SIMPLE SURVEY ON SEISMIC PERFORMANCE OF ELEMENTARY AND SECONDARY SCHOOL BUILDINGS IN TAIWAN

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ABSTRACT

In the past years, Taiwan was attacked by three major earthquakes. They are Ruei-Li, Chi-Chi and Chia-Yi earthquakes. According to the reconnaissance reports, school building was the type of structure that was most seriously damaged. Lack of integral planning, weakness along corridors, effect of short columns, imbedded pipelines and lack of lateral reinforcement are some of the answers to the collapse of school buildings even though the design seismic force for school buildings is 25% higher than the ordinary buildings. Serious casualties and losses may be resulted from the collapse of school buildings under strong earthquakes. Furthermore, school buildings are usually assigned as emergency shelter soon after earthquakes. Therefore, in this paper, an economic and efficient method for simple survey on seismic evaluation of typical school buildings is proposed based on the common structural types, seismic weaknesses, failure modes and experimental data. It is used to grade the seismic performance of school buildings.

Keywords: school buildings; seismic performance; simple survey

INTRODUCTION

The buildings of elementary and secondary schools in Taiwan encountered Ruei-Li earthquake (on July 17, 1998), Chi-Chi earthquake (on September 21, 1999) and Chia-Yi earthquake (on October 22, 1999) in the past years. In the disaster area of Ruei-Li earthquake, many school buildings were badly damaged, the cover concrete of columns spalled, the core concrete cracked, the longitudinal reinforcement buckled, and their seismic resistance was greatly reduced. During Ruei-Li earthquake, many school buildings were on the brink of collapsing, but during Chi-Chi earthquake, many school buildings were collapsed. According to the report published by Ministry of Education, 786 schools (1958 classrooms) were damaged in Chi-Chi earthquake. Even in Taipei City, which is about 150 km far away from the epicenter, there were 67 schools damaged. If Ruei-Li earthquake were not happened during summer vacation and the Chi-Chi earthquake were not happened in late night, the total casualties would have been much more.

Lack of seismic performance is a common problem for the existing buildings in elementary and secondary schools in Taiwan. Serious casualties and losses may be resulted from the collapse of school buildings under strong earthquake. Furthermore, school buildings are usually assigned as emergency shelter soon after earthquake. Therefore, the strategy for seismic evaluation and retrofit of school buildings is suggested in this paper. An economic and efficient method for simple survey on seismic evaluation of typical school buildings is proposed based on the common structural types, seismic weaknesses, failure modes and experimental data. (NCREE 2000)

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SEISMIC DEFICIENCY

Lack of Integral Planning

In Taiwan, most of school buildings in elementary and secondary schools lack an integral planning in advance. On the contrary, most school buildings were constructed and expanded in a patchy way and this caused insufficient seismic resistance as an aftermath. Owing to the population growth in the school district and the rising of multifarious new branches of teaching, the number of existing classrooms is no longer enough. Hence the school authorities strive for expenditure from year to year. If the budget allows, new classrooms will be built in the horizontal or vertical directions of the existing classrooms at different times in order to solve the problems of under-classroom. No matter the new classrooms horizontally connected with or built on the top of the old classrooms, the original structural system will be seriously spoiled and the seismic resistance is thus greatly reduced.

The new classrooms expanded in the horizontal direction are usually connected together with old classrooms so as to obtain the continuity of activity space for pupils and teachers. Being constructed at different times, the old classrooms and the new classrooms are different in height, weight or stiffness so that they may possess different fundamental vibration periods. Therefore, when an earthquake strikes, the old and new classrooms do not vibrate in-phase, but vibrate out-of-phase. Under this circumstance, if the adjacent seismic gaps are not wide enough, those classrooms will pound or impact each other. The amplitude of the pounding and impact force is so large that may cause the complete failure and collapse of columns in adjacent buildings.

The way to expand school buildings in vertical direction is to overbuild the new classrooms on the top of the old ones. The seismic force that is undertaken by the classrooms is the inertia force of the floors of the buildings. The seismic force of each floor is in direct proportion to the weight and the acceleration respectively. Adding new classrooms atop old ones shall make the weight of school buildings become heavier. The higher the school buildings, the larger the acceleration will be. This makes the vertical distribution of the seismic force of the school buildings look like an inverted triangle. Therefore, overbuilding atop will seriously endanger the seismic resistance of the original school buildings.

Building classrooms without integral design and arbitrarily overbuilding in accordance with expenditures and needs will make unexpected change in the mechanical behaviors of the structural system and result in brittle failure and collapse. In fact, when in need of extra classrooms, it is wiser to build the new classrooms in a new site or dismantle the old classrooms and rebuild the new ones. At the beginning stage, school buildings ought to have integral plan and design and make every effort to pursue the rule of simple structural systems. Thus, school buildings will tend to be the mode of ductile failure under the attack of strong earthquake and follow the highest principle that the school buildings will not collapse even under strong earthquakes.

Collapse along Corridor

Most school buildings in Taiwan were designed based upon the standard blueprint announced in 1966. According to the standard blueprint, classrooms are allocated side by side in a row. Outside the classrooms, there is a corridor that is cantilevered without columns. Normal to the corridor, classrooms are partitioned by using brick wall that is continuous in the gravity direction. However, along the corridor, there are doors and windows for entrance and natural light. No walls are continuous in the gravity direction. Cantilevered corridor may be good for view and for student activity on the first floor. But, there are only 2 columns, single span normal to the corridor so that there is a lack of redundancy. Without sufficient redundancy, stress cannot be redistributed effectively and ductility of the structures is not satisfied. Therefore, there is a strong tendency that school buildings collapse along the corridor and there is no case recorded that school buildings collapse normal to the corridor.
In 1967, the compulsory education in Taiwan was extended to 9 years. The classroom standard design blueprint announced in 1966 was to match the stringent requirement in the construction of classrooms. At that time, there was no concept of seismic resistant design. If double corridors, supported by columns at the free end, are adopted for classrooms, there are four columns, three spans normal to the corridors. Strength and ductility can be highly enhanced with the increase in the degree of redundancy. Therefore, catastrophic collapse can be avoided. Besides, if the amount of wall can be increased and kept continuous in the gravity direction, the possibility of collapse may be decreased.

Effect of short columns

In order to utilize the natural light and the natural ventilation, it is fully occupied by windows and doors along the direction of the corridors. At the upper portion of the columns, the columns are constrained by the window frame made of aluminum. At the lower portion of the columns, they are constrained by windowsill made of brick walls. Since the window frame is much softer in stiffness than the windowsill, the effective length of the column is shortened. The shorter the column, the larger is the shear force. Therefore, the columns tend to be failed in the shear mode rather than the flexural mode and X-shaped cracks were observed. If a seismic gap is cut between the column and windowsill, the effective length of the column will not be shortened and flexural failure can be guaranteed. The seismic gap may be shimmed with water-tight material.

Imbedded Pipelines

All lifelines including water supply, drainage and electricity are imbedded inside the columns. Consequently, the effective area of the columns is greatly reduced. The dimension of the columns is not large, in the range of 30 to 50 cm. After drainage pipe that is usually more than 5 cm in diameter is imbedded, the area occupied by the pipe cannot be neglected. The strength of the column is reduced due to the imbedded pipes. Therefore, there should be independent space for the lifelines or the pipes may be exposed outside the column.

Lack of Transverse Reinforcement

The space of lateral reinforcement in the columns of existing buildings exceeds 20 cm. Since lateral reinforcement is very useful in providing confinement for core concrete, prolonging buckling of longitudinal reinforcement and prohibiting shear failure. In lack of lateral reinforcement, there is a tendency that the columns of school buildings are in the mode of brittle failure and brittle failure is the most undesirable one. The ductility of the columns can be enhanced effectively by seismic retrofit strategies such as steel jacketing and carbon fiber jacketing.

STRATEGY

In order to tackle the problem of seismic deficiency for school buildings effectively, there are three stages of screening: simple survey, preliminary evaluation and detailed evaluation. The first stage of screening is simple survey which is conducted by school administration. In simple survey, a chart is designed to collect school data and building data. School data include: address of the school, and number and names of school buildings. Building data include: number of stories, year of design or construction, condition of the building, dimension of the floor plan, number of columns and the cross-sectional dimension of each typical columns in each frame, number of walls and the cross-sectional dimensional dimension of each typical walls in each frame. After the survey chart is filled, relevant data are submitted through internet. Before simple survey is launched, workshop is held to train school administration how to conduct the survey.

The second stage of screening is preliminary evaluation which is conducted by professionals. In preliminary evaluation, a chart is designed for the professionals to carry out the evaluation. In addition to the names of the school and the building, the data include: design ground acceleration,
number of stories, floor area above the first story, cross-sectional areas of columns, reinforced-concrete walls, four-side bounded brick walls and three-sided brick walls, and conditions of the building.

The third stage of screening is detailed evaluation which is conducted by professional engineers. Three methods are adopted in Taiwan. They are strength and ductility method, push-over method using ETABS and simplified push-over method. Seismic retrofit is conducted by professional engineers. Four methods of seismic retrofit for school buildings were verified experimentally. They are reinforced-concrete jacketing of columns, steel jacketing of columns, wing walls added to columns and composite columns added to partition brick walls. It is suggested that detailed evaluation and retrofit design of a school building are conducted by the same professional engineer so that the responsibility is clarified. Moreover, it is also suggested that detail evaluation and retrofit design must be review by a panel so that the quality can be guaranteed. In the stage of retrofit construction, inspection is necessary.

**SIMPLE SURVEY**

The seismic performance of school buildings is considered as the ratio of capacity to demand. The seismic capacity of the school buildings is computed by superimposing the shear strength of vertical members, walls and columns. The seismic demand is determined from the weight and location of school buildings. The seismic performance is further modified according to the conditions of the buildings. Simple survey is conducted by school administration such as director of general affairs, section chief of general services, or teacher with background of civil engineering or maintenance. The information of the survey was submitted to the National Center for Research of Earthquake Engineering through internet.

**Fundamental Assumptions**

Perpendicular to the corridors, classrooms are partitioned by walls, which are continuous in the gravity direction. However, along the corridors, there are windows and doors for entrance and natural light, and walls are seldom continuous in the gravity direction. Therefore, all damaged and collapsed school buildings failed along the corridor so that the seismic performance along the corridor is dominant. Since seismic force is accumulated from the top to the bottom of the school buildings, shear force at the first story is the largest. In addition, the school buildings are quite regular from story to story. Hence, the seismic performance of the first story is the most critical one and only the first story is evaluated. Because of the presence of the floors and windowsills, beams become stronger and the columns are relatively weaker. The school buildings are damaged and collapsed due to the failure of vertical members. Therefore, only columns and walls are taken into account for the seismic performance of the school buildings.

From the statistics of 30 school buildings in Tainan area in southern Taiwan, the mean of the dead load per unit floor area is 913 kg/m² and the standard deviation is 102 kg/m². Since the dead load at the roof floor is relatively low, the average dead load per unit area above the first story is assumed to be 900 kg/m² for simplicity. Moreover, from statistical data, the compressive strength of concrete and the yielding strength of steel reinforcement are, respectively, 160 kg/cm² and 2800 kg/cm² for the existing school buildings. (Hwang et al. 1996)

**Shear Strength of Vertical Members**

In simple survey, all walls are considered as three-side bounded brick walls, which are bounded below and above by beams and bounded one side by columns. When the brick wall is three-side bounded, the width varies from 20 to 180 cm and the height 260 to 280 cm. The average modulus of rupture for bricks is 18.5 kg/cm². Based on the empirical formula, the shear strength of three-sided bounded
brick walls, \( \tau_w \) is about 1.5 kg/cm\(^2\). The weighting factor for the shear strength of the wall is assigned as 0.5.

Along the corridors of the school buildings, the depth of columns varies from 25 to 35 cm and the spacing of transverse reinforcement varies from 20 to 30 cm. In this paper, the depth and width of the columns are assumed to be 30 cm and 40 cm, respectively. The transverse reinforcement is #3 rebars with spacing 25 cm. The shear strength of reinforced-concrete column is contributed by concrete and lateral reinforcement. The shear strength of reinforced concrete column \( \tau_c \) is computed to be about 15 kg/cm\(^2\). The weighting factor for the shear strength of the reinforced-concrete columns is assigned as 5.0

**Fundamental Seismic Performance**

In typical school buildings, there are at most four frames along the corridors. The school administration is asked to submit the number of walls and the dimension of the typical wall in each frame. From the submitted data, the cross sectional area of the walls on the first floor can be computed as:

\[
A_w = \sum_{i=1}^{4} N_{wi} B_{wi} T_{wi}
\]  

where \( N_{wi} \) is the number of walls; \( B_{wi} \) is the breath of the typical wall; and \( D_{wi} \) is the width of the typical wall in the \( i \)-th frame along the corridor. From the submitted data of the columns, the cross sectional area of the columns on the first floor can be computed as:

\[
A_c = \sum_{i=1}^{4} N_{ci} B_{ci} D_{ci}
\]  

where \( N_{ci} \) is the number of columns; \( B_{ci} \) is the breath of the typical column; and \( D_{wi} \) is the depth of the typical wall in the \( i \)-th frame along the corridor.

From the submitted data of the school building, the total floor area above the first story can be computed as:

\[
A_f = N_S L_S B_S
\]

where \( N_S \) is the number of stories; \( L_S \) is the length of the floor plan; and \( B_S \) is the width of the floor plan in the school building. The peak ground acceleration factor for seismic zones \( Z \) can be determined from the location of the building.

According to the capacity and demand for the seismic performance of school building can be computed as:

\[
E = \frac{0.5A_w + 5A_c}{10ZA_f}
\]

**Modification Factors**
Corrosion of reinforcement: If the reinforcement corrodes and concrete spalls in the columns or beams, the modification factor is \( q_1 = 0.95 \).

Crack and leakage: If the beams or columns crack and leakage of water occurs, the modification factor is \( q_2 = 0.95 \).

Differential settlement and inclination: If substantial deformation of the school building is induced by differential settlement, the modification factor is \( q_3 = 0.95 \).

Redundancy: If the corridor of the school building is cantilever and no column at the exterior side, the modification factor is \( q_4 = 1.00 \). If columns exist at the exterior side of the corridor, the modification factor is \( q_4 = 1.05 \).

Seismic gap: If seismic gap from adjacent buildings is less than 7 cm multiplied by the number of stories, the modification factor is \( q_5 = 0.95 \).

Short columns: Since effect of short columns is very common for typical school buildings, the modification factor for all school buildings is assigned as \( q_6 = 0.90 \).

The total modification factor \( Q \) is defined as:

\[
Q = q_1 q_2 q_3 q_4 q_5 q_6
\]

Seismic Performance Index

The seismic performance index \( I_s \) is defined as:

\[
I_s = EQ = q_1 q_2 q_3 q_4 q_5 q_6 \left( \frac{0.5 A_w + 5 A_c}{10 Z A_f} \right)
\]

Since school buildings are public buildings, the seismic demand is amplified by an importance factor \( I = 1.25 \). Therefore, if the seismic performance index of a school building is \( I_s < 80 \), the school building may collapse when encountered by an earthquake of 475-year return period. If the performance index is \( 80 \leq I_s \leq 100 \), the school building will be damaged when encountered by an earthquake of 475-year return period. If the performance index is \( I_s > 100 \), the school building will not be seriously damaged when encountered by an earthquake of 475-year return period.

Statistics Analysis

In Taiwan, there are 3,497 elementary and junior high schools. Among them, 3,419 schools (about 98%) completed the simple survey and submitted school data and building data to the National Center for Research on Earthquake Engineering. The data base possesses data for 12,650 school buildings and the data for 11,060 school buildings (about 87%) are valid.

According to the statistics analysis, the means of the length and depth for the floor plans of school buildings are 52.9m and 11.5m, respectively. The mean of the number of stories for school buildings is 2.8. The mean of the floor area of the first floor for school buildings is 616m². The mean of the spans along the corridor for school buildings is 4.0m. The mean of the ratio of column area to floor area for school buildings is 57.0cm²/m². The seismic design codes of buildings were revised in 1982.
and 1997. 39% of school buildings were built before 1982, 41% between 1982 and 1997, 15% after 1997 and 5% unknown. 80% of the school buildings scored with fundamental seismic performance less than 80, 18% between 80 and 100, 38% above 100. After consideration of the conditions for the school buildings through modification factor, 55% of the school buildings scored with seismic performance indices less than 80, 16% between 80 and 100, 29% above 100.

**CONCLUSIONS**

Among governmental buildings, elementary and secondary schools are the most highly distributed and spacious ones so that schools should play the role of emergency centers for natural disasters. Therefore, the structural safety of school buildings is so important and the seismic design force for school buildings was 25% higher than ordinary buildings. However, according to the reconnaissance report for Ruei-Li, Chi-Chi and Chai-Yi earthquakes, the damage of school buildings is the most serious one among all types of buildings. In the stages of planning, design and construction for school buildings, the civil engineering professionals should be fully involved and responsible for the structural safety. Once school buildings still stand erect during natural disasters, the lives of teachers and students can be safely protected and the schools can be served as the regional emergency centers.

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**REFERENCES**


Figure 1. Distribution of fundamental seismic performance

Figure 3. Distribution of seismic performance indices