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EVALUATING THE SEISMIC REINFORCEMENT OF EXISTING SCHOOL BUILDINGS USING SEISMIC CONDITIONS

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Abstract

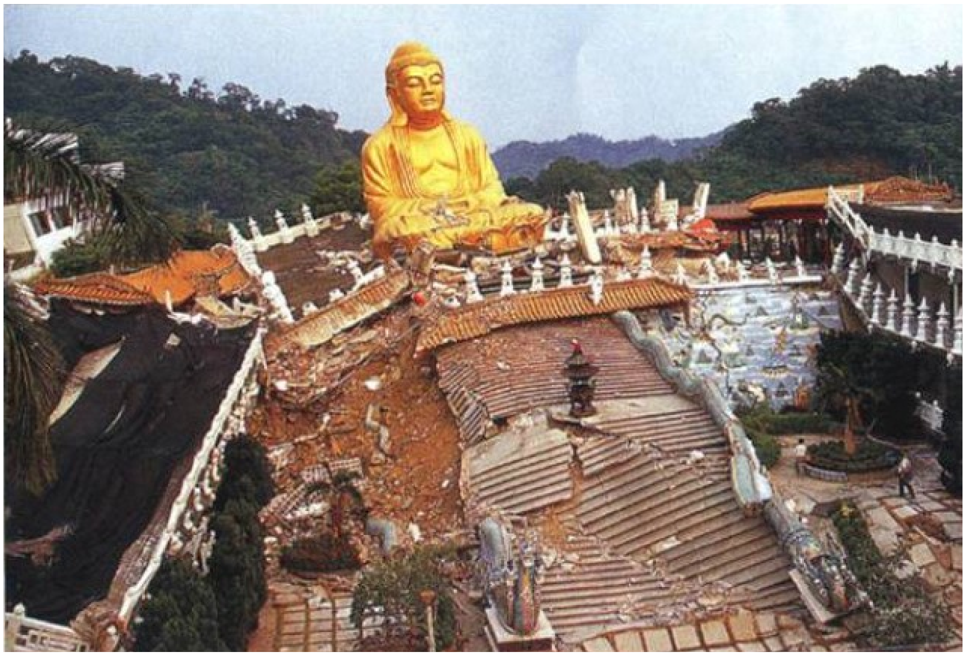
This paper examines the functionality and effectiveness of structural seismic reinforcement carried out in Taiwanese school buildings and public markets by examining the seismic behavior of these buildings when affected by shear banding. The following four conclusions are drawn: (1) School buildings and public markets located in non-shear banding areas are considered to be earthquake-resistant buildings because they meet the conditions that the buildings are aseismic. (2) All buildings and structural analytical models on which lateral pushover tests were conducted and which were subsequently used for the evaluation of the seismic reinforcement of school buildings and public markets, were deemed to be earthquake-resistant buildings because the bottom ends of their building columns maintained the horizontal and continuous conditions set in the original design. (3) Earthquake-resistant buildings do not need structural earthquake-resistant reinforcement, and effective structural earthquake-resistant reinforcement changes a building that is not earthquake-resistant to one that is earthquake-resistant. (4) The structural seismic reinforcement of school buildings and public markets in Taiwan only improves resistance of the pillars of these already earthquake-resistant buildings against ground vibration, so the necessity and effectiveness of this procedure are limited. Based on the above conclusions, it is suggested that the effect of shear banding should be recognized and buildings subject to shear banding should be identified and targeted for earthquake reinforcement.

Keywords: buildings, seismic reinforcement, pushover, shear banding, ground vibration.

Introduction

After the 1974 release of the first edition of the code for the seismic design of buildings in Taiwan, the recommended level of ground vibration fortification has continued to increase due to continuing damage sustained by buildings during subsequent tectonic earthquakes (Construction and Planning Agency, Ministry of the Interior, 2015). In fact, the seismic fortification level has doubled that of the original edition due to the high frequency of damage (Su, 2016), an example of which is shown in Figure 1. It was initially expected that the latest code for seismic design of buildings would ensure that a building would not be damaged during a tectonic earthquake of magnitude 7.3. However, even newly constructed buildings were left severely tilted after the 0206 Meinong earthquake that struck Taiwan in 2016, which had a magnitude of only 6.4 (see Figure 2 for details).

(a) Tilt and fall failure (Taiwan Yunlin Fugui Mingmen Building).



(b) Collapse failure (Wanfo Temple, Taichung, Taiwan).

Figure 1. Building failure phenomena due to the 1999 Jiji earthquake (magnitude 7.3) (Hsu *et al*., 2020).

(a) Severe tilt failure (New Wanglin Building, Tainan, Taiwan) (Hsu and Ho, 2016).

(b) Overturning failure (Weiguan Building, Tainan, Taiwan).

Figure 2. Building failure phenomena due to the 2016 Meinong earthquake (magnitude 6.4) (Hsu, 2018).

As more papers are published on shear banding, it is becoming increasingly clear that it is the major cause of building failure during tectonic earthquakes (Hsu *et al.,* 2016, 2018, 2020; Lin *et al*., 2022), and the underlying mechanisms of failure induced by shear banding are being clarified (Figure 3).

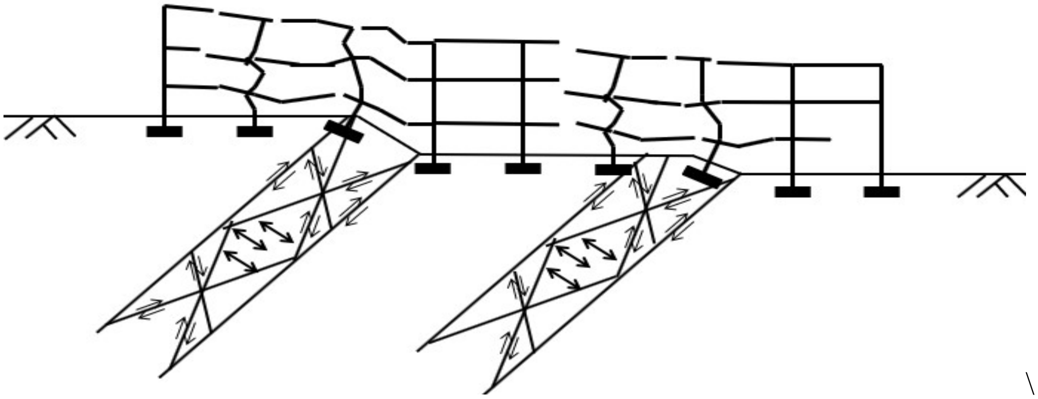


Figure 3. The building failure mechanism induced by shear banding.

After the 921 Jiji earthquake in 1999, Taiwan completed the structural seismic reinforcement of a large number of school buildings, and after the 0206 Meinong earthquake in 2016, a part of the public market also underwent structural seismic reinforcement. The cost of this seismic reinforcement exceeded NT$40 billion (Zhong, et al., 2009), and countries like Taiwan in earthquake zones need to develop a simple method to distinguish earthquake-resistant and non-resistant buildings to help engineers quickly and accurately identify buildings that need structural seismic reinforcement. This would allow cost-effective structural seismic reinforcement to be carried out, and thus satisfy seismic performance design goals.

Seismic and Aseismic Behavior of Buildings

As proposed by Lin *et al.* (2022), a building is seismically stable if “during a tectonic earthquake, the plane on which the bottom ends of the columns of the building are located can continue to remain horizontal and continuous” and unstable if "during a tectonic earthquake, the plane on which the bottom ends of the columns of the building are located cannot continue to remain horizontal and continuous."

Since the existing seismic design code for buildings only refers to fortification against ground vibration, it can only ensure that buildings in non-shear band areas (Figure 4) meet the seismic requirements, but cannot ensure that buildings affected by shear bands (Figure 5) meet the seismic requirements.

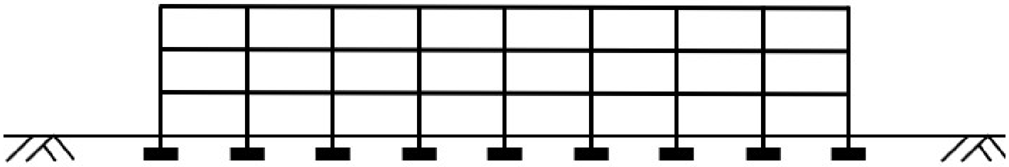


Figure 4. Buildings in non-shear band areas.

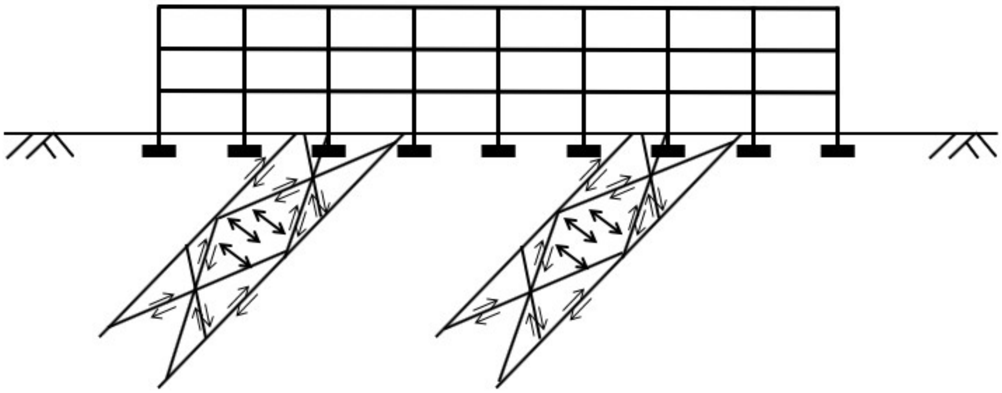


Figure 5. Buildings in shear band areas.

Results of Lateral Pushover Tests and Analyses

Taiwan has carried out the structural seismic reinforcement of school buildings and public markets. The reinforcement design (Qiu, 2016) was based on the results of lateral pushover tests and analyses conducted by the National Center for Research on Earthquake Engineering. This paper focuses on two school buildings, Ruipu Elementary School in Taoyuan and Sincheng Junior High School in Hualien, after the 921 Jiji earthquake, whose damage is shown in Figure 6, The situation after completing the lateral pushover tests is illustrated in Figure 7. The results of numerical analyses designed to check whether the buildings satisfy the seismic requirement are shown in Figures 8.

(a) Ruipu Elementary School in Taoyuan

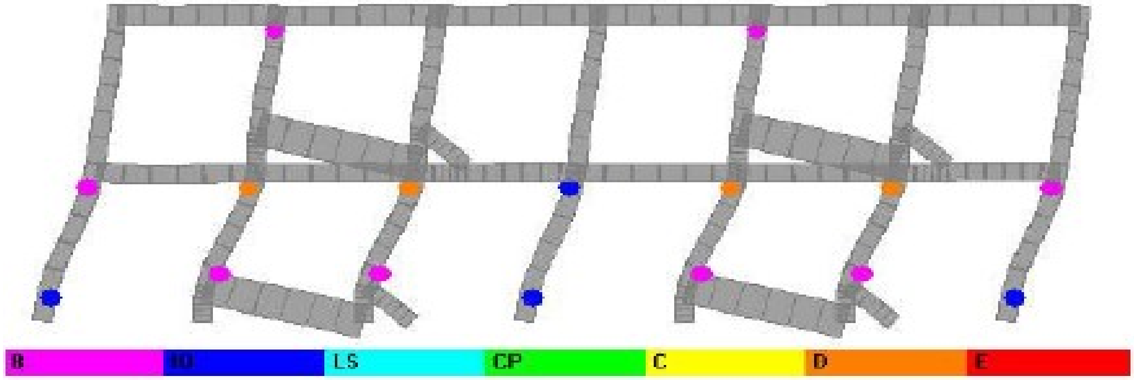
(b) Sincheng Junior High School in Hualien

Figure 6. School buildings after the 921 Jiji earthquake (Zhong, *et al*., 2013).

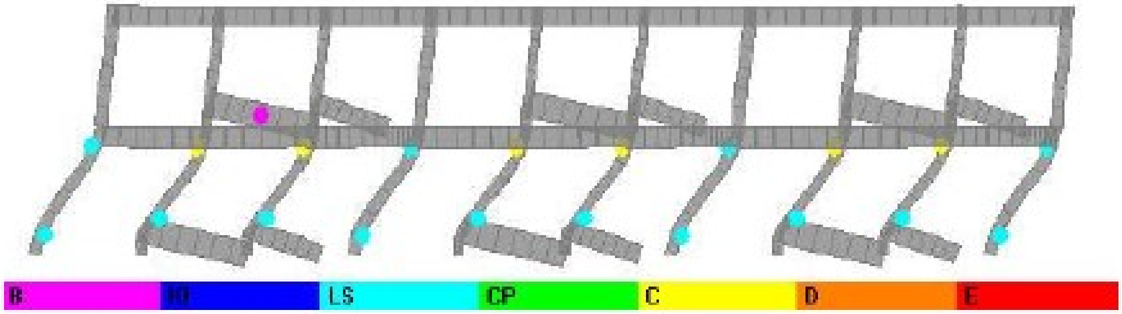
(a) Ruipu Elementary School in Taoyuan

(b) Sincheng Junior High School in Hualien

Figure 7. School buildings after the implementation of the lateral pushover tests (Zhong, *et al*., 2013).



(a) Ruipu Elementary School in Taoyuan.



(b) Sincheng Junior High School in Hualien.

Figure 8. Models of the school buildings after the implementation of the lateral pushover analyses (Huang, 2009).

Analysis of Earthquake Resistance of School Building

1) Check using the building seismic design code

Since Ruipu Elementary School and Sincheng Junior High School were both constructed before 1974 and since the most recent code for the seismic design of buildings promulgated in Taiwan after the 921 Jiji earthquake in 1999 was upgraded to recommend twice the seismic fortification level of the original 1974 code (Su., 2016), the National Center for Research on Earthquake Engineering determined that the two school buildings were not earthquake resistant.

2) Check using the conditions proposed by Hsu et al.

Figure 6 shows that neither Ruipu Elementary School nor Sincheng Junior High School were damaged during the 921 Jiji earthquake, and the planes on which the bottom column ends are located maintained the level and continuity set in the original design. Therefore, they satisfy the earthquake resistance conditions and both buildings are deemed to be earthquake-resistant.

This is confirmed by results of the lateral pushover tests and analyses shown in Figures 7 and 8, respectively, which also show that the planes on which the bottom column ends are located remained horizontal and continuous. Therefore, these two school buildings meet the earthquake-resistant conditions and are again both deemed to be earthquake-resistant school buildings.

Comparison and Discussion of Results

1) The method chosen to check whether a school building or public market is earthquake-resistant is critical to the correctness of the test. For buildings located in non-shear band areas, as shown in Figure 4, when the bottom column ends of a physical building or structural analysis model are set as fixed, the ground vibration response of the building cannot be affected by shear banding during a tectonic earthquake. Since the building fully satisfies the seismic resistance conditions under these settings, it is considered to be an earthquake-resistant building.

2) For a building located in a shear band area, as shown in Figure 5, shear banding causes the building to move, and the plane where the bottom column ends of the building is located will be unable to maintain the horizontal and continuous initial setting, and therefore the building would not be considered earthquake-resistant.

3) Following from the item 2, when lateral pushover tests or lateral pushover analyses are performed on buildings in shear band areas, the buildings will move as a result of the shear banding. Therefore, if the bottom column ends of a physical building or structural analysis model located in a shear band area are set as fixed in the tests or analyses, then

this could yield flawed results and unstable buildings potentially being misidentified as stable buildings.

4) Buildings in shear band areas will be damaged after non-seismic conditions are induced under shear banding. Buildings in non-shear band areas will maintain their seismic condition during a test or analysis, and will be laterally pushed over under the seismic condition. Since the above two failure mechanisms are completely different, the results of a lateral pushover test or analysis cannot be used as the basis for structural seismic reinforcement design.

5) Since the input of a 3D ground vibration force into a structural model requires that the bottom column ends of a building be fixed, the vibration response test and analysis are carried out under conditions which assume that the building is earthquake resistant. Therefore, the results of such tests cannot be used to explain why a building is not earthquake resistant.

6) The seismic reinforcement methods used by the National Center for Research on Earthquake Engineering include reinforced concrete (RC) expansion column reinforcement, RC wing wall reinforcement, RC shear wall reinforcement, and composite column reinforcement. The purpose of these seismic reinforcement methods is to increase the axial strength, shear strength, flexural strength, and toughness of the columns. However, buildings that received such reinforcement were all earthquake-resistant buildings and were not damaged by the 921 Jiji earthquake. The reason for this is that they are all buildings located in non-shear band areas or buildings located in shear band areas but that were not affected by shear banding. The problems with this are that a) reinforcement of the columns to make buildings earthquake-resistant in non-shear band areas is unnecessary, and b) reinforcement of the columns of buildings in shear band areas does not necessarily change them into aseismic buildings.

Conclusions and Suggestions

This paper checked the actual function of the structural seismic reinforcement of school buildings and public markets completed in Taiwan at tremendous expense using the conditions proposed by Lin *et al.* (2022) for buildings to be aseismic. The following four conclusions were drawn:

1) The conditions proposed by Lin *et al.* (2022) for buildings to be aseismic are satisfied by buildings in non-shear band areas and by buildings in shear band areas that are not affected by shear banding. The conditions are that the plane where the bottom column ends of an aseismic building are located maintains the horizontal and continuous conditions set in the original design during a tectonic earthquake.

2) The seismic reinforcement of the school buildings and public markets in Taiwan adopted the results of the

lateral pushover tests of the physical buildings and analyses of the structural models proposed by the National Center for Research on Earthquake Engineering. Since the bottom column ends of the buildings were set as fixed, the lateral pushover tests and analyses assumed the buildings satisfied the conditions for the buildings to be aseismic.

3) Buildings that are not aseismic need seismic reinforcement, and effective seismic reinforcement means the conversion of a building to one that is aseismic. In other words, seismic reinforcement of a building that is already aseismic is unnecessary and should not be referred to as “seismic reinforcement”.

4) Since the seismic reinforcement of school buildings and public markets in Taiwan only aim to improve the ground vibration resistance of the columns of existing buildings that already behave aseismically, the effectiveness of such seismic reinforcement is low and of questionable necessity.

Based on the above conclusions, the authors suggest that the use of the concept of the seismic conditions being controlled by shear bands should be promoted in the future, so as to identify the buildings that are not aseismic and allocate funds to buildings that really do need seismic reinforcement. By changing a non-aseismic building into an aseismic building, the seismic reinforcement of a building clearly achieves the seismic performance design goals.

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