Damage to urban buildings in zones of intensities VIII and VII during the Wenchuan earthquake and discussion on some typical damages*

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Abstract The outline and typical characteristics of damages to building in Jiangyou city and Anxian county (intensity VIII), Mianyang city and Deyang city (intensity VII) are introduced in the paper. The damage ratios, based on the sample statistics of multi-story brick buildings together with multi-story brick buildings with RC frame at first story (BBF), are presented. Then some typical damages, such as horizontal cracks of brick masonry buildings, X-shaped cracks on the walls under windows, the damages to columns, beams and infill walls of frame buildings and the damage to half circle-shaped masonry walls, are discussed.

Key words: Wenchuan earthquake; damage to building; seismic intensity

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1 Introduction

Based on post-earthquake field survey, the damage to city buildings in high intensity zones were introduced in former paper (Sun et al, 2008). The outline of damage to urban buildings in typical moderate intensity zones, such as in Jiangyou city and Anxian county (intensity VIII), Mianyang city and Deyang city (intensity VII), are presented in this paper. Besides, in each city the damage ratios of multi-story brick masonry and BBF buildings are provided, and then some typical damages including those in high intensity zones are discussed.

The building types in the earthquake area, in order of numbers, are multi-story brick masonry buildings, BBF buildings, RC frame buildings, self-built brick wooden or brick masonry houses. In addition, there are some high rise RC frame-shear wall (or frame-tube) buildings in Mianyang city and Deyang city.

Because of the complicated topographic and geologic site conditions and various buildings, nearly all kinds of damages to buildings could be found during this strong earthquake. In this paper, only more common

damages are introduced. Besides, surveyed results show that the damage ratios between brick masonry buildings and BBF buildings have no significant difference, thus the presented damage ratios are based on the statistics of mixing samples of these two kinds of buildings. The statistical samples were from three or four different places of each city, which were chosen to cover the urban area as much as possible.

Although the seismically designed buildings showed good performance on the whole, many new problems were revealed. In this paper, some general damage problems are discussed, including horizontal cracks of brick masonry buildings, X-shaped cracks on the walls under windows, the damage to columns, beams and infill walls of frame buildings and the damage to half circle-shaped masonry walls. At last, the relevant suggestions are proposed.

2 Typical damages to buildings and damage ratios

2.1 Intensity VIII zones

2.2.1 Jiangyou city

The distance from Jiangyou city to central fault is about 22 km.

In the city, multi-story brick masonry buildings

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account for the majority, followed by BBF buildings, RC frame buildings and self-built brick or brick-wooden houses.

During the earthquake, a few self-built houses collapsed, many other buildings cracked or damaged in varying degrees on brick walls or infill walls.

The typical damages to brick and BBF buildings are shown in Photo 1. Although judging by outward appearance these buildings seem no serious problems, in fact, their lateral seismic resisting capacity is obviously reduced.

The most damages to RC buildings appeared on

Photo 1 Typical damages to brick and BBF buildings. (a) Through inclined crack on transverse wall; (b) Through inclined crack on transverse wall; (c) Through X-shaped cracks on interior longitudinal wall; (d) X-shaped cracks on the wall under window; (e) Cracking along the mortar joint between base ring beam and brick wall.

infill walls, only a few structural members suffered slightly cracking, some stairs broke off, in company with concrete crushing. The damages to a 7-story frame building appeared on infill wall and top ends of two columns in second story are shown in Photo 2. Poor performance of infill walls, damages to stairs and stair beams of a 6-story frame building can be seen in Photo

3, but it should be mentioned that the main structural members of this building keep intact.

Generally, it could be seen that RC buildings showed better seismic performance than those of other types of structures. Only a few columns or beams cracked slightly and the most damages concentrated on non-structural members.

Photo 2 Damage to a 7-story frame building. (a) Outward appearance; (b) Damages to middle column and infill wall in second story; (c) Crack on side column in second story.

Photo 3 Damage to stair, stair beam and infill wall of a 6-story frame building.

The damage ratios are investigated based on 94 samples, in which the brick and BBF buildings are 65 and 29 respectively, and the results are given in Figure 1.

2.1.2 Anxian county

Anxian county consists of old town and new town. The old town (Anchang, intensity VIII) is about 10 km to central fault and the damage was heavier than that of new town (Huagai, intensity VIII minus), which is about 26 km to central fault. Except there are more old self-built houses in old town, both the building types

and damage characteristics are basically the same as those in Jiangyou city, here not repeat it again.

The damage ratios of brick and BBF buildings in Anxian county are given in Figure 2 based on 64 samples, in which the numbers of brick and BBF buildings are 47 and 17 respectively.

2.2 Intensity VII zones

2.2.1 Mianyang city

The distance between Mianyang city and central fault is about 47 km.

Figure 1 Brick and BBF building damage ratios in Jiangyou city.

The building types in this city are similar with that in Jiangyou city, except there are higher rise buildings. The main damage characteristics are thin inclined shear cracks on the walls of brick or BBF buildings (an example as shown in Photo 4), heavy damages of infill

Photo 4 Thin inclined crack on the wall in first story of a 7-story brick building.

Photo 6 Thin inclined crack on infill wall in upper story of a 21-story frame-shear wall building.

Figure 2 Brick and BBF building damage ratios in Anxian county.

walls in a few of RC frame buildings (Photo 5), slight inclined cracks on infill walls of high rise buildings (Photo 6), stairs broke off in a frame building (Photo 7) and partial collapse of a few of self-built houses (Photo 8).

Photo 5 Infill wall failure in first story of a 6-story frame building.

Photo 7 Stairs broke off in a 9-story frame building.

Photo 8 Partial collapse of a self-built 3-story house.

The damage ratios of brick and BBF buildings are given in Figure 3 based on 67 samples, in which the numbers of brick and BBF buildings are 60 and 7 respectively.

Figure 3 Brick and BBF building damage ratios in Mianyang city.

2.2.2 Deyang city

The distance from Deyang city to central fault is about 51.0 km.

Both the building types and damage characteristics of this city are similar with those of Mianyang city, except more horizontal cracks could be found on brick buildings (as shown in Photo 9). Generally, the damage is a little lighter than that of Mianyang city.

The 135 buildings (130 brick buildings and five BBF buildings) were investigated and the damage ratios are shown in Figure 4.

Photo 9 Horizontal crack along mortar joint between brick wall and base ring beam of a 6-story brick building.

Figure 4 Brick and BBF building damage ratios in Deyang city.

3 Discussion on some typical damages to buildings during this earthquake

3.1 Horizontal cracks of multi-story brick masonry buildings

During this earthquake, many brick masonry buildings suffered horizontal cracks, which could not frequently be seen in the past earthquakes. Most horizontal cracks occurred along mortar joints between base ring beams and brick walls. The light extended a part joint in some buildings (Photos 1e and 9) and the heavy ones thoroughly cracked with the steel bars in construction column cutting off and brick walls shifting in other buildings (Photo 10). Besides, there were some other horizontal cracks appeared along the mortar joint between the ring beams of first or second story and their connected walls or at some other positions of brick walls.

The probable factors leading to these cracks are ①

the poor mortar bonding caused by inappropriate construction after casting and curing the ring beams; ② when building mainly shakes along one direction, the walls in this direction crack and deform under strong shear forces, at this time, some seismic forces transfer to the normal walls, make them suffer bending and result in horizontal cracking at bottom position as shown in Photo 11.

Photo 10 Mortar joint between base ring beam and wall cracks thoroughly, wall shifts and steel bars in construction column cut off.

Photo 11 Transverse wall cracks horizontally by bending after shear damage to longitudinal wall.

Horizontal cracks have basically no influence on vertical loading capacity of building but seriously reduce lateral resisting capacity. Therefore, much attention should be paid to retrofitting this kind of damage and improving the seismic performance of new buildings against horizontal cracking.

3.2 The damage to the wall under window for brick masonry and BBF buildings

The past earthquake experience showed that when earthquake acted mainly along the longitudinal direction of a masonry building, the damage first appeared on the

walls between windows because the windows and doors reduce the cross section of walls at that level. Therefore, based on this damage pattern, the longitudinal seismic resistance capacity is determined by checking the strength of total longitudinal wall's cross sections at windows level, this method is generally adopted by us. However, nowadays as the windows are enlarged and construction columns are built in the wall between windows, this damage pattern has changed, which could be obviously observed during this earthquake, that is, many damages first occurred at the walls under windows as shown in Photos 1d and 12. And with seismic force increasing, the building would damage as shown in Photo 13.

Photo 12 X-shaped cracks at walls under windows.

Photo 13 Heavy damage at walls under windows.

The Photo 13 states that the deformation of external longitudinal wall is no longer the shear type, but becomes a deformation system of multi-coupled walls connected by very weak coupling beams (walls under windows). This damage shows that ① the weak region of this type of building in longitudinal direction has transferred to the walls under windows, thus to improve the seismic performance of this region is a new subject; ② at present, the seismic resisting capacity checking method of seismic code for masonry buildings, which is

established based on the assumption of shear deformation, is not suitable for this type of structure and new checking method should be developed.

3.3 First story damage and infill wall's role for RC frame buildings

Shear deformation is the main characteristic of frame structure and this leads to relatively larger deformation at first story. Besides, the larger shear force, relatively higher height and larger space (less infill walls to meet the commercial or official requirements) are all occurring at first story. All of these make the first story easily attacked by earthquake. This could fully be seen from this earthquake, for example, many damages to first story were found in high intensity zones as shown in Photos 14 and 15.

Photo 14 First story's columns of a constructing frame building inclined and buckled at their ends.

The damage to frame buildings shows that the infill walls first failure during earthquake, at the same time, they dissipate a great amount of earthquake energy and play a positive role to protect structural members from damages. Therefore, the RC frame buildings showed excellent seismic performance during this earthquake (although many infill walls were damaged, they have no serious influence on the safety of buildings), for instance, the structural members of frame buildings were damaged very few comparatively in above mentioned cities.

However, if the infill walls are located in inappropriate positions, they will play a negative role, mostly make columns become short ones and being damaged by shear force as shown in Photo 16. Besides, the infill walls lead to a great difference of interstory stiffness, for example, the stiffness difference between first story and upper stories as shown in Photos 14 and 15.

Photo 15 First story's columns of a commercial residential frame building inclined and buckled at their ends.

Taking the influence of infill walls into consideration during seismic design is important for it can more reasonably estimate the interstory stiffness ratio (for example, the ratios of the buildings shown in Photos 14 and 15 could not pass through design, if we do this), dynamic characteristics and seismic performance of buildings.

3.4 Damage to half circle-shaped brick walls

Many damages to half circle-shaped brick external walls were found during this earthquake and two examples are shown in Photos 17 and 18.

Masonry wall can resist larger seismic force along the wall direction, but is very weak to carry seismic force in normal directions. The transmission paths of forces in half circle-shaped brick external walls are very complex and thus the walls are extremely easy to suffer damage during shaking. In view of this reason, this kind of shaped structure should be avoided in seismic zones.

4 Conclusions

1) The basic design intensities in four cities mentioned in this paper are Jiangyou VII (VI before 2001), Anxian VII, Miangyang VI and Deyang VI (Ministry of Construction of the People's Republic of China, 2001) and practically suffered intensities were VIII, VIII, VII and VII respectively, which are corresponding to their rare earthquake fortification criterion to prevent collapse

respectively. For brick masonry and BBF buildings, in VIII zones, the average basic intact ratio and slight damage ratio are 24.3% and 43.6% respectively; in VII zones, these ratios are 57.6% and 24.2% respectively. The intact and slight damage ratios are even higher for RC buildings. On the whole, the most seismically designed buildings exhibited better performances, which exceed the levels expected by seismic code. Self-built houses and those buildings which have some problems in design or construction take the majority of a few serious damaged or collapsed buildings. All of these demonstrate that the design and construction strictly according to seismic code are very important for building's seismic safety.

(a)

(b)

Photo 16 Damage to short columns brought about by infill walls in an eight story frame building. (a) Second story's column; (b) Third story's column.

Photo 17 Damage to half circle-shaped brick wall in a seven story frame building.

Photo 18 Damage to half circle-shaped brick wall in a five story school building.

2) Many brick masonry and BBF buildings suffered horizontal cracking during this earthquake and two main reasons leading to this kind of cracking are discussed in the paper. It is specially emphasized that although these horizontal cracks basically have no influence on vertical loading capacities of buildings, they significantly reduce their lateral resisting capacities and thus how to retrofit these damaged buildings should be considered seriously. In addition, the construction method to avoid cracking along the mortar joint between ring beam and brick wall should also be improved for new buildings.

3) Nowadays, as the windows are enlarged and

construction columns are built in the walls between windows, the damage pattern of masonry structures in longitudinal direction has changed and the damages to walls under windows were found far more than those of the walls between windows during this earthquake. This shows that there are some problems in current method of checking building's lateral resisting capacity based on the cross sections of the walls at window level. Therefore, the mechanical analysis model corresponding to this damage pattern and lateral resisting capacity checking method need to be developed.

4) The infill walls laid reasonably and correctly may play an important role to protect main structural members from damages for frame buildings. During seismic design, taking the infill wall's influences into consideration may ① more correctly estimate the seismic performance of buildings; ② more reasonably calculate the interstory stiffness ratio to avoid the weak story occurred (for example, the weak first story discussed above); ③ avoid to lay them in inappropriate

positions resulting in frame columns to become short ones. In view of these reasons, the seismic code should have some regulations about how to consider the infill wall's influence during seismic design.

5) Half circle-shaped brick walls are very easy to damage during earthquake and thus this kind of shaped structure should be avoided in seismic zones.

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