IN-SITE PUSH OVER TESTS AND SEISMIC ASSESSMENT ON SCHOOL BUILDINGS IN TAIWAN

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ABSTRACT

In Taiwan, many school buildings suffer severe damage in earthquakes due to their typical architectural pattern. 4 in-site push over tests of school buildings were carried out to study the effects of different retrofitting measures and to verify the seismic assessment methods. The specimens include a 2-floor building with 3 classrooms of Hsin-Cheng Junior High School, Hualien, and a 2-floor school building of Kouhu Elementary School, Yulin. The latter was consists of 8 classrooms and cut into 3 specimens, each has 2 classrooms, while the rest 2 classrooms reinforced by steel bracing to provide reacting support. Specimen in Hualien was a typical school building with no walls in the longitudinal direction, while specimens in Yulin has an typical one, one with original brick wing walls, and one with new RC wing walls as retrofit in the longitudinal direction. 6 hydraulic actuators were placed at the top of each floor of each specimen to provide lateral loading along the longitudinal direction. While being lateral loaded, some of the specimens were subjected to extra vertical loads by added weights on the slabs. The test results show that wing walls can efficiently improve lateral strength of school buildings. A seismic assessment method is introduced and the comparison between analytical method and test result is presented in this paper.

Keywords: in-site test, seismic assessment, school building, push-over

INTRODUCTION

Numerous school buildings in Taiwan were damaged in the earthquakes. Because of their standard plan that with all the openings in the longitudinal direction and partition walls in the transverse direction, common failure patterns such as failure in the longitudinal direction due to lack of walls, short-column effect due to constrain by windowsills, and strong-beam-weak-column effect due to non-ductile reinforcement and slabs that connect with the beams were found (Loh & Sheu 1999). Therefore it is urgent to assess and improve the other existing school buildings’ seismic capacity for facing the possible coming earthquakes.

In order to realize true structural behavior, in-site test of existing school buildings are employed to verify assessment method and retrofit measures. The research team composed of crews of National Center for Research on Earthquake Engineering (NCREE), the department of construction engineering, National Taiwan University of Science and Technology (NTUST) and National Yunlin University of Science and Technology (NYUST), the department of civil engineering, Dahan Institute of Technology (D_HIT) and National Taiwan University (NTU) were allowed to use two old school buildings that are about to be demolished as the subject of 4 push over tests of original and retrofitted

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specimens. The test results can be used to not only verify the seismic analysis model but also the effect of different retrofit methods.

**TEST DESCRIPTION**

The 4 specimens belong to 2 typical school buildings of Hsin-Cheng junior high school, Hualien, and Kouhu elementary school, Yunlin, respectively. Both buildings have 2 floors and unilateral corridor with columns. In order to simulate typical failing behavior by earthquake, every specimen was loaded by monotonic static lateral force along its weak axis, the longitudinal direction.

**Test Plan & Setup**

Fig. 1 shows the test setup of Hsin-Cheng test. The specimen consists of 3 classrooms in each floor was cut from the other part of the building. The original brick walls in longitudinal direction were also demolished to let the specimen become the typical type. Six hydraulic actuators were placed at each cut beam end of each floor to apply lateral load along the longitudinal direction. To provide reacting support, steel bracings were placed in the spans behind actuators as reinforcement.

![Figure 1. Specimen and test setup of Hsin-Cheng test.](image)

Fig. 2 & 3 show the setting of one of the actuators and steel bracings. Lateral loads applied in the 1st floor and 2nd floor were controlled manually to remain the proportion 1:2 during the test to simulate earthquake load by fundamental mode of typical low-rise RC buildings.

![Figure 2. Actuator setting](image)  ![Figure 3. Reacting Steel Bracings](image)
Subject building of Kouhu tests consists of 8 classrooms in each floor. As shown in Fig. 4(a), along the longitudinal direction, there were original brick wing walls beside every column in 1F. Some old school buildings with such brick wing walls survived the Chi-Chi Earthquake, so they were reserved in one of the specimens as one kind of retrofit measures. The building was cut into 5 parts: 3 specimens with 2 classrooms each for three push over tests, and the rest 2 classrooms reinforced to become loading and reacting ends. The other 2 specimens besides the one with brick wing walls were a typical type specimen without any wing walls and another retrofitted specimen with new-built RC wing walls, so the efficiency of different retrofit measures can be compared.

![Picture of the subject building](image)

**Figure 4.** The subject building and test plan of Kouhu tests.

![Specimens of Kouhu tests](image)

**Figure 5.** Specimens of Kouhu tests.

The setup and loading measures in Kouhu tests are basically the same with Hsin-Cheng Test. Fig. 4(b) shows how the building was divided. Before the tests, both sides of classrooms were removed to leave the space for pushing over. Then the building was firstly cut between classroom 6 and 7. Specimen B (for Brick) with brick wing walls including classroom 7 & 8, was the first one to be pushed over from classroom 6. Specimen R (for RC wall) with original brick wing walls removed and RC wing walls built instead including classroom 1 & 2, was the second one to be cut and pushed over from classroom 3. Finally one span of classroom 6 was removed and specimen F (for pure Frame) including classroom 4 & 5 with the brick wing walls demolished was cut and pushed over from classroom 3. As shown in Fig. 5, in specimen B, brick wing walls identical with those in 1F were built in 2F to prevent prior failure of 2F. New foundations and tie beams were also built with the RC wing walls in specimen R for preventing overturning of the wing walls. Besides, 80tf of water in a tank and 120tf of soil were added respectively to the top of 1F and 2F of each specimen to simulate that if they support more floors.

**Instrumentation and Recording**

Displacement gauges were set at both free end and loaded end to measure the relative displacement of each frame in each floor of specimens. While the specimens were tested, loading stopped at about
every 0.25–0.5% drift, so that damaging condition can be recorded via pictures and sketching of cracks by the staff. When maximum lateral capacity of specimens showed, loading continued until the capacity fell down to 85% of maximum in Hsin-Cheng test and until total collapse of specimens in Kouhu tests. A steel frame and two RC struts were put respectively in the classrooms of Hsin-Cheng and Kouhu tests as safety support. They were supposed to support the specimen from completely collapse and endangering the staff.

Section and Material Property

Material strength and details of reinforcement were found by sampling after the tests. Average concrete compressive strength and steel yielding strength is respectively about 26MPa and 320MPa in Hsin-Cheng test and about 23MPa and 389MPa in Kouhu test (Lee, 2005). Average compressive strength of bricks and brick piers are respectively 26MPa and 5.8MPa in Hsin-Cheng test and 22MPa and 7.3MPa in Kouhu tests (Lin, 2006).

Fig. 6 & 7 show the structural plan and detail of vertical members of specimens. Steel ratio of columns are about 2% in both Hsin-Cheng and Kouhu tests. The hoop spacing was found to be 20cm in Hsin-Cheng test and 25cm in Kouhu tests.
TEST RESULTS

Failing Behavior

Fig. 8 shows pictures of the 4 specimens when they were severe damaged. Several common failure patterns were found. Since school buildings usually have identical plan in every floor and usually the 1st floor carries the largest lateral load, it’s expectable that most damage and deformation happened in 1F of all the specimens. However, although two of the specimens has vertical members retrofitted by wing walls, the strong-beam-weak-column effect still showed in every specimen. The beams and slabs remained almost non-damaged even when the columns and wing walls failed and the specimens nearly collapse.

![Picture of specimens](a) Hsin-Cheng specimen  
(b) Kouhu specimen B  
(c) Kouhu specimen R  
(d) Kouhu specimen F

Figure 8. Pictures of the specimens nearly collapse

But under the global similarity, different local failure modes showed in vertical members. Fig. 9(a) shows typical flexural failure happened to the ordinary columns of Hsin-Cheng specimen, while diagonal shear cracks showed in Fig. 9(b) before flexural failure happened to the short columns because the constraint by windowsills causes larger shear stress in them.

Fig. 10(c) shows that the so-called flexural-shear failure happened to the short columns of Kouhu specimen F due to the same reason. Because the columns were shorter than those of Hsin-Cheng specimen, failure of top ends of these columns became shear-control. Fig. 10(a) and 10(b) show that both brick and RC wing walls fail by shear. The shear cracks and failure extended through the columns beside wing walls as if they were jointed. It is obviously that failure mode of a vertical member is related to the ratio of its height to width. Flexural failure shows in slender members, shear failure shows in short and wide ones, and flexural-shear failure shows in those between, although the line between is still not clear.
Figure 9. Failure modes of vertical members in Hsin-Cheng test

(a) Shear failure in brick walls of specimen B
(b) Shear failure in RC walls of specimen R
(c) Flexural failure in ordinary columns and Flexural-shear failure in short columns of specimen F

Figure 10. Failure modes of vertical members in Kouhu tests

Push Over Curves

Fig. 11 shows the experimental push over curves of the 4 specimens. The Hsin-Cheng specimen shows better ductility and deforming ability because of more higher columns and less shear failure, while all the 3 Kouhu specimens show brittle curves due to the shear failure of vertical members. Maximum strength of the 2 typical specimens, Hsin-Cheng specimen and Kouhu specimen F, are 2915kN and 2119kN, respectively. The ratio of strength (10:7) happens to be proportional to the number of columns of the 2 specimens. It suggests that there might be a simple relation between the column amount and seismic capacity of typical school buildings. Maximum strength of the 2 retrofitted specimens, Kouhu specimen B and specimen R, are 2893kN and 2750kN, respectively. It means the wing walls can improve lateral capacity of typical school buildings efficiently. Furthermore, although the brick walls are usually not considered as structural
members in RC structures, the test result shows that if the size and area of brick walls are sufficient, the strength they can provide can be better than expected.

Figure 11. Experimental push over curves

COMPARISON WITH ANALYTICAL MODEL

Introduction of Analytical Model

Simplified push over analysis, an analytical model (Tu, 2004) that is developed for seismic assessment of low-rise RC buildings is used to compare with the test result. Basic assumption of this model is the strong-beam-weak-column behavior that observed in typical low-rise RC buildings in Taiwan. Base on the behavior, it is assumed that the beam and slab are rigid and seldom fail. So the structure deforms like a shear building as shown in Fig. 12, and the story shear strength can be considered as the summation of contributions of every vertical member in the story.

Figure 12. Concept of Calculating Story Shear

Figure 13. Concept of Calculating Story Load-Displacement Curve
Then since all the vertical members connected to the same rigid slab, they must have a common deflection at the same time, so the story shear can be obtained by superpose shear forces of every vertical member at a certain deflection, as shown in Fig. 13. Finally, by assuming that the lateral load in each story distributes as a reverse triangle suggested by ATC-40 (ATC, 1996) and the shear building deformation governed by fundamental mode, base shear and roof displacement can be get as shown in Fig. 14.

\[ F_1 = Q_B \left( W_i h_i / \Sigma W_i h_i \right) \]

\[ Q_2 = F_2 + F_3 \]

\[ Q_3 = F_3 \]

\[ Q_1 = F_1 + F_2 + F_3 = Q_B \]

(i) Vertical distribution of lateral loads

(ii) Calculation of roof displacement

Figure 14. Calculation of Base Shear and Roof Displacement

The load-displacement curves of individual vertical members can be obtained by analytical or empirical models. Fig. 15 shows the models used in this paper, where a tetra-linear curve is used for RC columns and RC walls and a polynomial curve (Chen, 2003) is used for brick walls.

Comparison of Analytical and Test Results

Fig. 16 shows the comparison of analytical and experimental push over curves of the 4 specimens. The “X” marks represent the analytical collapse point, which is defined by appearance of shear failure of any vertical member or the strength decreasing to be less than 80% of the maximum strength. Some modifications were made during the analysis. Since the RC wing walls have higher height to width ratio, they were modeled as columns but not walls. Then the columns beside brick wing walls were considered only fail by shear so the analysis could be correspond to real structural behavior. The comparison shows that the analytical model underestimates about 25% of the maximum strength of the 2 typical specimens. However, it also presents well prediction to strength and stiffness of the two retrofitted specimens. A little bit overestimate shows in the specimen with RC wing walls might because that the new-built foundations and tie-beams were not stiff enough to provide sufficient reacting support. Despite the errors for push over curves, the analytical method still shows correct estimation for failure modes of vertical members.
Figure 16. Comparison of Analytical and Experimental Push Over Curves

The reason of underestimate might be the neglected out-of-plane contribution by brick infilled partition walls lay in transverse direction of the specimens. The 24cm-thick brick partition walls were constructed in a traditional method that brick walls were constructed before the frame but not in-filled after the frame were built. Therefore the brick partition walls stayed in the boundary frame even until the specimens collapse and deformed simultaneously with the boundary columns as shown in Fig. 17. It suggests that the brick walls might carried part of the stress in boundary columns and helped the specimen to stand after short columns failed. However, further research is still needed for estimating the possible out-of-plane strength of the brick infilled partition walls.

Figure 17. The brick infilled partition walls jointed with boundary frames
CONCLUSIONS

Four in-site push over tests of existed typical and retrofitted school building specimens were presented in this paper. Their structural behavior and failure pattern were recorded. All the specimens were pushed by static lateral load until collapse, numerous valuable data, includes the behavior after maximum strength were provided.

The test results show that wing walls, no matter made of brick or RC, can improve the maximum strength of school buildings efficiently. However wing walls usually have brittle shear failure, so their improvement to ductility and energy dissipation is limited.

A simplified analytical model is employed to compare with the test results. Comparison shows that the analytical model presents well prediction to the retrofitted specimens while it is too conservative to the specimen with only rigid frame. Possible reason of error might be the neglected out-of-plane contribution by brick partition walls. Further research is undergoing for the out-of-plane behavior of brick walls.

Also further in-site tests of school buildings include tests by cyclic loading or other retrofit methods are being planned.

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