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Shaking Table Tests on Collapse Patterns of Eight Different Multi-Storey with Different Structures

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ABSTRACT
In this paper, shaking table tests on collapse patterns of totally eight multi-storey building samples with different structures are introduced. The collapse patterns of the two comparable masonry infill RC frame structures show that the different damage sequence and collapse time as well as the effects of the different floor arrangements to the aseismic capacity of the RC frame structures even with same column-beam system. The collapse patterns of the two comparable masonry buildings with same clay brick wall and in-situ concrete floor show the different damage patterns and collapse time due to the different window opening sizes. The collapse patterns of other two comparable masonry buildings show that the damage severity and the aseismic capacity as well as the collapse time and ruin structure are influenced by the precast hollow RC floor and composite RC floor used in the samples. The collapse patterns of the two comparable bottom RC frame supported masonry buildings mainly show the different effects caused by the different storey stiffness ratios. Test observations as well as the main results are summarized and explained. The results would provide useful reference for seismic design of the anti-collapse building as well as the decision-make in the emergency rescue activities in earthquake site.

KEYWORDS: *shaking table test, collapse pattern, RC frame structure, masonry building, bottom RC frame*

1. GENERAL INSTRUCTIONS

The earthquake is a natural disaster which endangers people's life and property seriously. Earthquakes happen about 5 million times a year all over the world, including nearly one thousand destructive earthquakes[1]. China is one of the most serious countries suffering from earthquake disasters. The strong earthquakes which happened in China in the past ten years, such as the Jiangxi Jiujiang earthquake in 2005, the Wenchuan earthquake in 2008 and the Yushu earthquake in 2010, the Lushan earthquake and the Ludian earthquake in 2014, etc., all caused a large number of casualties and huge economic losses[2].

The nature of the earthquake disaster is a kind of civil engineering disasters, and the main cause of civil engineering disasters is the lack of buildings' aseismic capacity[3]. After the Wenchuan earthquake, magistoseismic area, such as beichuan county, xuankou town, yingxiu town, etc., more than half of the buildings collapsed or severely damaged, and some building groups or buildings near street collapsed in crowds. In the earthquake, "strong beam weak column" failure in frame structures, serious failure of wall piers in masonry structure, floor slab falls in precast floor slab buildings and bottom storey full collapses in brick masonry structures with bottom frame, these four types of earthquake damage were the most notable [4,5]. The paper put forward the corresponding seismic measures against these four types of earthquake damage, and validated them through the shaking table test.

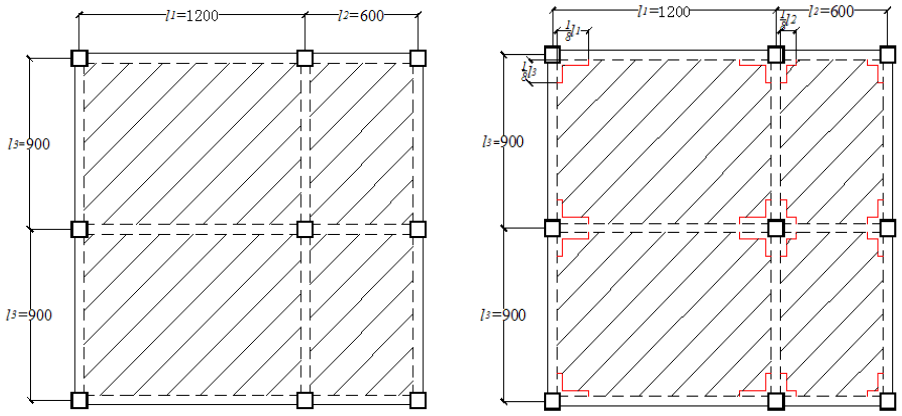
2. RC FRAME STRUCTURE TEST OF VERIFYING THE "STRONG COLUMN WEAK BEAM" MEASURE

In the 5.12 wenchuan earthquake, the desired "strong column weak beam" failure mechanism did not appear in the teaching complex building of the xuankou middle school, which collapsed very seriously. Collapse resistance of the RC frame structure is closely related to the yield mechanism. Frame beams yielding firstly can significantly increase the energy dissipation capacity of the structure, but if yielding appears in columns firstly, the structure becomes an unstable system and easy to collapse. Domestic and foreign researches showed that the strengthening of in-situ concrete floor to frame beams, which has a significant impact both on seismic performances and collapse patterns of frame structures, is the main reason impacting "strong column weak beam" failure mechanism of structures[6-8].

At present, the researches about the "strong column weak beam" failure mechanism mainly focused on the contribution of floors to frame beams. Usually the researches attempted to solve the problem by changing the bending moment enlargement coefficient of the end of columns and considering the floor flange width and reinforcement at the end of beams. Starting with the viewpoint how to avoid the contribution of floors to frame beams, this paper puts forward the limited disconnection measure between the four corners of in-situ concrete floor and beams. According to the current standards of China, two 1/5 scale test models of four-storey in-filled RC frame structures with 2×2 spans were designed and made, one with common floor slabs and another with the limited disconnection floor from beams at the corners. Through the shaking table contrast tests of the two models, the effect of the measure to the failure pattern and the collapse resistance of frame structures was analyzed.

2.1 Test Overview

Two 1:5 scale models were tested to simulate the damage of the teaching complex building of the xuankou middle school during earthquake. The floor layout of the two models are shown in the figure 2.1, the model A with common floor slabs and the model B with the limited disconnection floor slabs from beams in beam-column joints.



(a) Model A (b) Model B

figure 2.1 Floor plans of the test models

2.2 Analysis of test result

Two test models both experienced five phases of “filler walls crack”, “beams and columns crack”, “filler walls damage”, “beams and columns damage” and “structure collapsed”. When PGA was low, the load was mainly suffered by filler walls, so filler walls cracked first. With the increase of PGA, the filler wall almostly exited working, the bending cracks and torsion-shear cracks in beams and columns significantly increased, and the load was mainly suffered by frame at this time. At the end, as the frame columns were yield failure, the whole structure began to collapse. Although the destruction processes of the two models were similar, there was much difference in the failure degree and pattern.

Viewed from the holistic damage condition of the models, damage at the end of frame columns of model A was obviously more serious than the damage of model B. Especially under a large PGA, the difference of failure modes between two models was bigger and bigger. Although frame columns’ damage was more serious than frame beams’ eventually of two models, the number of plastic hinge of beam in model B is far more than the number in model A. Ductility of Model B structure was well. Finally, model A collapsed, in stark contrast, while model B was not completely destroyed, as shown in figure 2.2.

All in all, the limited disconnection measure between the floor slabs and the ends of beams changed the failure pattern of frame structures, effectively delayed the destruction of frame columns and improved the ability of deformation of frame structures. It is of benefit to achieve the fortification goal of "no collapse in strong earthquake".

Figure 2.2 Destruction condition（Left one is model B, right one is model A）

3 INFLUENCE OF STIFFNESS RATIOS OF PIER/SPANDREL WALLS ON THE COLLAPSE RESISTANT CAPACITY OF MASONRY STRUCTURES

Damage degree of masonry structure under earthquake is directly related to the seismic capacity of the walls of main structure (especially bearing wall). The failure masonry structure walls cause the whole structure collapse or serious damage and the different failure patterns of walls result in the different seismic performance of the whole masonry structure. The most popular three kinds of wall-failure patterns of multi-storey masonry structure in earthquake are shown as follows: wall piers first destruction, spandrel walls first destruction, both wall piers and spandrel walls destruction at the same time. Spandrel wall first destruction is means that the wall under windows failure firstly, which will not cause the destruction and collapse of the whole structure, instead which can consume part of the seismic energy and increase the seismic performance of the whole structure. It conforms to the multi-channel fortification of design concept of codes. Based on this idea, two test models with different stiffness ratios of pier/spandrel walls were designed to verify that increase the stiffness ratios of piers/spandrel walls can improve the seismic ability of masonry structure.

3.1 Test Overview

The prototype of test model was designed by PKPM software, whose plane size was 9.0m×5.4m, layout used three bays (3.0m×3)×two depths (4.2m+1.2m), floor number was 3, all the storey height was 3m. Doors and windows were decorated on the longitudinal walls, the cross walls did not open holes. Wall thickness was 240mm, the constructional column section was 240mm×240mm, the ring beam section was 240mm×300mm, the floor slab thickness was 120mm. The concrete strength grade of floor slab was C25, and the concrete strength grade of ring beam and constructional column was C20, reinforcement was used HPB235. Clay brick strength grade was MU10, mortar was used M2.5. Constructional measures to meet fortification intensity IX degree. The test models were designed and made according to the 1/4 scale. The model elevations were shown in figure 3.1 and figure 3.2. The stiffness ratio of piers/spandrel walls of model C was 0.75, and model D was 1.14.

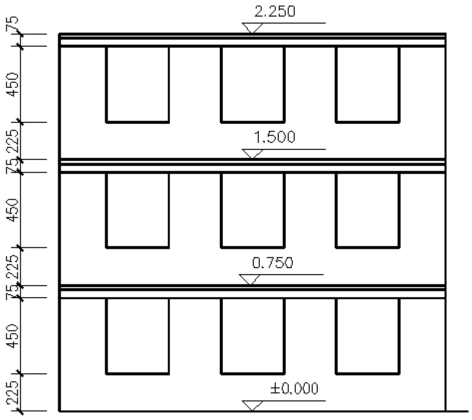


Figure 3.1 Elevation of model C

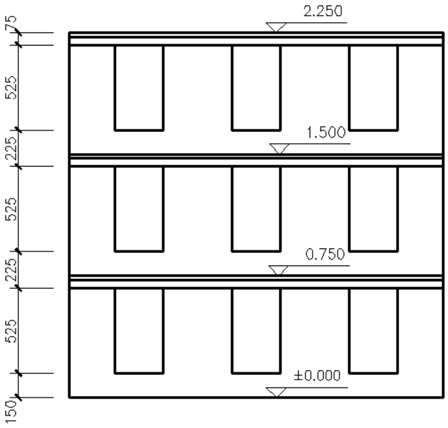
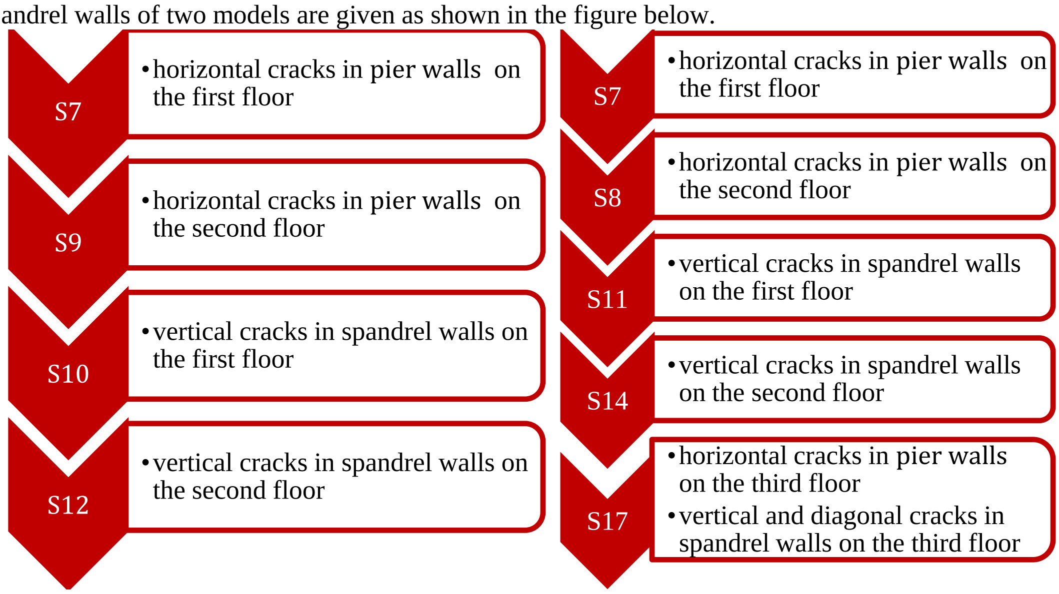


Figure 3.2 Elevation of model D

3.2 Analysis of test result

This paper mainly concern about the influence of the stiffness ratio of pier/spandrel walls on the failure pattern and collapse resistance of masonry structures. Therefore, the destruction phenomenon and order of the pier walls and spandrel walls of two models are given as shown in the figure below.



S7
- horizontal cracks in pier walls on the first floor

S9
- horizontal cracks in pier walls on the second floor

S10
- vertical cracks in spandrel walls on the first floor

S12
- vertical cracks in spandrel walls on the second floor

S7
- horizontal cracks in pier walls on the first floor

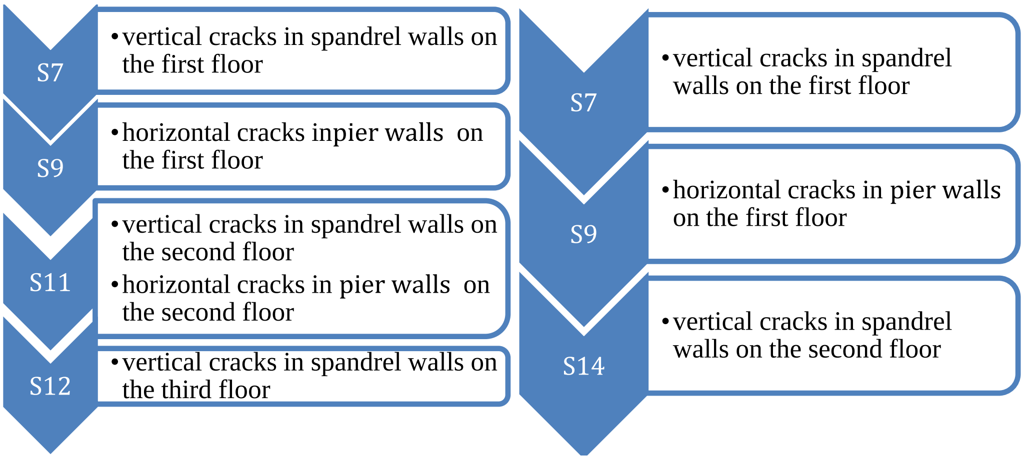
S8
- horizontal cracks in pier walls on the second floor

S11
- vertical cracks in spandrel walls on the first floor

S14
- vertical cracks in spandrel walls on the second floor

S17
- horizontal cracks in pier walls on the third floor
- vertical and diagonal cracks in spandrel walls on the third floor

Figure 3.3 Destruction process of external longitudinal walls of model C in axis Ⓐ (left) and axis Ⓒ (right)



S7
- vertical cracks in spandrel walls on the first floor

S9
- horizontal cracks inpier walls on the first floor

S11
- vertical cracks in spandrel walls on the second floor
- horizontal cracks in pier walls on the second floor

S12
- vertical cracks in spandrel walls on the third floor

S7
- vertical cracks in spandrel walls on the first floor

S9
- horizontal cracks in pier walls on the first floor

S14
- vertical cracks in spandrel walls on the second floor

Figure 3.4 Destruction process of external longitudinal walls of model D in axis Ⓐ (left) and axis Ⓒ (right)

It can be seen that, pier walls were failure first and then spandrel wall were failure in the model C. Its failure pattern was similar to the "strong beam weak column". While in the model D, spandrel walls were failure first and then pier walls were failure. Spandrel walls fully absorbed the seismic energy, which was benefit to improve the collapse resistant capacity of the structure. Its failure pattern was similar to the "strong column weak beam". Therefore, this test showed that the failure pattern and aseismic capability of masonry structure can be improved significantly by controlling the stiffness ratio of pier/spandrel walls.

4 TEST OF VERIFYING REINFORCEMENT MEASURE FOR PRECAST HOLLOW SLAB MASONRY STRUCTURE

The multistory brick masonry structure with precast slab has poor integrity and low ability of resisting progressive collapse. The most houses are masonry structure with precast slab in Qinghai Yushu, and more than 50% of the masonry houses were destroyed even collapse in the 2010 earthquake. It is necessary to study how to improve the seismic capacity and the ability to resist collapse of the masonry structure with precast slab. To solve this problem, this test uses the approach of adding cast-in-place layer on precast slab to reduce the fall risk of floor and improve the collapse resistant capacity of masonry structure in the strong earthquake.

4.1 Test Overview

The prototype of test models is a three-layer masonry structure, the longitudinal walls with window and door openings, and the cross walls without openings. The three crosses of x plane dimension (parallel to the cross wall direction) are respectively 4.2m, 3m and 4.2m, and the three crosses of y plane dimension (parallel to the longitudinal wall direction) are all 3.3m. The section size of constructional column is 370mm×370 mm, and the section size of main beam and ring beam is 370mm×180mm. The thickness of precast slab is 120mm, thickness of interior and exterior wall is 370mm. The bottom storey height is 3.9m, and upper storey height is 3.3m. Masonry parts are made of MU15 sintering brick and M7.5 cement mix mortar. Concrete members are made of C20 concrete. The rebar of beam, column and slab is HRB335, the stirrup of beam, column and the tie bar of wall are HPB235. Seismic construction measures are in accordance with 8 degree seismic requirements of the multi-storey brick masonry buildings, with the site class II.

The test made two 1/ 6 scale models of masonry structure with precast slab with three layers and 3×3 cross. The model E is precast slab masonry structure, and model F is precast slab and cast-in-place concrete layer masonry structure. The plan of two models is shown in figure 4.1.

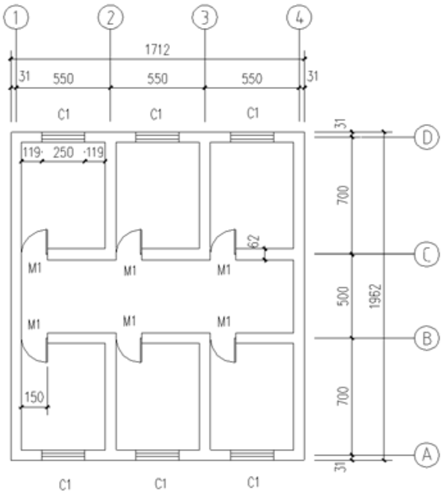


Figure 4.1 Floor plan

4.2 Analysis of test result

To study on the differences of seismic capacity and failure mode of the two models, the paper summarizes the main failure phenomena. At the end of the load case, model E and F were not collapse. The main failure of model E was in the bottom layer. With the motion input increased, the damage developed from the bottom to the upper layers, as the bottom destroyed further and the second or third layers appeared obvious damage. The failure mode of model F was similar with that of model E. The bottom layer was heavily damaged, and the third layer was slightly damaged. The damage degree of model F was lower than the model E.

During the whole test, the cracks of model E were slight in small earthquake action, but they were increased developed obviously in the large earthquake action. Horizontal cracks on the pier walls and diagonal cracks on the window corners were most, and the latter ones developed obviously. Although the cracks of model F were more obvious than model E in small earthquake action, but with the increasing of input ground motion, the damage development of model F was slower than the model E.

a Diagonal crack at the corner of window in axis Ⓐ b Diagonal crack at the corner of window in axis Ⓓ

Figure 4.2 Destruction of model E

a Diagonal crack at the corner of window in axis Ⓐ b Diagonal crack at the corner of window in axis Ⓓ

Figure 4.3 Destruction of model F

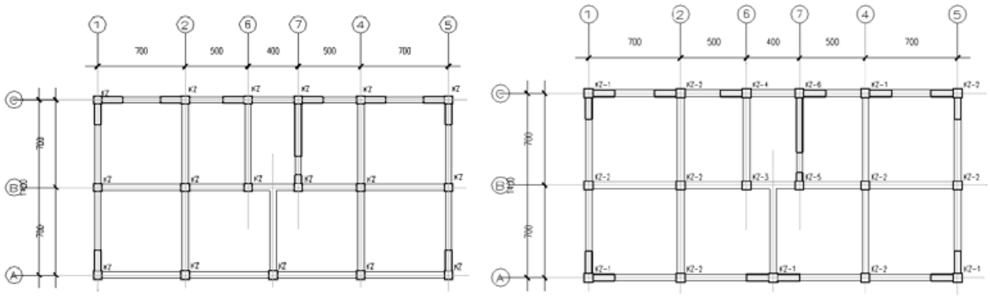
5 TEST OF BOTTOM FRAME MASONRY STRCUTURES WITH DIFFERENT STOREY STIFFNESS RATIOS

Bottom frame masonry structure is wildly used in areas of south China. According to incomplete statistics, more than 20 million existing buildings are belong to this kind of structure, where more than 120 million people live. However collapsed rate of these structures in the earthquake is very high. After the Wenchuan earthquake, more than 80% bottom frame brick masonry structure collapsed in Beichuan County [9]. Thus, study how to improve the collapse resistance and control the failure mode of bottom frame brick masonry structure is of great significance. By increasing the wing wall to change the stiffness ratio of frame structure and masonry structure, the test achieves the goal of improving the seismic capability of the bottom frame masonry structure.

5.1 Test Overview

Test prototype model using PKPM software to design, 4 layer bottom frame multi-story masonry structure, two cross for X direction, four cross for Y direction, each cross is 4.2 m; The column section at the bottom of the frame is 400 mm x 400 mm, and the beam section is 300 mm x 300 mm, constructional column section is 240 mm x 240 mm, the ring beam section is 240 mm x 300 mm, inner and outer wall thickness 240 mm, the bottom layer is 4.5 m, and the other layer is 3.0 m. Masonry components are made by MU10 sintered brick and M10 cement mixing mortar. Concrete components are made by C30 concrete. Longitudinal bars of beams, columns and concrete seismic walls are made by HRB335. Stirrup of beams, columns and concrete seismic walls are made by HPB300. Classification of design earthquake for the model is the first group; and the seismic design intensity is 7 degrees (0.1 g), site category is class II.

According to the 1/6 scale, two test models have been made respectively. The lateral stiffness ratio between the bottom frame and the upper masonry structure layers were 1.11 (Model G), and 2.23 (Model H). The difference of Model G and Model H is only in the underlying frame structure. Model H have more longitudinal four pieces of concrete seismic walls, as shown in figure 5.1.



(a) Model G (b) Model H

Figure 5.1 Plan of bottom frame

5.2 Analysis of test result

After the condition of T20, the frame storey of Model G damage seriously and mainly lost bearing capacity, but the masonry part was mainly intact. The shear walls in axial ⑦ appear “X” shear crack. Concretes at the end of frame columns on the side of axial A were all crushed, frame columns were unable to work. The shear wall in axial ① and axial ⑤ cracked completely and appeared a large inclination deformation. The destruction of framework storey in C axis was lighter than other parts. At the condition of T22, the frame columns on the side of axial A all could not work, the model occurred serious inclination deformation and collapse.

Figure 5.2 Destruction of model G after T20

Figure 5.3 Collapse of model G

After the condition of T22, in the model H, the spandrel walls in axial A between axial ① and axial ③ on the second and the third floors appeared crack. The part in axial C between axial ④ and axial ⑤ on the first and the second floors began to appear fine crack. The overall destruction of the structure was lighter than moderate damage. After Model G collapsing, model H experienced additionally 6 times earthquakes(PGA>0.4g) and then collapsed, as shown in the figure 5.5.

Figure 5.4 Cracks on spandrel wall of model H

Figure 5.5 Collapse of model H

The upper masonry structure of model G had few cracks, while the bottom frame structure was severely damaged. The stigma and pedestal cracked firstly indicates that the design of model G was not reasonable. Almost all the earthquake energy was absorbed by the ground floor. The upper masonry part of model H cracked firstly and then the bottom frame part followed. Although model H finally collapsed from the damage of ground floor, the upper part also took part in the earthquake resistance, absorbed lots of energy and enhanced the seismic capacity of the structure. The test result shows that adjusting the lateral stiffness ratio between the bottom frame part and the upper masonry part could enhance the seismic performance of bottom frame masonry structure.

6 CONCLUSIONS

Aimed at the four most common types of earthquake damage phenomenon in the recent ten years, the paper provides corresponding seismic measures, and verifies the effectiveness of the measures through the tests. These measures can be used to the seismic design of new building, and reinforcement or reconstruction of existing construction.

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