LESSONS LEARNED FROM WENCHUAN EARTHQUAKE: TO IMPROVE THE SEISMIC DESIGN OF SCHOOL BUILDINGS

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ABSTRACT :
School buildings collapsed or were seriously damaged in the 512 Wenchuan earthquake. Thousands of students and teachers were killed. There has been a significant social impact. Structural safety of school buildings during seismic activity was a seriously concern after the earthquake. In this paper, the structural characteristics of damaged school buildings are surveyed and seismic evaluation of these structures is discussed. A series of measures for improving the seismic performance of school buildings in terms of building function, structure types and configurations, and materials used are discussed.

KEYWORDS:
school building, seismic performance, seismic design, vulnerability to earthquakes, Wenchuan Earthquake, field survey

1. INTRODUCTION

In the afternoon of 12 May 2008, Wenchuanin Sichuan Province, China was struck by an earthquake with a magnitude 8 on the Richter scale. The effects were felt in Beijing, Shanghai and Taipei etc., as far as 1700km away. In hundreds and thousands of collapsed buildings, more than 40 school buildings completely collapsed and hundreds of buildings irreparably damaged. More than 14,000 students and teachers died; about 20% of the total amount of people died. This implies that the damage to school buildings caused more people died than that to the other kinds of building. Such a disaster is not an individual case happened in past strong earthquakes around the world. For instance, in Kashmir earthquake happened in October 2005, there were about 17,000 school children lost their lives during the devastating. School building collapse is a common phenomena in earthquakes happened in Algeria, Former Yugoslav Republic of Macedonia, Italy, Mexico, New Zealand, Portugal, Turkey, the United States and Venezuela. An international conference of school safety was held in Islamabad, Pakistan just two days after the Wenchuan earthquake. At the closing ceremony of this conference, Mr. Salvano Briceno, the Director of the Secretary of the United Nations International Strategy for Disaster Reduction (UNISDR), said, ‘Schools, hospitals and other critical infrastructures need to be systematically upgraded and retrofitted in earthquake prone areas if we want to save lives, vulnerability to earthquakes still being a main cause of deaths in disasters.’

In this paper, based on the field survey, the vulnerability of school buildings exposed from the Wenchuan earthquake is briefly summarized. The attention is drawn on engineering designs/structural solutions for safer seismic resistant construction schools. Issues related to structural shape, structure types and configurations, and materials used etc. are discussed and some suggestions for improving the seismic safety will be further discussed.

2. THE EARTHQUAKE VULNERABILITY OF SCHOOL BUILDINGS

The death of so many students and teachers and the collapse of large number of school buildings in the earthquake have attracted a social-wide attention. The data of the survey result which provides the information of collapsed and damaged school buildings is shown in Figure 1.

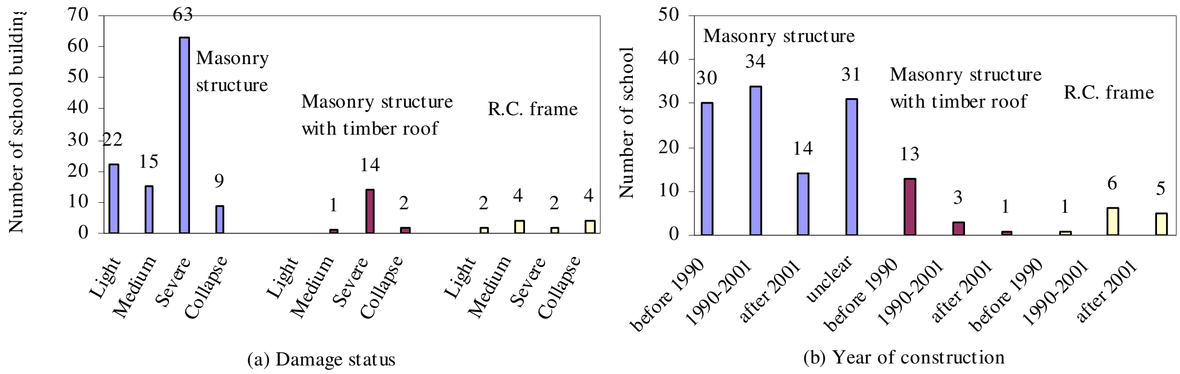

Figure 1 Survey results of damaged school buildings in Wenchuan earthquake

Except for the poor construction and substandard material, the followings might be other major reasons which induced the collapse of schools in the earthquake from the initiative investigation after the earthquake:

- More than 90% of the school buildings were built in late 80s and early 90s in the last century; the buildings were designed based on an old design code, in which the seismic element was not considered sufficiently or appropriately.

- Comparing with the general one-storey dwelling houses nearby the schools in rural area, most of the school buildings in the affected regions are multi-storeys, e.g. three- or four-storeys or more. The structures of them were supposed to withstood more severe earthquake shock than that of dwelling houses

- Most of the collapsed school buildings are teaching buildings. The spacing of structural walls or columns or the span of floor/roof slab is larger than that of general dwelling houses. The global stiffness is weak and a significant difference in the stiffness exists in the two directions.

- Precast and prestressed concrete hollow-core slabs were widely applied in floor and roof systems in these collapsed school buildings. The poor connection between floor/roof slab and supporting wall/beam can not provide uniform stiffness and transfer forces evenly to beams and walls.

- There is no enough lateral support on walls and the out-of-plan stiffness of the walls are very poor. Some cross beams sit on walls directly without a concrete padding block to spread bearing forces and the connection between cross beam and wall is poor.

- Staircase and corridor collapsed during the earthquake. The exit was cut off and people could not escape safely in time.

Considering the advantage and disadvantage characters of school buildings, we should be able to find some practical methods to improve their seismic performance by means of architectural design and structural deign etc.

3. CURRENT CONDITION AND FUTURE DEVELOPMENT ON DURAL PRIMAY AND SECONDARY SCHOOLS

Generally, there are at least one secondary school and one or a few primary schools in each town of Sichuan provenience (Southwest of China). With the popularization of nine-year compulsory education system and the improvement of the accommodation conditions, there is a trend that the kindergartens, primary and secondary schools will be combined together to form a fundamental education centre. Thus, the number of students will increase sharply. However, as the birth rate decreased year by year, the number of the students will be gradually reduced thereafter. Based on current circumstances, there are 6 to 10 classes in every primary school and secondary school and there will be 12 to 20 classes in each combined school in the future. If the laboratories are counted, there will be at least 3 to 5 of them in one school. Most of the main school buildings have three storeys with 3 to 4 classrooms on each floor. Currently, there are also some cottage or two-story buildings available in case there are more students. Therefore, the design of new schools should be considered under both current and future situation as well as the requirements of sustainable development.

4. IMPROVE THE SEISMIC DESIGN OF SCHOOL BUILDINGS

4.1. The selection of proper system and the configuration for the structure

One of the most critical decisions affecting the capability of the structure of the buildings to withstand earthquake ground shaking is the choice of a proper system or the structure type，its basic plan shape and configuration.

There are many types of Building structures and configurations and there is, of course, no universal ideal configuration for any particular type of building. However, there are certain basic or guiding principles of seismic-resistant design that can be used as guidelines in selecting an adequate building configuration including the structural layout, the structural system, the structural material and the non-structural components.

4.1.1 Structural Layout

The most popular shapes of building plan in Southwest part of China are rectangular, L-, H- and U-shaped. In particular, in order to satisfy the functional requirement or for aesthetic purpose, the layout of some school buildings is L-shaped, which will cause serious torsion effect during the earthquake. Therefore, in the selection of the building layout, an uniform stiffness arrangement is strongly recommended as specified in Chinese seismic design code GB50011-2001. A good seismic performance building layout may be rectangular, +-shaped, and H-shaped forms which can provide a relatively uniform stiffness on both directions. These three forms of layout have a better seismic performance during the earthquake than the L-shaped and U-shaped layout. Generally, because of the end effect in plan, the external walls at both ends of a building would burden the most serious seismic forces, where arranging some office rooms with small space is recommended to increase the stiffness of the buildings and improve the overall the longitudinal stiffness. A good example is the teaching building of the Centre Primary School of Mianyuan Town. In the teaching building, small size office rooms were arranged at its both ends (see Figure2). Even though the external walls of the office rooms at both ends were seriously damaged, the main structure of the teaching building did not collapse during the earthquake. There were shear cracks on the longitudinal walls under windows but no obvious cracks appeared on other walls of the classrooms. Comparing with other one-story buildings in the school, three-story government buildings and other residential buildings in the town, this teaching building showed a better seismic performance in the earthquake. Therefore, the increased stiffness at both ends of the building improves the overall building stiffness and seismic capacity.

Figure 2 The damage of the main teaching building of the Centre Primary School of Mianyuan Town

4.1.2 Height of the building

According to the Chinese Code "Primary and Secondary Schools Design Code (GBJ99-86)" clause 5.2.1 'Primary school building should not exceed 4 stores and secondary school buildings should not exceed 5 stores'. Most of the school buildings are 3~4 storey buildings. For school buildings in seismic zone, the height of the building is recommended not to exceed four stores for the easy exit purpose.

4.1.3 Structural systems

The brick masonry structure and the reinforced concrete frame structure are very popular in rural areas of China particularly the former one. Although it is recommended to use R.C. frame structure only for school buildings after the earthquake, we should also consider that brick masonry buildings strictly designed and constructed under seismic design code and construction requirements can satisfy the basic seismic requirements. From the local financial situation point of view, an efficient and a reasonable usage of local building materials is practical. By means of some further optimizations of the architectural and structural design, the safety of the brick masonry structural school buildings in the earthquake can be improved.

4.2 Improve the integrity of brick masonry building – the application of restrained brick masonry structure.

It is of utmost importance to ensure integral action between the floors/roof and their supporting walls/beams, between horizontal and longitudinal walls, as well as among the individual component of the main parts of the whole structural system.

4.2.1 Seismic performance of school buildings

The general poor practices exist in current buildings includes:

- The ring beam is not arranged at the same level as precast concrete slab or beneath it. Some of the ring beams were also worked as a window lintel.

- The ring beam is not a closed system; it does not form a 'ring'.

- In GB50011, it is required that the ring beam should be arranged on each floor. However, most of the buildings were built in 80's or 90's in last century before the requirement published and it is not hard to understand there is no such arrangement in those buildings.

The importance of tying all components of the structure is illustrated by Figure 3. The collapse of the upper part of the brick walls on the sidewalk is due to the lack of proper connection with the roof. A building should be tied at the roof and floor levels continuously from exterior to exterior walls.

The ring beam and the structural/seismic column can not only significantly increase the strength and ductility of brick masonry wall before the damage but also prevent collapsing and scattered after cracking. The significant contribution of the ring beam and structural column on improving seismic performance of school buildings can be found from many cases. For example, one major reason that a school building in Xiang'e primary school did not collapse was the structural columns arranged in brick walls. A three-storey school building in Hanwang town secondary school was seriously damaged and the external wall fell down but the building was not collapse because of the contribution of ring beams (Figure 3).

Figure 3 The collapse of the external wall of the teaching building of Hanwang Town Secondary School

4.2.2 Improve the seismic capability of the longitudinal wall

The seismic capability of vertical elements (brick wall in brick masonry structure) is the most important guarantee for a structure seismic safety. The design methodology for RC frame structure is ‘strong column - weak beam’. Although no one mentioned ‘strong wall- weak floor’ design method for brick masonry structure, the wall deign is more important than the floor design.

For the functional purposes, a significant character of school buildings is their large open space. With purposes of the effective usage of natural lighting and nature ventilation, the window openings on longitudinal walls are also very large and these large openings correspondingly reduce the size of the wall pier between windows. As the result, for brick masonry structures, it would seriously reduce the in-plan stiffness and resistance of the longitudinal walls, particularly for the wall pier supporting main cross beams.

Typical damage modes：

- Wall pier in-plan share damage (Figure 4). According to the Chinese code GB99-86, clause 5.3.2, ‘the standard width of the wall between the windows should not exceed 1.2 m’. Such a requirement is based on only considering the light and the ventilation. However, from the structural point of view, the in-plan stiffness of longitudinal wall will be significantly reduced by applying such a restriction. The width of the wall pier is too small to sustain both the longitudinal in-plan share force and the vertical pressure during earthquake; it leaded to short column shear failure. In some cases, there is no concrete bearing block beneath the main cross beam. The load from the beam could not spread to the brick masonry wall evenly and that may cause local compressive failure of the brick wall. It further induced beam and floor slab collapse.

Figure 4 The collapse of the external wall

- Spandrel wall in-plan damage is mainly shear damage (Figure 2c).

- Out-of-plane bending damage/collapse. The out-of-plan collapse of longitudinal brick masonry wall is also very common in this earthquake particularly the walls supporting cross beams. Figure 3 shows the damage of the main teaching building of Hanwang Town Secondary School. The longitudinal wall collapsed although Special-Shaped brick columns were designed to support the cross beams and increase out-of-plan stiffness of external wall. Two conclusions can be drawn from this damage: the out-of-plan stiffness of longitudinal wall is weak although the special-shaped brick columns have been designed; the RC beam did not work well with brick column because it was made of different materials and the connection was not carefully optimized (no tie bar to connect these two elements together).

Based on the seismic performance of external wall and design code requirements, it is not practical to increase the width of the wall pier between the windows to increase its shear capacity and it is not effective to use special-shaped brick column to enhance out-of-plan stiffness. Therefore, it is recommended to use restrained brick masonry wall to replace the traditional masonry wall with a ring beam and a seismic column (structural column). This means seismic column should be arranged not only at the conjunction of horizontal and longitudinal walls but also under the cross beam and other locations such as both sides of openings. Also, it is recommended to provide an additional RC structural beam beneath the window if it is too large. These structural columns and beams will effectively restrain masonry walls and work together with them. The restraint masonry structure has much better seismic performance than dose the traditional masonry structure. Comparing with RC frame structure, the restraint masonry structure can save up to 20% construction cost.

4.3 Precast concrete slab (PCS)

Currently, PCS are still widely used in most parts of the country particularly in rural area. For the structural integrity, the cast-in-situ concrete slab is definitely better than PCS. However, compared with the cast-in-situ concrete slab, the PCS has many advantages, such as low cost, simple and rapid construction, good noise isolation effect and bunch production in factory which is much easier for the quality control. The most important character is its relatively light weight which will induce smaller earthquake effect comparing with cast-in-situ concrete. There are so many examples that buildings with PCS were not collapse because of good connection details.

The most common phenomena in this earthquake relating to PCS failure is the loose of the connection between PCS and supporting beam/wall and the lost connection between two PCSs. Most of the collapses of buildings were caused by the wall or the column failure before the slab failure.

However, this does not mean that the precast concrete slab is well designed/constructed. The PCS usually sits on top of the beam or the wall without a bond. Such a joint can not transfer the load effectively and the slab can not provide the lateral restraint to the beam or the wall. Such wall is equal to the one without lateral support which works as cantilever structure. It is no doubt that the stress and the deformation will increase.

There is no prohibition of using PCS in Chinese seismic design code and it is not practical to prohibit its usage nationally. If we can combine the advantages of both the cast-in-situ concrete and the PCS to modify the existing PCS and its design and construct it strictly according to standards, the PCS could meet the requirement of the structural integrity and the structural safety for seismic design.

4.3.1 Strengthen the connection between the precast concrete slab and the beam or the wall

One of the easiest ways to strengthen the connection is to increase the support length of slab, such as using T-beam instead of rectangular beam. Many T-beam supported precast concrete slabs had no crack or loosen from beam but the supporting walls were cracked or damaged (such as the Han Wang Zhen secondary schools and Qi-Fu secondary schools). In addition, GY407-1996 clause 3.3 provides a detailed guide on the construction method of PSC support end. In this requirement, the 'beard bars' should be cast together with the ring beam to improve the strength of the joint between the precast slab and the beam/wall. Concrete bearing block should also provide beneath the slabs to spread compression forces to walls. Alternatively, Bison company, the design and manufacture company of the structural precast concrete products, provides simple and effective details on PCS end connection as shown in Figure 5.

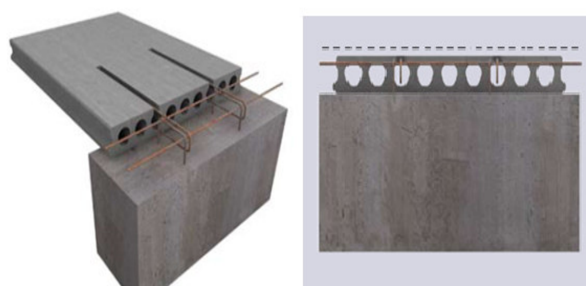

Figure 5 End slot in PCS units (Bison, August 2007)

4.3.2 Using semi-precast concrete slabs to improve the global stiffness of floor

The poor connection between adjacent concrete slabs makes PCS fail to cooperate as a uniform floor. In order to improve the connection strength, similar to precast concrete segment on segmental bridge construction, the shear key may be applied at the edges of the slab to transfer shear forces in vertical and longitudinal directions to make each PCS work together. Of cause, a potential problem is that the shear key may not sustain heavy loads because of its thickness. Alternatively, combine the advantages of both PCS and the cast-in-situ concrete. Semi-precast concrete slab is recommended shown in Figure 6. By this method, no mould is required for cast-in-situ concrete and that can provide stable connection between two slabs. Therefore, the integrity of floor will be improved. Although this method will induce the additional construction process, comparing with the cast-in-situ concrete slab, it can save a lot of labor and material resources. As a conclusion, we should look for more effective ways and be creative to improve PCS seismic performance rather than only focus on its shortcomings.

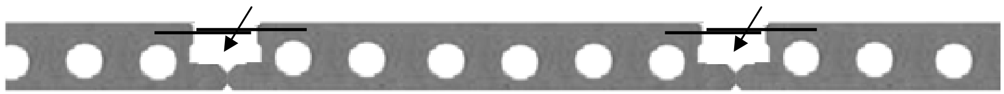

Figure 6 Recommended semi-precast concrete slab

4.4 Staircase

As the escape passageway, staircase and external corridor should further improve their seismic capabilities. In fact, the stairwell is much smaller than the classroom, some of them showed good seismic capacity than classrooms (such as the Juyuan Secondary School). However, there were still many cases of staircases collapse. Except for the heavy selfweight of staircase, the crowed people during earthquake increased the load applied on it. Another very important reason is that the staircases are generally supported on the beams at both ends as an one way slab and there is no any side restrain. Not only the railing side is free(there is no railing side), but also there is no any structural connection between the staircase and the side wall of stairwell. So many staircases fall down because of lacking enough support. Design code requires that no solid wall be permitted on the railing side. If the staircase is a cast in-situ, it is difficult to cast the staircase inside the wall. For these reasons, the staircase slab is generally restrained in longitudinal direction but free in transverse direction. It is not good for seismic behavior especially under the transverse ground movement. Another general damage phenomenon is the collapse of the infill wall of stairwell which blocked the escape passageway. It is recommended to provide another cantilever beam from the wall at the middle of staircase to provide later restrain to it and an additional structural column in the stairwell to connect the beam and confine the wall.

4.5 Cantilever external corridor.

External corridor is not only popular in Southwest China but also in Northwest and South China. It can effectively use natural ventilation and lighting. However, immediately after the earthquake, it was recommended that it should be prohibited to use cantilever-style external corridor for school buildings and it is proposed to add additional columns to support it. From the mechanical point of view, comparing with the cantilever external corridor, the one with column support has better lateral stability during earthquake. However, we should note that the tension bars in cantilever slab were designed on the upper part of the section to sustain hogging moment, and there is generally no bar at the bottom. If simply provided column to strengthen the structure, the cantilever slab will become a simply support slab or a continue slab, and there will be sagging moment at the middle of slab which will induce bottom slab crack since there is no tension bar.

We also find that many school buildings adopted real brick masonry parapet on external parapet in order to achieve code requirements. The thickness of parapet is the same 240 mm or even up to 310 mm as that of the general external wall and the height reached 1100mm. This is no doubt that a very large concentrate dead load applied at the free end of cantilever slab. Therefore, it induced greater earthquake effect under earthquake. At the same time, the escape people during the earthquake increased the live load, causing the collapse of the external corridor. However, we also found some external corridors with light parapet were not seriously damaged (xx secondary school). It is concluded that reduce the selfweight of parapet is an effectively way to reduce seismic hazard. Comparing with the additional columns to support external corridor, reducing the selfweight of parapet of the corridor is a more cost-effective approach to reduce the seismic effect.

5. IMPROVE THE ESCAPE PASSAGEWAY ESCAPING CAPACITY

Generally there are hundreds of or even more than one thousand students and teachers in a teaching building. Once an earthquake happened, it is easy to cause confusion, resulting in heavy casualties because of psychological tension, evacuation traffic, and streaming intensive. There were also some successful escape examples during the earthquake because of good organizations. For example, all of the buildings including teaching buildings and accommodation buildings were collapsed in Maluxiang Central Elementary School, but all 1,400 teachers and students were not even injured because of the timely and orderly ease.

Current design code GBJ 99-86 requires that the width of external corridor be no less than 1.8 m. The hogging moment is rather large if a cantilever slab is adopted. However, if the external corridor could be modified from one side to both sides of the building and reduce the width from 1.8m to 1.2 m (wide enough for two people pass). It will not increase the total amount of steel bars and concrete so much but make the structure more symmetrical. Once earthquake happened, people can escape from both sides of the buildings and the live load of escaping people could almost be distributed on the two corridors equally which will not cause too much eccentric moment. Moreover，since there are two corridors, even if one of them was interrupted, people can also escape from the other side. It will increase the chance of survival.

Reduce the number of turning of staircase can also improve the people’s escaping speed. If two external corridors were adopted, scissors type staircases are recommended.

6. CONCLUSIONS

In addition to increase seismic design level and improve the quality control of construction and materials, this paper focused on how to improve the seismic performance of the primary and secondary schools in rural area and how to improve the hard ware of students’ escape lute from the overall layout point of view, details of building connections and the escape passageway. In addition, the site selection of building is also important to avoid the disasters caused by the earthquake. In conclusion, according to China's national condition and the characteristics of primary and secondary school buildings in rural area, we can find practical ways to increase the earthquake resistance capacity of buildings to provide a safe and comfortable learning environment for children.

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