Wenchuan Earthquake Field Reconnaissance on Reinforced Concrete Framed Buildings With and Without Masonry Infill Walls

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ABSTRACT: This paper focuses on the seismic performance of multi-story reinforced concrete (RC) frames with and without masonry infill wall, which were affected by the 8.0 magnitude earthquake that struck northwestern Sichuan, China, on May 12, 2008. Field reconnaissance was carried out in Dujiangyan, Hanwang, and Yingxiu in order to investigate the types of damage observed in the infill walls and/or the bounding frames. Seismic code requirements are discussed and compared with observed details. Many structural deficiencies were highlighted by the earthquake damage, which include: soft and weak stories, strong-beams and weak-columns, short columns, interaction between the infill walls and the bounding RC frames.

KEYWORDS: Field reconnaissance, Infill wall, Reinforced concrete frame, Wenchuan Earthquake

1. INTRODUCTION

An 8.0 magnitude earthquake occurred on the 480 km-long and 100 km-wide Longmenshan fault on the northwestern margin of the Sichuan Basin, China, at 2:28 p.m. on May 12, 2008. The epicenter of the earthquake was located at 103.4° east and 31° north and near Yingxiu town, Wenchuan county, 73 km northwest of Chengdu, 21 km west of Dujiangyan. The location of the epicenter is shown in Figure 1. The geographic region affected by the earthquake was somewhat narrow banded and centered on the fault stretching from Yingxiu in the southwest to Beichuan in the northeast. Widespread collapses and severe damages of buildings were observed in the epicenter region. Many of these affected buildings were reinforced concrete (RC) frame structures with and without infill walls. According to the Ministry of Civil Affairs of P. R. China, the death toll was 69197, the number of people who were injured was 374176, and additional 18209 people were still missing as of July 24, 2008. The majority of deaths and injuries were in Yingxiu, Dujiangyan, Hanwang and Beichuan, mainly caused by the collapsed buildings.

Following the earthquake, a reconnaissance team was dispatched to the epicenter region to learn firsthand about the performance of the civil infrastructure. The paper starts by a review of the code for seismic design of buildings in China. Subsequently, the performance of the RC frame structures with and without infill walls is presented in details. Finally, the paper concludes with some suggestions to be considered in the seismic design of such structures in earthquake epicenter regions.

2. CODE FOR SEISMIC DESIGN OF CONCRETE BUILDINGS IN CHINA

After the 1969 Xingtai earthquake, seismic design of buildings was considered and the code for seismic design of buildings (TJ11-74 [1]) became in effect since 1974 in China. A revised edition (TJ11-78 [2]) came out in 1978 after the 1976 Tangshan earthquake. Early editions (e.g. 1974 and 1978) of the code for seismic design were based on allowable stress design making use of safety factors. Major changes were introduced into the seismic code in 1989 (GBJ11-89 [3]) and 2001 (GB50011-2001 [4]). The latest two versions of the seismic code were based on ultimate strength design.

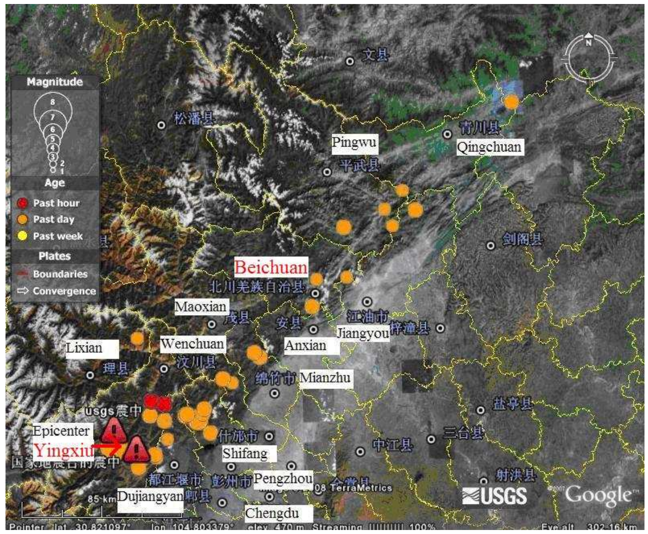

Figure 1 Map of Wenchuan earthquake epicenter region

In the 1989 edition of the seismic design code, RC buildings should be designed to form ductile systems. The basic principles in that regard are: (a) columns should be stronger than beams, (b) shear strength of a column must exceed shear force associated with the plastic moment in the column, (c) shear resistance in beam-column joints is sufficient, and (d) beam reinforcing bars anchorage in the beam-column joint is adequate. In the 2001 edition of the code [4], detailing requirements are more stringent for systems with high ductility.

3. PERFORMANCE OF RC FRAMES WITH AND WITHOUT MASONRY INFILL WALLS DURING WENCHUAN EARTHQUAKE

3.1. Weak-beam and Strong-column

Little damage to moment-frame beams in the Wenchuan earthquake epicenter region was observed by the reconnaissance team because columns were generally weaker than beams. However, one of the requirements in designing ductile frames is strong-column and weak-beam, according to the current code for seismic design, that is, most structures are designed to have sufficient ductility to survive an earthquake. This means that elements will yield and deform, but they will be strong in shear and continue to support their load during and after the earthquake. The reconnaissance team toured a number of frame buildings and found that many frame buildings collapsed due to weak-column and strong-beam in the epicenter region. Figures 2 and 3 show the plastic hinges occurring at the top and bottom of columns. From the pattern of damage, it was concluded that the RC slabs that were cast monolithically with the beams played an important role to contribute to the stiffness of the beams when the structure was shaken under the earthquake motion.

3.2. Soft Story Due to Effect of Infill Walls

Many residential and commercial buildings in the epicenter area experienced severe damage to the first story. Generally, the ground stories of these buildings were used for commercial space or as parking space, and the upper stories were used as residential apartments. Hollow clay tiles and gas-concrete masonry infill walls are widely used in the epicenter region of Wenchuan earthquake. In Dujiangyan area, some of these buildings had less, even no infill walls (or other strong and stiff lateral load resisting elements, e.g. shear walls or strong columns) in the first story to increase the parking or commercial spaces. However, such buildings had many infill walls in two orthogonal directions as partitions in the upper stories to define residential spaces. Such an arrangement of tiles infill walls created stiffness discontinuities in these buildings, which may have contributed to their collapse by concentrating the drift demands in the first story. The high in-plane stiffness of the masonry infill walls, which is developed by diagonal compression strut action, can significantly affect the response of the more flexible moment-resisting RC or steel bounding frames [7-12]. It was observed that damage to masonry infill walls was concentrated in the lower stories of buildings. Figure 4(a) shows a six-story building where the first story is parking and has less infill walls while the upper stories are residential and have many infill walls. The building leaned to the west after the Wenchuan earthquake with about 200 mm drift concentrated in first story columns, Figures 4(b) and (c).

Figure 2 Plastic hinging in columns

Figure 3 Weak-column and strong-beam

(a) Leaned 6-story building in Dujiangyan (b) Measuring column drift (c) Typical column damage

Figure 4 Formation of a soft and weak story

Figure 5(a) shows two RC frame buildings in Dujiangyan, the frontal one of the photograph is a six-story building, discussed in the previous paragraph, Figure 4, the back one is a five-story building with some infill walls in the ground floor, Figures 5(b) and (c). As mentioned before, the former building experienced about 200 mm drift in the first story, whereas the latter building exhibited shear cracks in the first story infill walls and minor damage in columns where infill walls likely played an important role in this better performance.

The first story of the building located in Yingxiu, Figure 6, collapsed during the Wenchuan earthquake, but damage of RC frame in the upper two stories with collapsed to damaged infill walls was limited. The infill walls that were made of hollow shale tiles had significant stiffness but low strength. The reconnaissance team observed that the first story had less infill walls than the upper stories. The brittle fracture of the first story masonry infill walls, prior to flexural yielding of the columns, significantly reduced the stiffness of the first story and suddenly overloaded the first story columns in shear, resulting in the observed non-ductile failure.

(a) Major damage (b) Moderate damage (c) Infill and column damages

Figure 5 Variability of building response after Wenchuan earthquake

Figure 6 Partial collapse of 3-story RC frame building with masonry infill walls in Yingxiu

Figures 7(a) and (b) show views of a five-story RC frame building in Dujiangyan where large lateral deformation in the transversal direction occurred during the Wenchuan earthquake. The first story was a commercial space and the upper stories were residential. The building was constructed with hollow shale tiles infill wall in the frames perpendicular and parallel to the sidewalk in the stories above the first story. In the first story of this building, masonry infill walls were only present in the back of the building with open front and sides. The lateral stiffness of the building was considerably larger in the direction parallel to the sidewalk compared with that perpendicular to the sidewalk, due to the different number of column. Deformation was concentrated in the first story perpendicular to the sidewalk. The first story columns in this building were severely damaged and likely close to loss of gravity load capacity. Figure 7(c) shows a collapsed apartment building adjacent to the one discussed before. The first two stories of this building collapsed, whereas damage in the upper three stories was limited.

Some commercial buildings on the side of streets were constructed with light walls in the frames perpendicular to the sidewalk to separate the space. On the other hand, masonry infill walls were present in the back face of the building with the front kept open in the first story for commercial use. Figure 8(a) shows a plan of part of the first floor where dimensions are given in mm. A typical view from the interior of a two-story commercial building is shown in Figure 8(b) where plastic hinges formed in the top and bottom of the columns in the direction parallel to the sidewalk and the collapsed infill walls are shown in Figure 8(c). The lateral stiffness of the building in the direction parallel to the sidewalk was considerably less than that perpendicular to the sidewalk. Thus, building lateral deformations were concentrated in the direction parallel to the sidewalk. The infill walls perpendicular to the sidewalk were almost always unreinforced and were not tied to frame members, so they could not deform with the frame during shaking losing the confinement from the frame and collapsing.

3.3. Damage Types of Masonry Infilled RC Frames

In general, earthquake damage of buildings can be divided into two categories: (a) structural damage and (b) nonstructural damage, both of which can be hazardous to building occupants. Typically, structural damage refers to degradation of the building's structural support systems (vertical and lateral force resisting systems), such as the building frames and walls. On the other hand, non-structural damage refers to any damage that does not affect the integrity of the structural support system. Examples of non-structural damage are a chimney collapsing, windows breaking or ceilings falling, piping damage, malfunctioning of telecommunications equipment, etc. Non-structural damage can still be life-threatening and costly. Generally, infill walls are likely regarded as non-structural element in structural analyses. Many studies (e.g. [5-10]) focused on experimental and computational investigation to understand the structural behavior and the dynamic properties of RC or steel frames containing masonry infill wall. The general conclusion is that the structural behavior and the dynamic properties of frames with infill walls are different from those without infill walls.

(a) Damaged 5-story building (b) Close-up of 1st story damage (c) Collapsed 5-story building

Figure 7 Views from two 5-story RC frame apartment buildings in Dujiangyan

(a) Partial plan view (b) Column plastic hinging (c) Collapsed infill walls

Figure 8 Views from a commercial RC frame building in Dujiangyan

Figure 9(a) to (f) show a group of photographs of infill walls in several three-story moment resisting frame buildings that were under construction during the time of the Wenchuan earthquake. All of these infill walls were constructed with hollow shale tiles, some of them had facing material or decorative surfacing. Some of the weakest hollow shale tiles suffered compression damage, and then parts of the infill wall collapsed at the time of the earthquake. However, the beams and the columns suffered mirror damage in the cases shown in Figures 9(a), (b) and (c). The lower strength and greater stiffness of the hollow shale tiles infill walls compared with the RC frames caused damage to concentrate in the former, which dissipated part of the earthquake energy and protected the RC frame. The beams and columns suffered moderate to major damage in the cases shown in Figures 9(d), (e) and (f). In all cases, infill walls suffered a combination of compression and shear damage.

Solid clay bricks were also used as infill walls in the old buildings in the epicenter region of the Wenchuan earthquake. Solid bricks have much more significant strength and elastic stiffness than the hollow shale tiles. In some case, no connection between frame and infill wall could be found. Therefore, the different lateral deformation between RC frame and the infill wall resulted in infill wall damage during the Wenchuan earthquake and damage in frame was minor, Figures 10(a) and (b). The levels of damage were similar in the bounding RC frame (particularly the columns) and the solid masonry infill wall, Figure 10(c). This was the case when the frame and infill worked in unison (due to proper connection between them) and interacted at the time of earthquake leading to simultaneous occurrence of column ductile flexural yielding and infill brittle cracking.

(a) Infill compression and shear and minor frame damages

(b) Infill shear and minor frame damages

(c) Infill compression and minor frame damages

(d) Infill compression and major frame damages

(e) Infill compression and shear and moderate frame damages

(f) Infill shear and major frame damages

Figure 9 Damages of masonry infilled RC frames after the Wenchuan earthquake

(a) Infill damage and minor damage to the RC frame

(b) Infill damage and minor damage to the RC frame

(c) Moderate damages to RC frame and infill wall

Figure 10 Effect of solid infill walls on the behavior of the bounding RC frame

3.4. Columns and Beams

Columns located between windows likely performed as short columns with high shear deformations. In this case, the height-to-length of the column without lateral confinement was less than two. Often, flexural damage was accompanied by compression and shear damages, refer to Figures 11(a) to (c) for typical short column damages after the Wenchuan earthquake. It is worth mentioning that the majority of moment-frame column failures was due to one of the following four causes (or a combination of them): (1) low strength of concrete in column; (2) excessive beam strength; (3) transverse ties are smooth bars of only 6 to 10 mm diameter; and (4) interaction between the columns and the full or partial (due to windows) masonry infill walls.

Tile infill walls contributed to the stiffness of the RC frame because of the high in-plane stiffness of the masonry infill walls, which were developed by diagonal compression strut action, indicated by N in Figure 12. Therefore, the column experienced a combination of shear and compression damage. The ductility of the column in an infilled frame decreased compared with the frame without infill wall.

(a) Windows in both sides (b) Infill in one side only (c) Partial infills in both sides

Figure 11 Short columns observed after the Wenchuan earthquake

One type of damage in RC beams that was resulted from the interaction between RC frame and the infill wall is shown in Figure 13, which is different from the usual flexural and shear damage caused by pure gravity loading. The beam was subjected to upward pressure causing flexural and shear damages. This upward pressure resulted from the infill wall under the beam which was damaged by cracking and tended to expand vertically.

(a) Photograph of infill and column damages (b) Free body diagram of the column adjacent to an infill wall

Figure 12 Diagonal compression strut caused by masonry infill wall

(a) View from outside (b) View from inside

Figure 13 Beam damage in a building on Zipingpu dam after the Wenchuan earthquake

4. CONCLUDING REMARKS

The reconnaissance team investigated many RC framed buildings with and without masonry infill walls following the Wenchuan earthquake. The paper briefly described the state-of-practice for building seismic design and construction in China. The seismic performance of RC framed buildings with and without infill walls has been presented in details, and evaluated considering the type of damage, the seismic design and construction practice in the earthquake epicenter region. Both poor construction practice and inadequate seismic design levels were the main reasons for most of the building collapses. Short columns, strong-beam and weak-column, use of inconsistent masonry walls, disregard of the effect of infill walls in design were among the main reasons for the widespread destruction in the epicenter region during the Wenchan earthquake.

ACKNOWLEDGEMENTS

The authors acknowledge the funding and logistical support provided by Office of the President and International Office, Sichuan University, Prof. and vice President Jian Shi, Prof. Shijing Yan, Prof. Ping Guan, and Prof. Jian-hui Deng, Chengdu, China, Office of International Strategy Development, University of California Office of the President, and Center for Information Technology Research in the Interest of Society, University of California, Berkeley.

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