SEIMIC RETROFIT PROGRAM FOR TAIWAN SCHOOL BUILDINGS AFTER 1999 CHI-CHI EARTHQUAKE

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ABSTRACT :

Based on the observations made after several major earthquakes occurred in Taiwan, school building has been found most vulnerable to severe earthquake damage among all building types. Although the seismic design force for school buildings has been 25% higher than the ordinary buildings, its performance to resist strong earthquake has been proved insufficient. Serious casualties and losses may be resulted from the collapse of school buildings under strong earthquake. Furthermore, school buildings are usually required to serve as emergency shelter soon after a major earthquake. The urgent need of seismic performance evaluation and enhancement works is evident. Lack of integral planning, lack of seismic resistance along corridors, effects of short columns, embedded pipelines and lack of lateral reinforcement has been found the key factors responsible for the collapse of school buildings. A three-stage strategy for seismic evaluation and retrofit of existing low-rise reinforced concrete school buildings has been proposed. It is based on the common structural types, seismic resistance, possible failure modes and available experimental data. Seismic-deficient school buildings are being retrofitted based on the performance index introduced in this paper.

KEYWORDS: School building, seismic evaluation, seismic retrofit

1. Introduction

A number of buildings in the primary and middle schools in Taiwan have suffered damages of various degrees during the Ruei-Li earthquake (July 17, 1998), Chi-Chi earthquake (September 21, 1999) and Chia-Yi earthquake (October 22, 1999) in the past decade. In the disaster area of Ruei-Li earthquake, many school buildings were severely damaged. The damage modes included the spalling of columns' cover concrete, cracking of core concrete, buckling of longitudinal reinforcement. The seismic resistance of these buildings should have been greatly reduced. These school buildings were on the brink of collapsing. Nevertheless many school buildings were collapsed during Chi-Chi earthquake. According to the report published by Ministry of Education, a total of 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 school buildings damaged. The total loss of life resulted from the Chi-Chi earthquake almost reached 2500. If Ruei-Li earthquake were not occurred during the summer break or the Chi-Chi earthquake were not took place in late night, the total casualties could have been much more.

Based on the damage statistics, a lack of seismic resistance appears to be a common problem in the existing primary and secondary school buildings in Taiwan. Significant casualties and property losses could be resulted from the collapse of these school buildings under strong earthquakes. Furthermore, school buildings might have to be assigned as emergency shelters immediately after a severe earthquake. For the purposes of conducting seismic performance evaluation and retrofit of these noted structures, a rather simple template has been developed in NCREE for preliminary seismic evaluation of typical school buildings. The proposed template is to evaluate the structural types, apparent seismic weaknesses, potential failure modes and the available experimental data. The complete strategy for seismic evaluation and retrofit of school buildings is introduced later in this paper. Some key factors, among many items, responsible for the poor seismic performance of school buildings are discussed hereafter.

2. Seismic Deficiency

2.1. Lack of Integral Planning

In Taiwan, a large number of old buildings in elementary and secondary schools appear lacking of an integral planning in advance. In stead, many old school buildings have been constructed and later on expanded in a patchy way. It was due to the population growth in the school district and the rising of multifarious branches of teaching, the number of existing classrooms was no longer enough. Hence the school authorities had strived for funding from year to year. When the budget allowed, new classrooms were added to the existing ones in the horizontal or vertical directions at different times in order to solve the problems of under-supply of classrooms. If the new classrooms were added horizontally, the structural system of the old school building could be spoiled. If the new classrooms were built on top of the old ones, seismic and gravity load demands on the old classrooms would be significantly increased. The new classrooms expanded in the horizontal direction are rather closely adjacent, if it is not connected, to the old ones so as to maintain the continuity of activity space for pupils and teachers. Having constructed at different times, the old and the new classrooms could be different in height, weight or stiffness. Thus, the two structures may possess different fundamental vibration periods. When an earthquake occurred, the old and new classrooms would vibrate not in-phase. Under this circumstance, if the adjacent seismic gaps were not wide enough, those classrooms could have pounded each other (Figure 1). The pounding could cause the complete failure and collapse of columns in the adjacent building.

The seismic force of each floor is in direct proportion to its floor weight and acceleration. The seismic shear force undertaken by the old classrooms would be the sum of inertia force of each floors of the entire school building. Building new classroom over the old ones would increase the story shear force and the overturning moment, result in the collapse of the entire structure during a severe earthquake (Figure 2).

As noted above, building classrooms without integral design are likely to make undesirable changes in the mechanical properties of the structural system. It could result in ponding or collapse of the building. Thus, without proper strengthening of the existing structure, adding new classroom to old ones is very hazardous. Accordingly, it is recommended that new classrooms be properly designed before it is built on its own foundation based on an integral plan.

Figure 1 Ponding damage due to insufficient seismic gap

Figure 2 Earthquake damage due to vertical building expansion

Figure 3 Short column damage

2.2. Collapse in the Longitudinal Direction

Most school buildings in Taiwan were designed based upon the standard floor plan developed in 1966. According to the standard floor plan, classrooms have been configured side by side in a row. Typically there is a corridor outside of the classrooms. The floor or roof above the corridor is often cantilevered without columns. Transverse to the corridor, classrooms are typically partitioned by using brick walls which are continuous in the gravity direction. However, along the direction of the corridor, doors and windows have been constructed for entrance and natural light. Only small amount of walls could be continuous. The noted cantilevered corridor may be convenient for students' activities on the first floor. Thus, it often leaves only 2 reinforced concrete frames along the corridor direction. Unfortunately, these two frames typically consist of short columns. These short columns are resulted from the concrete or brick windowsill constructed between the columns. The adverse effects of the short column on the seismic performance of RC frame structures will be highlighted later in this article. Based on the worldwide observations on school building damages, there is a strong evidence that school buildings tend to collapse along the corridor. There seems no case recorded that school buildings collapse transverse to the corridor direction.

In 1967, the compulsory education in Taiwan was extended from 6 to 9 years. The standard classroom floor plan noted above 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.

2.3. Effect of short columns

In order to gain lighting and ventilation, the two exterior side of the classrooms have been built with windows and doors. At the upper portion of the columns, it is often constrained by concrete or brick lintel above the window. At the lower portion of the columns, it is typically constrained by the noted infill below the windowsill. Thus, the effective length of the column has been significantly shortened. During a earthquake, the shear demand on the shortened column is therefore greatly increased. Unfortunately, these columns have been constructed with poor concrete and without sufficient shear reinforcement. Consequently, the columns have been found frequently failed in the shear mode, with X-shape cracks commonly observed (Figure 3). As a matter of fact, if a seismic gap had been cut between the column and the infill, the effective length of the column would not be shortened. In this manner, a more desirable flexural failure mode could be achieved. The seismic gap could be filled with compressible but watertight material.

2.4. Imbedded Pipelines

Utility lines, including water supply, drainage and electricity have been embedded inside the columns. Consequently, the effective area of the columns is substantially reduced. The cross-sectional area of the columns is typically about 25 to 30 cm square. After a 5-cm diameter minimum drainage pipe is embedded, the column cross-sectional area is greatly reduced. The strength of the column has been evidently reduced and was never carefully taken into account. It is obvious that a complete separate space for running the utility lines is needed.

2.5. Lack of Lateral Reinforcement

The spacing of column transverse steel reinforcement in many old buildings has been found exceeding 20 cm. Transverse steel reinforcement is essential in confining core concrete, prolonging buckling of longitudinal reinforcement and prohibiting shear failure. The lack of lateral reinforcement should help to explain why the school building columns have often been failed in a brittle shear failure mode. The ductility of this kind of columns can be effectively enhanced by seismic retrofit using steel or carbon fiber jacketing.

3. Strategy

In order to effectively tackle the seismic deficiency problems for school buildings in Taiwan, three stages have been proposed for screening, including simple survey, preliminary evaluation and detailed evaluation. The simple survey is conducted by school administrators. In a simple survey, a chart has been developed for collecting school data and building data. School data include street address of the school, the number and the identification of school buildings. Building data include the number of stories, the year of design or construction, condition of the building, floor dimension, number of columns and the cross-sectional dimension of the typical column in each frame, number of walls and the cross-sectional dimension of the typical wall in each frame. After the survey chart is filled, data entries are submitted through internet. Before the extensive simple survey was launched across all school districts, workshop has been held to train school administrators responsible for conducting the survey.

The second stage of screening, preliminary evaluation is conducted by professionals. In a preliminary evaluation, a chart has been developed for the professionals to carry out the evaluation. In addition to the identification 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 and three-side bounded brick walls, and conditions of the building.

The third stage of screening is the detailed evaluation conducted by professional engineers. Three methods have been adopted in Taiwan. It includes (1) strength and ductility method, (2) push-over method using commercial computer program such as ETABS, and (3) simplified push-over method. Seismic retrofit design is conducted by professional engineers. Three seismic retrofit techniques for school buildings have been verified experimentally in NCREE. It includes reinforced concrete jacketing of columns, steel jacketing of columns and wing walls addition adjacent to columns. The proposed strategy of seismic evaluation and retrofit of these school buildings has been accepted and implemented by the Taiwan Ministry of Education. It has been recommended by NCREE research team that detailed evaluation and retrofit design of a school building be conducted by the same professional engineer so that the responsibility can be clearly defined. Moreover, it is also suggested that the detailed evaluation and retrofit design must be reviewed by a panel so that the engineering work quality can be guaranteed. In the final stage of retrofit construction, inspection has been prescribed.

3.1. Simple Survey

The seismic performance of school buildings can be evaluated from its seismic capacity to demand ratio. The seismic capacity of the school buildings is computed by superimposing the shear strength of various vertical members such as 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 has been conducted by school administrators such as director of general affairs, section chief of general services, or teacher with knowledge on civil engineering or building maintenance. The information of the survey has been submitted to the computer server in NCREE through internet.

3.2. Fundamental Assumptions

Transverse to the corridors, classrooms are typically partitioned by walls, which are continuous in the gravity direction. However, along the corridors, there are windows and doors for entrance and natural light. These walls are seldom continuous in the gravity direction. Damages and collapses of school buildings have been found occurred only along the corridor. Thus, seismic performance is evaluated along the corridor direction only. Since seismic shear force at the first story is larger than other story, and the school buildings are quite regular from story to story, thus, seismic resistance of the first story is most critical. Therefore seismic vulnerability of the first story needs to be evaluated. Due to the presence of the concrete slab and the lintel above the window, the beams became stronger than the columns. The school buildings were often damaged or collapsed due to the failure of vertical members. Therefore, only columns and walls are taken into account for the seismic resistance of the school buildings.

From the statistics of 30 school buildings surveyed in Tainan area in southern Taiwan, the mean of the dead load per unit area is $913\,\mathrm{kg/m^2}$ and the standard deviation is $102\,\mathrm{kg/m^2}$. Since the dead load at the roof floor is lower than typical classroom floor, the average dead load per unit area above the first story is assumed to be $900\,\mathrm{kg/m^2}$ for simplicity. Moreover, from statistical data, the compressive strength of concrete and the yielding strength of steel reinforcement are, respectively, $160\,\mathrm{kg/cm^2}$ and $2800\,\mathrm{kg/cm^2}$ for the existing school buildings.

3.2.1. Shear Strength of Vertical Members

In the simple survey, all walls are considered as three-side bounded brick walls. These walls are bounded between the top and bottom beams, and bounded one side by a column. 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 $18.5\,\mathrm{kg/cm^2}$. Based on the empirical formula, the shear strength of three-sided bounded brick walls, τ_W is about $1.5\,\mathrm{kg}/\mathrm{cm}^2$. 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 35cm 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 a spacing of 25 cm. The shear strength of a reinforced-concrete column is contributed by concrete and lateral reinforcement. The averaged shear strength of a typical reinforced concrete column τ_C has been found about $15\,\mathrm{kg}/\mathrm{cm}^2$. The weighting factor for the shear strength of the reinforced-concrete columns is assigned as 5.0.

3.3. Fundamental Seismic Performance

In a typical school building, there are at most four frames along the corridor. The school administrator is asked to record the number of walls and the dimension of the typical wall in each frame. From the data, the cross sectional area of the walls on the first floor can be computed as:

$$A_W = \sum_{i=1}^{4} N_{Wi} B_{Wi} D_{Wi} \tag{1}$$

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. From the data of the columns, the cross sectional area of the columns on the first floor can be computed as:

$$A_C = \sum_{i=1}^{4} N_{Ci} B_{Ci} D_{Ci} \tag{2}$$

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.

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

$$A_f = N_S L_S B_S \tag{3}$$

where N_S is the number of stories; L_S is the length of the floor; and B_S is the width of the floor in the school building. The designed peak ground acceleration factor, Z associated with a specific seismic zone can be determined from the location of the building.

Based on the capacity versus demand ratio, the seismic performance of school building can be conveniently evaluated as:

$$E = \frac{0.5A_W + 5A_C}{10ZA_f} \tag{4}$$

Additional modification factors noted below may apply to further improve the results of the evaluation.

3.4. Modification Factors

Corrosion of reinforcement: If the reinforcement corrosion or concrete spalling is found in the columns or beams, the modification factor is $q_1 = 0.95$.

Crack and leakage: If the beam or column crack or leakage of water is found, the modification factor is $q_2 = 0.95$.

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

Redundancy: If the corridor is cantilever and no column is found at the exterior edge of the corridor, the modification factor is $q_4 = 1.00$. If columns exist at the exterior edge of the corridor, the modification factor is $q_4 = 1.05$.

Seismic gap: If the seismic gap from an adjacent building is less than 7 cm multiplied by the number of stories, the modification factor for irregularity is $q_5 = 0.95$.

Short columns: Since the presence of short columns is very common in typical school buildings, the short-column modification factor is required for all school buildings as $q_6 = 0.90$.

The effects of all these modification factors, Q is defined as:

$$Q = q_1 q_2 q_3 q_4 q_5 q_6 \tag{5}$$

3.5. Seismic Performance Index

The seismic performance index I_s is defined as:

$$I_s = EQ = q_1 q_2 q_3 q_4 q_5 q_6 (\frac{0.5A_W + 5A_C}{10ZA_f}) \tag{6}$$

Since school buildings are public, the seismic demand is increased using an importance factor $I = 1.25$. Therefore, if the seismic performance index of a school building is $I_s < 80$, the school building is likely to collapse when subjected to an earthquake of 475 years return period. If the performance index is $80 \le I_s \le 100$, the school building is likely to be damaged when subjected to the same design earthquake. If the performance index is $I_s > 100$, the school building should not be seriously damaged when subjected to the noted level of earthquake. The school buildings are not required to go through the preliminary evaluation if its performance index I_s is greater than 100. Higher priority for preliminary evaluation has been given to school buildings having I_s index smaller than 80.

4. Preliminary Evaluation

The fundamental assumptions for the preliminary evaluation are the same as those for simple survey. Since preliminary evaluation is conducted by professionals from academic or engineering community, the results should be more meaningful. The results of the preliminary evaluation have been submitted to the computer server in NCREE through internet.

4.1. Shear Strength of Vertical Members

In the school buildings, when the brick wall is four-side bounded, the width typically varies from 500 to 700cm and the height 260 to 280cm. Based on the empirical formula, the shear strength of four-sided bounded brick walls, τ_{BW4}, is about $3.0\,\mathrm{kg/cm^2}$. The weighting factor is assigned as 1.0. As mentioned previously, the shear strengths of three-sided brick walls τ_{BW3} and reinforced-concrete columns are about $1.5\,\mathrm{kg/cm^2}$ and $15\,\mathrm{kg/cm^2}$, respectively. The corresponding weighting factors τ_C are 0.5 and 5.0, respectively.

From the experiments conducted at NCREE on reinforced concrete frames with and without in-filled reinforced concrete walls, it is found that the shear strength of reinforced concrete walls is about $24.0\,\mathrm{kg/cm^2}$ by the regression analysis. The weighting factor is assigned as 8.0.

4.2. Fundamental Seismic Performance

Based on the demand versus capacity ratio for seismic performance evaluation of school buildings, the fundamental seismic performance of the school buildings E is computed as:

$$E = \frac{0.5A_{BW3} + A_{BW4} + 5A_C + 8A_{RCW}}{10ZA_f} \tag{7}$$

where A_{BW3}, A_{BW4}, A_C and A_{RCW} are the cross-sectional area in cm^2 of three-side bounded brick walls, four-side bounded brick walls, reinforced-concrete columns and reinforced-concrete walls in the first floor along the corridor, respectively. Additional modification factors noted below may apply to further improve the results of the evaluation.

4.3. Modification Factors

Regularity: If the dimensions of convexity in both directions are larger than 15% of the dimensions of school building in the corresponding direction, the modification factor for regularity is $q_1 = 0.95$. If the school building is regular both in elevation and plan, the modification factor for regularity is $q_1 = 1.05$. For any other conditions, the modification factor for regularity is $q_1 = 1.00$.

Soft and weak story: If more than 2/3 of the walls of any story are not extended continuously to the lower story, the modification factor for soft and weak story is $q_2 = 0.80$. If 1/3 to 2/3 of the walls of any story are not extended continuously to the lower story, the modification factor for soft and weak story is $q_2 = 0.90$. If less than 1/3 of the walls of any story are not extended continuously to the lower story, the modification factor for soft and weak story is $q_2 = 1.00$.

Crack, corrosion and leakage: If the degree of crack, corrosion and leakage is serious, the modification factor is $q_3 = 0.90$. If there is no crack, corrosion and leakage, the modification factor is $q_3 = 1.00$. For any other conditions, the modification factor for crack, corrosion and leakage is $q_3 = 0.95$.

Differential settlement: If substantial deformation of the school building is induced by differential settlement, the modification factor is $q_4 = 0.90$. Otherwise, the modification is $q_4 = 1.00$.

Redundancy: If the floor above the first story corridor is cantilever and no column at the exterior edge of the corridor, the modification for redundancy is $q_5 = 1.00$. If there is only one corridor at one side of the school building and columns exist at the exterior edge of the corridor, or there is a corridor at the middle of the school building, the modification for redundancy is $q_5 = 1.10$. If there are two corridors at both sides of the school building and columns exist at the exterior edge of the corridors, the modification factor for redundancy is $q_5 = 1.20$.

Short columns: If more than 50% of the columns are confined by infills under the windowsills, the modification factor for short columns is $q_6 = 0.90$. Otherwise the modification factor is $q_6 = 1.00$. The effects of all these modification factors, Q can be computed as stated in Equation (5).

4.4. Seismic Performance Index

The seismic performance index I_s is defined as:

$$I_s = EQ = q_1 q_2 q_3 q_4 q_5 q_6 \left(\frac{0.5A_{BW3} + A_{BW4} + 5A_C + 8A_{RCW}}{10ZA_f}\right) \qquad (8)$$

If the seismic performance index of a school building is $I_s < 80$, the school building is likely to collapse when it is subjected to an earthquake of 475 years return period. If the performance index is $80 \le I_s \le 100$, the school building is likely to be damaged when subjected to the same design earthquake. If the performance index is $I_s > 100$, the school building should not be seriously damaged when subjected to the noted level of earthquake. The school buildings are not required to go further through the detailed evaluation if its performance index I_s is greater than 100. Higher priority for detailed evaluation has been given to school buildings having I_s index smaller than 80. It has been recommended by the NCREE research team that the seismic retrofit design work, when it is found necessary, be conducted by the same engineer performs the detailed evaluation.

5. Seismic Retrofit Research

Before the full implementation of the cost-effective seismic retrofit schemes for improving seismic performance of existing school buildings, an extensive research program was launched in 2003. Since then, a great number of large scale specimens have been tested in NCREE (Tu et al. 2006). In addition, several in-situ collapse tests of school buildings were conducted in recent years (Hwang et al. 2007). More detailed information can be found in the link of the web site: www.ncree.org.

6. Conclusions

Among many type of governmental buildings, primary and middle schools have been found the most spacious and uniformly distributed according to the distribution of populations. Therefore, school buildings are likely to play a very important role for emergency response purposes immediately after a natural disaster. Hence, the structural safety of school buildings is evident. This explains why the seismic design force for school building structures has always been 25% higher than ordinary buildings. However, according to the observation made from the Ruei-Li, Chi-Chi and Chai-Yi earthquakes, damages of school buildings has been the most serious one among all building types. The specific features of the school building structures noted above should help to explain why it had suffered the most during a severe earthquake. Based on the NCREE proposed strategy for the seismic evaluation and retrofit of school buildings noted in this paper, the Taiwan Ministry of Education has implemented an extensive program for improving the seismic performance of elementary and secondary schools. A significant number of school buildings are being retrofitted for a higher seismic resistance. A different strategy has been formulated by NCREE for seismic evaluation and retrofit of buildings for police and fire departments.

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