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AN IMPORTANT FACTOR NEGLECTED IN THE SEISMIC REINFORCEMENT PERFORMANCE DESIGN OF SCHOOL BUILDINGS: SHEAR BANDING

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Abstract

The performance design goal of seismic reinforcement of school building structures is to ensure that they do not collapse in a severe earthquake, thus safeguarding teachers and students. However, in the design process and design content, only areas with ground vibration energy, which accounts for less than 10% of earthquake energy, are fortified, and areas with shear bands, where more than 90% of earthquake energy is involved, are not fortified. Therefore, the substantive significance of the results obtained from pushover analysis and a test method based on the results of the earthquake-resistant reinforcement plan for school building structures in Taiwan are explored. There are four main findings. (1) The proposed conditions for maintaining stability of school buildings during an earthquake are that the rigid stratum remains rigid, the horizontal stratum surface remains horizontal, and the continuous stratum surface remains continuous; and if the stable conditions cannot be maintained, the school buildings will collapse. (2) In traditional pushover tests and analysis, the conditions of the school building and the structural analysis model are consistent with the proposed conditions for maintaining the stability of the school building during an earthquake. Therefore, in the traditional pushover test and analysis, the results do not truly reflect what actually happens during an earthquake leading to the collapse of school buildings because the shear banding effect is ignored. (3) After the first edition of the seismic design code for buildings in Taiwan was promulgated in 1974, the ground vibration fortification level was continuously increased after successive earthquakes without certification. As a result, the cross-sectional area and the number of ribs of structural elements on the upper part of the buildings have unnecessarily increased. (4) Although the Ministry of Education of Taiwan has spent a considerable amount of money on earthquake-resistant reinforcement of school buildings, the reinforcement is limited to improving the fortification level against ground vibration, so that the buildings could still collapse due to shear banding in a future earthquake. Based on the above results, it is suggested that future revisions of the code be based on the actual need for separate protection to ensure the stability of school buildings in shear banding zones and non-shear banding zones. This is the best way to avoid excessive ground vibration fortification in non-shear banding zones and to avoid under-fortification against shear banding in shear banding zones.

Keywords: seismic reinforcement, performance design, school building, shear banding, ground vibration, pushover.

Introduction

During the 1999 Jiji earthquake, 656 school buildings in the earthquake-stricken area of Taiwan were destroyed. The Executive Yuan issued a plan to assess the vibration resistance and reinforcement of buildings on November 27, 2008. The Ministry of Education entrusted the National Center for Research on Earthquake Engineering (NCREE) to promote the earthquake-resistant reinforcement plan for school buildings, with total funding of NT$40 billion (Ye, *et al*., 2000).

The seismic reinforcement of school building structures adopts performance design. First, school buildings are categorized into general school buildings and emergency evacuation school buildings. Then, the structural damage level is selected as moderate or slight damage, and the ground vibration and surface acceleration corresponding to a 475-year return period earthquake are used for analysis and design (Ye, *et al*., 2000).

Traditional Pushover Analysis Method

Based on the requirements for seismic evaluation, the ability of a school building to resist lateral force under nonlinear displacement is initially evaluated by pushover analysis.

In the pushover analysis, the NCREE recommends using structural analysis programs such as ETABS, MIDAS, or PISA3D to obtain the relationship curve between the base shear force V and the roof lateral displacement Δ, which is the structural capacity curve shown in Figure 1 (Zhong, et al., 2009).

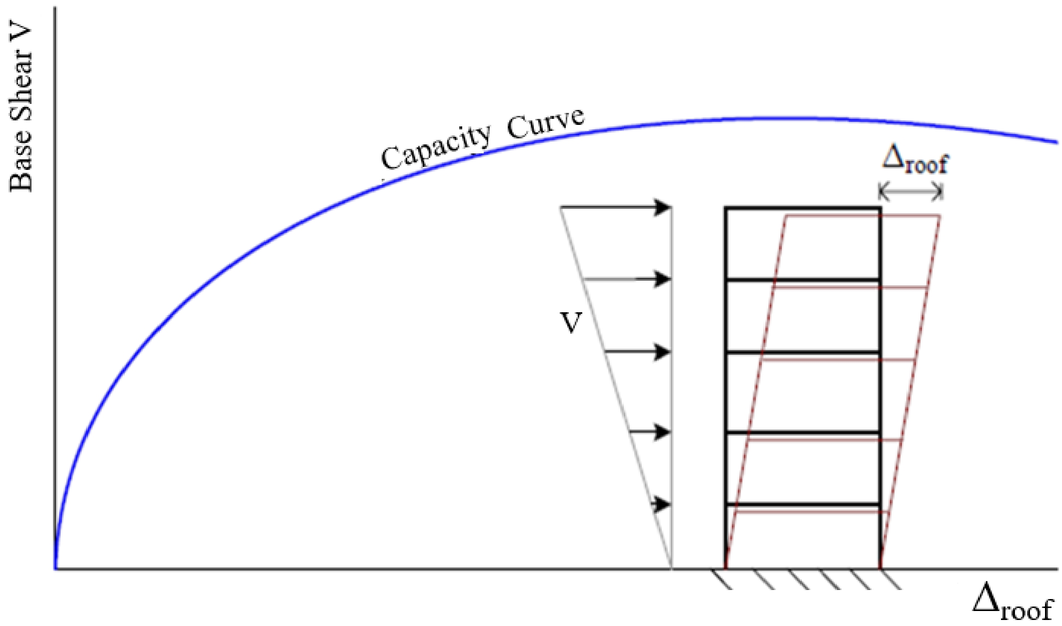


Figure 1. Schematic diagram of the structure capacity curve (Zhong, et al., 2009).

When the column is subjected to lateral external forces, the NCREE uses the hyperbolic force-deformation mechanism shown in Figure 2 to obtain the nonlinear hinge parameters of the structural elements (Zhong, et al., 2009). Then, under the action of a ground vibration force, an equivalent diagonal bracing is used to simulate the brick wall and an equivalent wide column is used to simulate the force behavior of the reinforced concrete (RC) wall. Then, before performing the pushover analysis, an auxiliary program can be used to analyze the parameters and the positions of the nonlinear hinge.

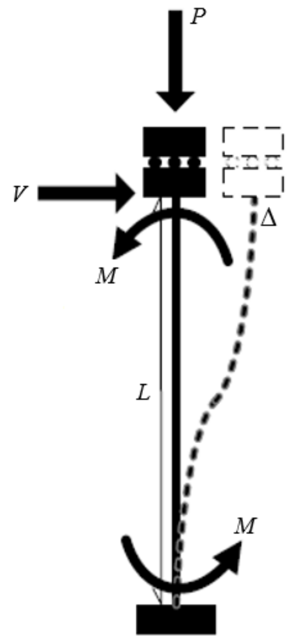


Figure 2. Hyperbolic deformation mechanism of a column under lateral force (Zhong, et al., 2009).

When the structure capacity curve of the school building is obtained by pushover analysis, it is generally based on the USA Applied Technology Council (ATC-40) capacity spectrum method, supplemented by the damping ratio correction coefficient specified in the seismic design code and the period and damping of any function point on the capacity spectrum curve. Then, the capacity spectrum curve of the equivalent single-degree-of-freedom system can be obtained by conversion. By analyzing the structure seismic performance curve and the surface acceleration corresponding to the performance goal, supplemented by the performance level, it can be judged whether the school building structure needs structural seismic reinforcement (Huang, *et al.*, 2009).

Traditional pushover test

The NCREE carried out the traditional pushover test for this project. The school building selected for the pushover test was Kouhu Elementary

School in Yunlin County, Taiwan (Figure 3), which was undamaged by the 921 Jiji earthquake (Ye, *et al*., 2008).

Figure 3. The undamaged school building after the 921 Jiji earthquake (Taiwan Yunlin Kouhu Elementary School) (Zhong, *et al*., 2013).

Traditional Pushover Analysis and Test Results

The NCREE conducted traditional pushover analysis on a structural model of the Yunlin Kouhu Elementary School building (Figure 3) and physical tests on the actual entire structure. A diagram of the deformed structural model obtained by the pushover analysis is shown in Figure 4; the deformed structure after the pushover test is shown in Figure 5; and the structure capacity curve obtained by the pushover analysis and test is shown in Figure 6.

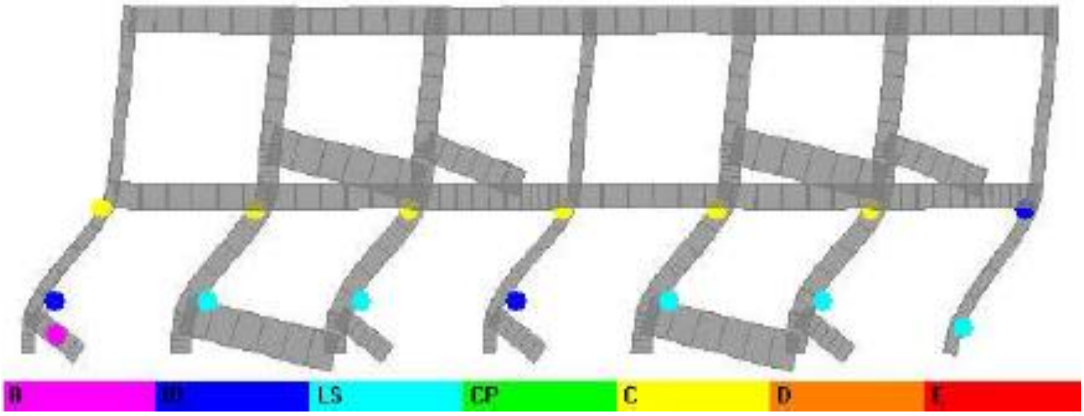


Figure 4. Diagram of the deformed structural model obtained from traditional push-over analysis (model of Kouhu Elementary School, Yunlin, Taiwan) (Huang, 2009).

Figure 5. The deformed school building after the traditional pushover test (Kouhu Elementary School, Yunlin, Taiwan) (Zhong, *et al*., 2013).

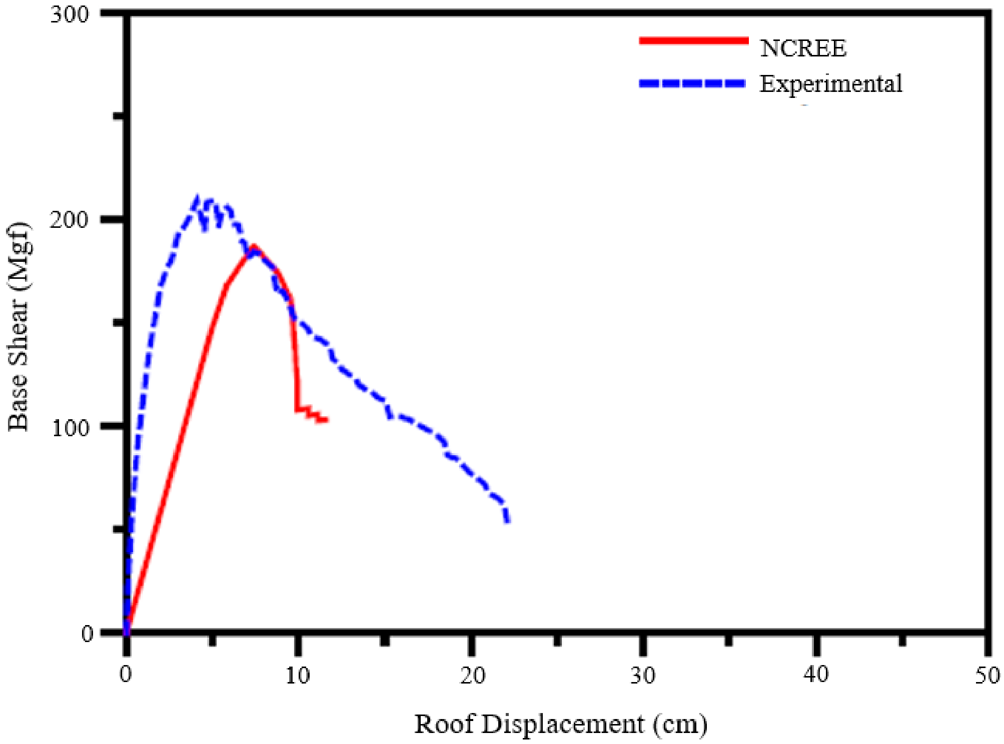


Figure 6. Comparison chart of the structure capacity curve obtained from analysis and experiment (Kouhu Elementary School, Yunlin, Taiwan) (Zhong, *et al*., 2013).

Traditional Seismic Reinforcement Methods for School Buildings

For the purpose of increasing the shear strength, flexural strength, axial strength, and toughness of a column, the seismic reinforcement methods recommended by the NCREE include RC expansion column reinforcement (Figure 7), RC wing wall reinforcement (Figure 8), RC shear wall reinforcement (Figure 9), and composite column reinforcement (Figure 10).

Figure 7. RC expansion column reinforcement method (Zhong, et al., 2009).

Figure 8. RC wing wall reinforcement method (Zhong, et al., 2009).

Figure 9. RC shear wall reinforcement method (Zhong, et al., 2009).

Note: In the picture, the engineer was conducting a welding bead quality inspection test

Figure 10. Composite column reinforcement method (Hsu, 2001).

The Proposed Conditions of Earthquake Resistance and Non-Earthquake Resistance of School Buildings

Taiwan extended its compulsory education from six years to nine years in 1968. During this period, a large number of school buildings were constructed with wavy roofs as shown in Figure 11. The design of these school buildings met the relevant regulations of the 1974 edition of the Code for Seismic Design of Buildings. In subsequent earthquakes, most of these school buildings remained stable (Figures 3 and 11), and only a few collapsed (Figure 12). Therefore, an in-depth investigation of the conditions of earthquake resistance and non-earthquake resistance of school buildings is paramount.

Figure 11. Sanmin Junior High School, Hualien, which remained stable during the 0206 Hualien earthquake in 2018 (Standard School Building of Hualien Sanmin Junior High School, 2016).

Note: The red line is the connection of the first floor.

Figure 12. Guangfu Junior High School, Taichung, which collapsed during the 921 Jiji Earthquake in 1999 (Hsu, 2018).

If the base of all the columns or the base of all of the foundations are coplanar when a school building is constructed and the stratum is rigid, the stratum surface is considered to be horizontal and continuous. In such cases, all of the basal ends of the columns are regarded as fixed without any relative displacement under loading conditions.

In an earthquake, the conditions for the school building to remain stable (and therefore be considered to be earthquake resistant) include the rigid stratum remaining rigid, the horizontal stratum surface remaining horizontal, and the continuous stratum surface remaining continuous. This is the main reason that the building of the Sanmin Junior High School, Hualien (shown in Figure 11) and the school building shown schematically in the center of Figure 13 remains stable during earthquakes. However, when shear banding occurring during earthquakes induces local tilted uplift and strain softening, the conditions for the school building to become unstable and therefore be considered non-earthquake resistant include the rigid stratum being unable to remain rigid, the horizontal stratum surface being unable to remain horizontal, and the continuous stratum surface being unable to remain continuous. This was the main cause of collapse of the Guangfu Senior High School building, Taichung (Figure 12) and shown schematically in the left and right buildings shown in Figure 13 during an earthquake.

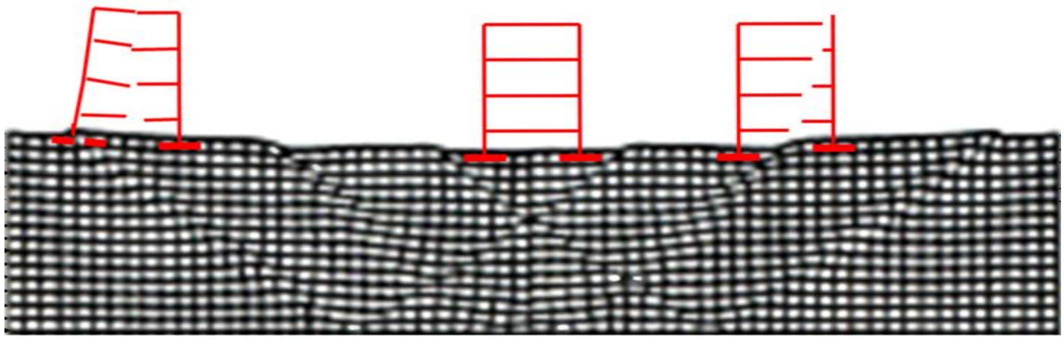


Figure 13. Schematic diagram of earthquake-resistant and non-earthquake-resistant school buildings (Hsu, 2018).

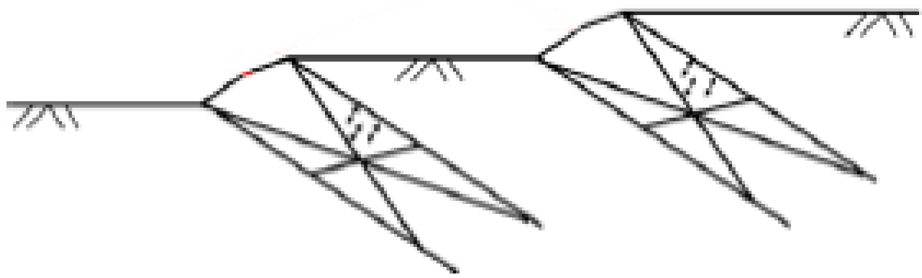
Effectiveness of Traditional Earthquake-Resistant Reinforcement Methods
for School Buildings

Taiwan has currently completed traditional seismic reinforcement of structures for a large number of school buildings, where performance design has also been implemented. This design process includes conceptual design, physical design, and implementation, and the design content includes performance goals, earthquake levels, performance levels, and importance classification.

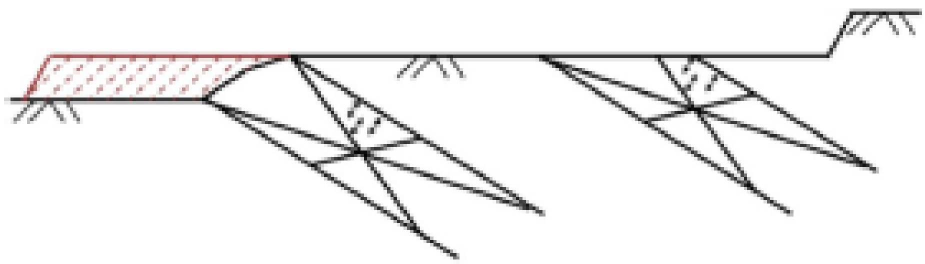
The overall engineering design process, design concept, and key content only fortify these buildings against the secondary effects of tectonic earthquakes (i.e., the ground vibration effect), which account for less than 10% of the energy of earthquakes, but not their major effect (i.e., the shear banding effect), which accounts for more than 90% of the energy associated with earthquakes (Coffey, 2019). Therefore, the performance design of the traditional school building structure for seismic reinforcement clearly sets performance goals that can pass design review, meet construction quality assurance, and use monitoring, maintenance, and management under the action of ground vibration; however, a school building may still collapse under the shear banding effect of an earthquake, so the design performance goals cannot always be achieved.

Comparison and Discussion of Results

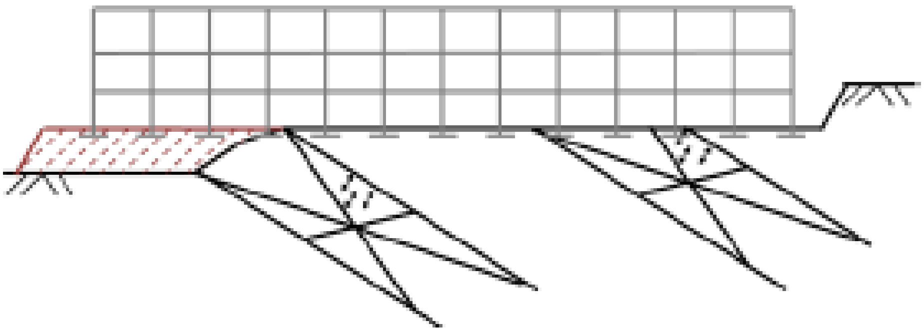
1) For the building of Guangfu Senior High School, Taichung, which collapsed in the 921 Jiji Earthquake (as shown in Figure 12), two step shear banding tilted slopes existed on the original site (shown in detail in Figure 14(a)) (Hsu, 2018). Before the school building was constructed, the site was backfilled during site preparation to achieve a horizontal ground surface (Figure 14(b)). Then, the whole school building was built on this horizontal surface (Figure 14(c)). However, during the 921 Jiji earthquake, due to the local shear banding tilting effect and strain softening effect (Figure 14(d)), the rigid stratum could not maintain its rigidity, the horizontal stratum surface could not remain horizontal, and the continuous stratum surface could not remain continuous. As a result, the school building could not maintain its designed earthquake resistance and collapsed.



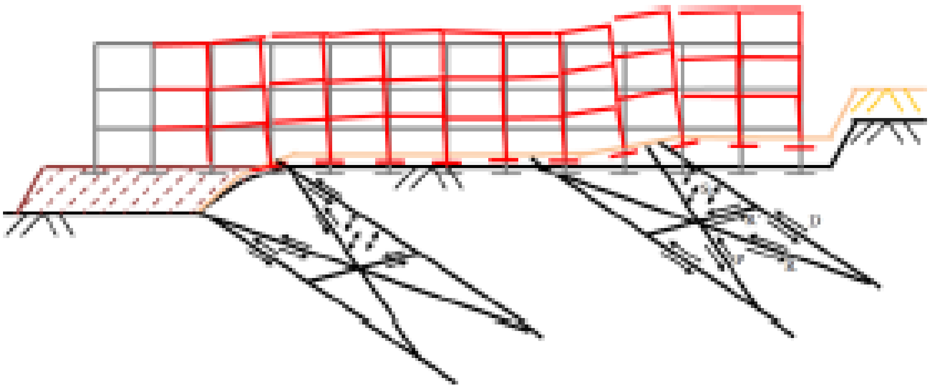
(a) Original state.



(b) The site after the excavation and filling.



(c) Completion of school building.



(d) Shear banding-induce school building collapse.

Figure 14. The construction and destruction Guangfu Junior High School, Taichung, Taiwan (Hsu, 2018).

2) For the buildings of Kouhu Elementary School in Yunlin, Taiwan (shown in Figure 3) and Sanmin Senior High School in Hualien, Taiwan (shown in Figure 11), since no shear band was present on the original site, the bottom ends of the horizontal plane of the original coplanar columns remained horizontal, the continuous ground remained continuous, and the rigid stratum remained rigid during the 921 Jiji and 0206 Hualien earthquakes Therefore, the school buildings remained stable and displayed earthquake resistance.

3) For the traditional pushover analysis and test of Kouhu Elementary School, Figures 4 and 5 respectively

show the bottom ends of all the columns that were originally coplanar in the structural analysis model and the actual school building. After the analysis and the test, it was evident that the horizontal plane had remained horizontal, the continuous plane had remained continuous, and the rigid geology had remained rigid. The school building structure is reinforced according to the traditional pushover analysis and test results in order to prevent the school building from collapsing in the shear banding zone. Therefore, such seismic reinforcement performance design is actually inefficient.

4) For the columns and girders of Taiwan's school buildings, the cross-section design has not been previously optimized. Therefore, the joints between columns and girders are prone to cracks (see Figure 15) or breakage (Figure 16) under excessive stress due to insufficient cross-sectional areas during an earthquake.

Figure 15. Cracks at the joint of a column and girder during an earthquake.

Figure 16. Break in the joint of a column and girder after an earthquake.

5) After the 921 Jiji earthquake, the NCREE, without evidence, attributed the cause of local collapse of school buildings to insufficient vibration resistance of the superstructural elements such as columns, beams, plates, and walls although collapse could have been induced by shear banding. Therefore, the seismic design codes that have been continuously revised have increased the vibration fortification levels of superstructure elements, with the result that design of cross-sectional areas and the amount of reinforcement at joints between columns and girders have been excessive (Figure 17).

Figure 17. Excessive cross-sectional area and excessive steel reinforcement resulting from revised seismic design code after the 921 Jiji earthquake.

6) Based on the needs of performance design, the revision of the seismic design code for school buildings should be based on the conditions of earthquake resistance and non-earthquake resistance of the school buildings discussed in this paper. Therefore, school buildings located in shear band areas should be fortified against both shear banding and ground vibration, while for school buildings located in non-shear band areas, only ground vibration fortification should be carried out.

7) Figures 3 and 11 show different school buildings located in non-shear band areas. These school buildings were constructed before 1968 and have remained stable during earthquakes. Therefore, it can be inferred that the ground vibration fortification level of the first edition of the Seismic Design Code of Buildings promulgated by the Con-

struction Agency of the Ministry of the Interior in 1974 is sufficient to ensure the stability of school buildings in non-shear band areas.

8) Evidence has shown that a major cause of collapse of school buildings is shear banding, but the revision of the design code has only increased the ground vibration fortification level. Thus, such revision of the seismic design code does not meet the actual needs. More appropriate revision should enhance fortification against shear banding as per the first edition of the code for seismic design of buildings.

Conclusions and Suggestions

In order to avoid the collapse of school buildings during earthquakes and the death of a large number of teachers and students, the Ministry of Education of Taiwan first issued a plan for the implementation of structural seismic capacity assessment and reinforcement after the 921 Jiji earthquake. The ministry then entrusted a large amount of money to the National Earthquake Engineering Research Center to promote the plan for the seismic reinforcement of school buildings. In this paper, through an in-depth review of traditional pushover test and analysis results based on the seismic reinforcement design of school buildings during the implementation of the plan, the following four conclusions were made:

1) For school buildings that comply with the existing seismic design specifications, the conditions that cannot maintain the stability of the school building during earthquakes are not the lack of vibration resistance of upper structural elements (such as columns, beams, plates, and walls), but that the rigid stratum cannot remain rigid, the horizontal stratum surface cannot remain horizontal, and the continuous stratum surface cannot remain continuous.

2) In the traditional pushover test and analysis, the mechanism of a school building's pushover is different from the collapse mechanism of the building during an earthquake because the conditions of the school building and structural analysis model are the same as the proposed conditions for maintaining the stability of the school building during earthquakes. Therefore, after earthquake-resistant reinforcement of the structure based on traditional pushover test and analysis results is carried out, the school building may still collapse due to shear banding during an earthquake.

3) Earthquakes frequently occur in Taiwan. The Ministry of the Interior and Construction issued the first edition of the Code for Seismic Design of Buildings in 1974. Despite the likelihood that shear banding during earthquakes caused buildings to collapse, the ministry continued to increase the vibration fortification level of all superstructure elements, without evidence, so that the cross-sectional area and the amount of reinforcement of superstructural elements were unnecessarily increased.

4) Although Taiwan's Ministry of Education has spent a lot of money on seismic reinforcement of school buildings, seismic reinforcement of the structures has been limited to the improvement of the ground vibration fortification level. Therefore, school buildings located in shear band areas may still collapse due to shear banding in future earthquakes.

Based on the above conclusions, the authors suggest that when future code revisions are made, fortification of structures should be based on the actual needs of the earthquake-resistance conditions of non-shear band areas and shear band areas separately. For school buildings located in non-shear band areas, only ground vibration protection is required for structural seismic performance design. The ground vibration fortification level addressed in the first edition of the building seismic design code promulgated by the Construction Agency of the Ministry of the Interior in 1974 is sufficient. For school buildings located in shear band areas, structures should be fortified against both shear banding and ground vibration in structural seismic performance design. The ground vibration fortification level of non-shear band areas is applicable in such cases. In this way it is possible to avoid waste caused by excessive ground vibration fortification in non-shear band areas and to avoid lack of safety in shear band areas due to failure to fortify against shear banding.

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