design personnel, and the school representatives agree with the planning and extent of the job. The review at the completion of work is an inspection to ensure that all the required work by the contract is fulfilled. The review committee consists of three members, all of which are selected from the Reviewer Archives of the Ministry of Education. The committee's opinion of the review is written by the coordinator of the committee.

The retrofitting project was carried out by the use of economical, effective, and traditional technologies. The overall retrofitting budget for unit floor area was limited to be TD$4,000/m^2, about 17% of TD$24,000/m^2, which was the cost of the reconstruction of the building. The project was mainly for seismic capacity retrofitting of the structures. Thus, the budget for repair of the building should not exceed 30% of the retrofitting budget.

2.5 Retrofitting construction

The quality of the school buildings' seismic retrofitting project should be inspected by the three-level public engineering work administrative system. The first level is a self-inspection by the constructor; the second level is conducted by the engineering unit of the user of the building together with the inspection contractor; and the third level is conducted by the government agency responsible for the project. In school buildings' retrofitting project, the school is the user of the building and it does not have engineering unit. Therefore, the effort of the inspection contractor is quite important.

School campuses are densely populated public areas, and safety is an important factor during the retrofitting construction on campuses. Therefore, before starting construction, a public hearing should be conducted in which the constructor explains the construction plan, the work schedule, and the plans for safety and environmental administration. The inspection contractor explains the plan for construction inspection. The purpose of this is to let the teachers, students, and their parents understand the safety measures during the period of construction.

The results from the census, preliminary evaluation, detailed evaluation, retrofitting design, and all stages of the construction process should be submitted to the school buildings seismic performance data bank in Taiwan so that the data can be used for analysis. The administrators can then understand the extent of the progress and the quality and special characteristics of the project, and provide information for decision making.

Numerous personnel are involved, since the schools conducted the bidding process to select contractors for the seismic capacity detailed evaluation, the retrofitting design, and construction. A unified operation specification for engineering contracts ensures that the contents of the evaluation and retrofitting satisfy the requirements of the original proposal. The Project Office for Seismic Upgrading of School Buildings assisted the Ministry of Education to issue operation specifications of evaluation and retrofitting. These operation specifications should be updated continuously when required.

2.6 Current process

The current status of the retrofitting plan is shown in Table 1. The preliminary evaluation, detailed evaluation, and retrofitting design have already been performed on the targeted number of buildings, and the completed retrofitting constructions have reached 6,420. The present task is to continue the effectiveness of the project, to improve the quality of each stage, and to generally evaluate the completion rates of the seismic capacity evaluation and retrofitting work to avoid any oversight.

Table 1 – Current progress of upgrading project

Stage	**No. of Completion Buildings**
Preliminary Evaluation	17,783
Detailed Evaluation	10,376
Retrofitting Design	8,957
Retrofitting Construction	6,420

In accordance with the teaching planning or the urban planning, some of the seismically insufficient school buildings were torn down or rebuilt. There are about 2,000 school buildings gone through this way, which costs about the same expense of the retrofitting program.

2.7 Budget and expenditure

In order to effectively control the expenditure of the project, it is necessary to understand the bidding price for each stage in the seismic upgrading of school buildings. Table 2 shows the statistical information of the unit bidding prices for each stage of the project. It can be seen from Table 2 that the final bidding price of the retrofitting construction work per unit floor area was TD$2,666/m^2, which was only 67% that of the budget TD$4,000/m^2. It may be concluded that it was effective to emphasize economical, effective retrofitting techniques, and to review the retrofitting design. Table 2 shows statistics of retrofitting construction expenses for senior high schools (including vocational schools). After technical review, the cost for retrofitting construction was only 82% of the original budget, and the final bidding price was only 67% of the original budget.

Table 2 – Bidding price statistics of school upgrading

	Original Budget	**Budget Approved by Reviews**	**Bidding Unit Price**
Retrofitting Construction	4,000 TD/m^2	3,262 TD/m^2	2,666 TD/m^2

Note: 1USD≒30TD

The main goal of seismic retrofitting is to make existing school buildings achieve the safety standard of seismic performance ensuring economical and reasonable expenses. The school building seismic upgrading plan in Taiwan requires that the expenses of the seismic retrofitting construction be within TD$4,000/m^2, and that the budget for reconstruction is TD$24,000/m^2. Therefore, in Taiwan's school building upgrading plan, the project is considered economical only when the retrofitting expenses do not exceed 17% of the reconstruction cost. Table 2 shows that Taiwan's retrofitting construction cost was TD$2,666/m^2, which was only 11% of the reconstruction cost (Fig. 9).

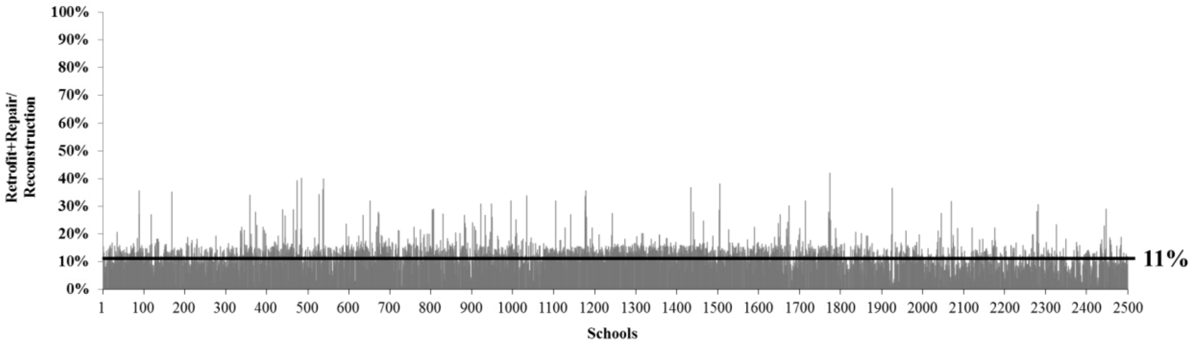


Fig. 9 – Taiwan's retrofitting construction costs for school buildings

3. Program for upgrading seismic capacity of residential buildings

Reinforced concrete buildings account for 75% of the total floor area in Taiwan. More than three quarters of these existing concrete buildings were constructed before 1999. Because of the less seismic demand and the inadequate seismic detailing, these older reinforced concrete buildings are prone to severe earthquake damage and even collapse. Worst of all is the deficiency of the soft first story due to the residential and commercial mixed usage. It was quite often observed that these soft first story buildings with non-ductile detailing were collapsed during earthquakes (Fig. 10). Enhancements to the seismic capacities through retrofitting are urgently needed for these vulnerable buildings.

(a) 14-story Condominium 2016 Meinong EQ

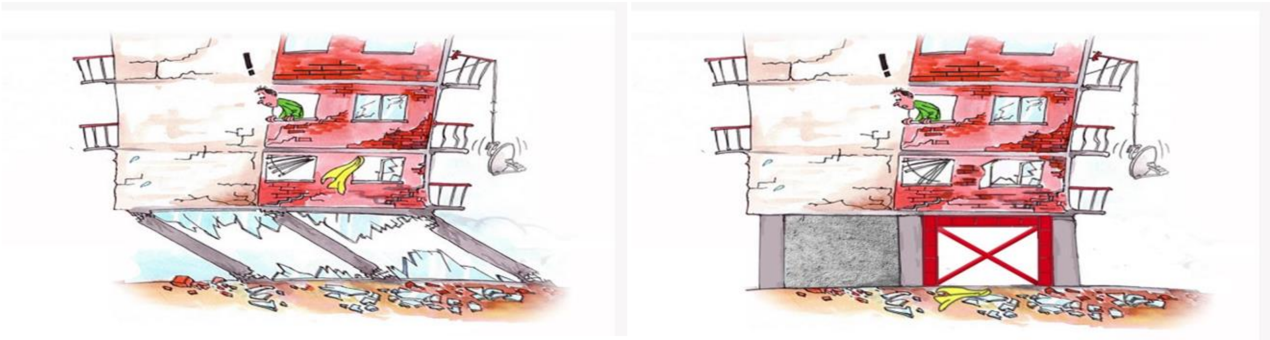
(b) 12-story Condominium 2018 Hualien EQ

(c) 11-story Hotel 2018 Hualien EQ

Fig. 10 – Collapsed buildings with soft first story

Seismic retrofit implementation for private buildings has been a major challenge in many earthquake-prone cities. Building owners are usually reluctant to adopt measures to reduce earthquake losses due to a lack of trust in seismic strengthening techniques and a lack of support for pro-social mitigation behaviours from public authorities. Because of the joint ownership of the real estate of condominium, it is extremely difficult to reach a consensus on retrofitting issue for private buildings.

In view of the building owners' reluctance to take seismic retrofitting measures, the Construction and Planning Agency of the Ministry of Interior Affairs of Taiwan launches a program to retrofit the residential buildings by phases. The aim of this program is to remove the seismic deficiency of the soft first story as a first priority for the residential buildings. To retrofit the parking lot in the first story without intervening the residential units above (Fig. 11) can be more attractive for building owners. By removing the seismic deficiency of the soft first story, it is expected that the collapse of building can be prevented.



(a) Building with soft first story (b) Removal of seismic deficiency

Fig. 11 – Concept for retrofitting the residential buildings by phases

A special feature of residential buildings is the installation of partition walls, such as infilled reinforced concrete walls or infilled brick walls, to maintain privacy (Fig. 12). In order to reduce the retrofitting cost, the seismic capacities of existing partition walls should be considered. The lateral load-dislacement curves of these partition walls have been developed, such as infilled reinforced concrete wall [14], infilled brick wall [15] and reinforced wall with opening [16]. Some new retrofitting measures using dry construction methods are also developed.

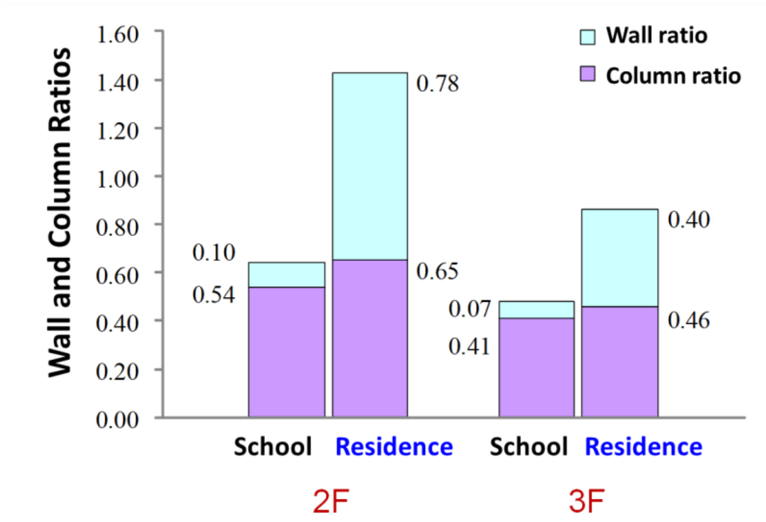


Fig. 12 – Comparison of wall ratio and column ratio for school and residential buildings

A newly completed example is shown in Fig. 13. It's a 6-story condominium with a parking lot in the first story. Ten shear walls were added in the first story. The floor area of the first story is 690 m^2 and the retrofitting cost is TD$3,700/$m^2$.

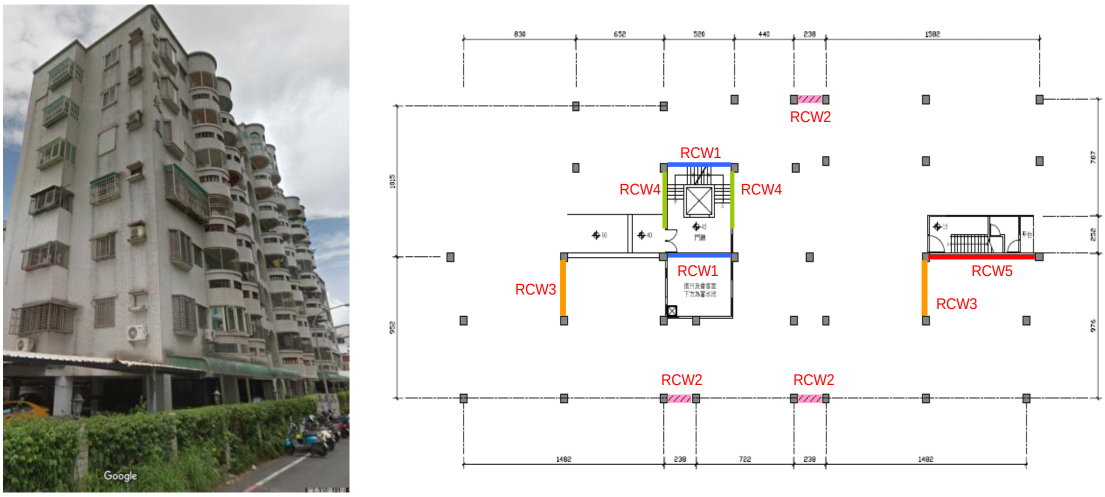


Fig. 13 – A example of removal of seismic deficiency of soft first story

4. Conclusions and remarks

The school retrofitting program issued by the Ministry of Education started from 2009 and continued to 2020. This program is fully developed and yields substantial results. The seismic retrofitting program for residential buildings by phases issued by the Ministry of Interior Affairs just started from 2018. This program is in the early stage.

It is hoped that, by seismic evaluation and retrofitting of school buildings and residential buildings, the general public of Taiwan would understand the importance of seismic retrofitting. This work may be continued and extended to more existing buildings in order to create a much secure homeland.

5. Acknowledgement

The authors would like to thank the officials of the Ministry of Education and the Ministry of Interior Affairs for providing information and guidance. This work done by the members of the National Center for Research on Earthquake Engineering is much appreciated.

6. References

[1] Hwang SJ, Chung LL, Chien WY, Yeh YK, Chow TK, Yeh YH, Chiou CK, Wang YK (2005): A proposal for seismic assessment and retrofit of elementary school buildings. *Journal of Architecture*, 54, 75-90. (In Chinese)

[2] Su KL (2008): Preliminary seismic evaluation method for typical school buildings in Taiwan. *Master Thesis*, National Taiwan University, Department of Civil Engineering, Taipei, Taiwan. (In Chinese)

[3] Chung LL, Yeh YK, Chien WY, Chai JF, Hsiao FP, Shen WC, Chiou TC, Chow TK, Chao YF, Yang YS, Hwang SJ (2008): Technology handbook for seismic evaluation and retrofit of school buildings. *Technical Report NCREE-08-023*, National Center for Research on Earthquake Engineering, Taipei, Taiwan. (In Chinese)

[4] Hsiao FP, Chung LL, Yeh YK, Chien WY, Shen WC, Chiou TC, Chow TK, Chao YF, Weng PW, Yang YS, Chu YL, Tu YS, Chai JF, Hwang SJ (2013): Technology handbook for seismic evaluation and retrofit of school buildings- Third edition. *Technical Report NCREE-13-023*, National Center for Research on Earthquake Engineering, Taipei, Taiwan. (In Chinese)

[5] Jaung WC, Chiou TC, Hsiao FP, Tu YH, Chien WY, Yeh YK, Chung LL, Hwang SJ (2008): In-situ pushover test of school building structure in Sin-Chen junior high school. *Technical Report NCREE-08-008*, National Center for Research on Earthquake Engineering, Taipei, Taiwan. (In Chinese)

[6] Jaung WC, Chiou TC, Hsiao FP, Tu YH, Chien WY, Yeh YK, Chung LL, Hwang SJ (2008): In-situ pushover test of school building structure in Kao-Hu elementary school. *Technical Report NCREE-08-044*, National Center for Research on Earthquake Engineering, Taipei, Taiwan. (In Chinese)

[7] Weng YT, Lin KC, Hwang SJ, Chiou TC (2008): In-situ pseudo-dynamic test and cyclic pushover test of existing school buildings. *Technical Report NCREE-08-004*, National Center for Research on Earthquake Engineering, Taipei, Taiwan. (In Chinese)

[8] Chung LL, Wu LY, Yang YS, Hwang YC, Lien KH, Chien WY, Yeh YK, Hwang SJ, Hsiao FP, Chiou TC (2007): In-situ monotonic pushover test on retrofit of school buildings by adding composite columns to partition brick walls. *Technical Report NCREE-07-058*, National Center for Research on Earthquake Engineering, Taipei, Taiwan. (In Chinese)

[9] Chiou TC, Hsiao FP, Chen SL, Sergio MA, Chiou YJ, Hwang SJ (2008): Field test and analysis for school building retrofitted by post-tensioned rods. *Technical Report NCREE-08-032*, National Center for Research on Earthquake Engineering, Taipei, Taiwan. (In Chinese)

[10] Chiou YJ, Shih CT, Hsiao FP, Chiou TC, Ruan JP, Hwang SJ (2008): Field test and analysis for school building retrofitted by RC jacketing system. *Technical Report NCREE-08-033*, National Center for Research on Earthquake Engineering, Taipei, Taiwan. (In Chinese)

[11] Chiou YJ, Liou YW, Hwang JQ, Hsiao FP, Chiu YC, Chiou TC, Hwang SJ (2008): Field test and analysis for school building retrofitted by steel-framing system. *Technical Report NCREE-08-034*, National Center for Research on Earthquake Engineering, Taipei, Taiwan. (In Chinese)

[12] Liu TW (2008): A study of validation on simplified push-over analysis. *Master Thesis*, National Cheng Kung University, Department of Architecture, Tainan, Taiwan. (In Chinese)

[13] Hong WC (2009): Study on seismic evaluation of school buildings based on push over analysis. *Master Thesis*, National Taiwan University, Department of Civil Engineering, Taipei, Taiwan. (In Chinese)

[14] Weng PW, Li YA, Tu YS, and Hwang SJ (2017): Prediction of lateral load displacement curves for reinforced concrete squat walls failed in shear. *Journal of Structural Engineering, ASCE*, 143(10), DOI: 10.1061/(ASCE)ST.1943-541X.0001872, 04017141.

[15] Chiou TC, and Hwang SJ (2015): Tests on cyclic behavior of reinforced concrete frames with brick infill. *Earthquake Engineering and Structural Dynamics*, 44(12):1939–1958, Wiley Online Library, DOI: 10.1002/eqe.2564.

[16] Yeh RL, Tseng CC, and Hwang SJ (2018): Shear strength of reinforced concrete vertical wall segments under seismic loading. *ACI Structural Journal*, V. 115, No. 5, September, pp. 1485-1494.

