OBSERVATIONS FROM RECENT EARTHQUAKES

In the last two decades, a large number of RC frames with URM infill walls have performed poorly during earthquakes, with some even collapsing. This e-document presents observations on damage to RC buildings with URM infill walls from four recent earthquakes: the 1999 Kocaeli (Turkey) earthquake, the 2008 Wenchuan (China) earthquake, the 2009 L'Aquila (Italy) earthquake and the 2010 Haiti earthquake. The Magnitude 7.4 Kocaeli earthquake took place on August 17, 2009 along the 1500-km-long North Anatolian fault in northwestern Turkey. The Magnitude 8.0 Wenchuan earthquake occurred on May 12, 2008 along the 480 km-long and 100 km-wide Longmenshan fault on the northwestern margin of the Sichuan basin in China. The Magnitude 6.3 L'Aquila earthquake struck the central region of Italy on April 6, 2009, near the city of L'Aquila, the capital of the Abruzzo region. The January 12, 2010 Magnitude 7.0 Haiti earthquake was centered approximately 25 km west of Port-au-Prince, the capital of Haiti.

Figure 1 below shows two buildings damaged by the Wenchuan earthquake: in both, damage is concentrated at the first story level. The building shown in Figure 1(a) is a six-story building in which the first story was used as a parking garage, with fewer infill walls than in the upper, residential stories. After the Wenchuan earthquake, the building leaned to the west, with about 200 mm of drift concentrated in the first story columns. Figure 1(b) shows a five-story RC frame building, in which the first story was used as a commercial space, while the upper stories were residential. This building was constructed using hollow shale tiles as infill walls, in the frames perpendicular and parallel to the sidewalk, in the stories above the first story. In the building's first story, URM infill walls were present only in the back: the front and sides of the building were open. The first story columns in this building were severely damaged in the earthquake and probably came close to losing their gravity load capacity, due to the combined effect of the "soft" first story and the torsional irregularity that was created by non-uniform distribution of infill walls around the building's perimeter.

(a) Six story building (b) Five story building

Figure 1. First story damage in two buildings, Wenchuan earthquake (photos by K. Mosalam)

Figure 2 contrasts the damage of the building shown in Figure 1(a) which is also the building in the front amongst the two buildings shown in Figure 2(a), with a building having more infill walls in the first story which is the building seen in the background on the bottom right in Figure 2(a). 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 the columns (Figure 2(b) and (c)). Presence of infill walls in the first story likely played an important role in this better performance.

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

Figure 2. Effect of the lack of first story infill walls on damage – Wenchuan earthquake (photos by B. Li)

Figure 3(a-f) shows infill walls in several three-story, moment resisting frame buildings that were under construction at the time of the Wenchuan earthquake. All of these infill walls were constructed using hollow shale tiles; some incorporated facing material or decorative surfacing. The interaction between URM infill walls and the surrounding frame depends upon the strength and stiffness of the infill wall relative to the bounding frame, as well as the interface between the frame and the infill wall. The lower strength and greater stiffness of hollow shale tile infill walls, compared to their RC frames, caused damage to concentrate in the infill walls, which dissipated part of the earthquake energy and thereby protected the RC frame. In the cases shown in Figure 3(a), (b) and (c), some of the weakest tiles suffered compression damage, and parts of the infill wall collapsed as a result. However, beams and columns suffered only minor damage. In the cases shown in Figure 3(e) and (f), beams and columns suffered moderate to major damage. In every instance, the infill walls suffered both compression and shear damages. Figure 3(d) shows an out-of-plane (OOP) infill wall failure (a failure mechanism characterized in the "Seismic Behavior of Infill Frames" e-document).

(a) Infill wall compression and shear damages (b) Infill wall shear damage (c) Infill wall compression damage

(d) OOP infill wall failure

(e) Infill wall compression and shear damages and moderate frame damage

(f) Infill wall shear damage and major frame damage

Figure 3. Damage to URM infilled RC frames, Wenchuan earthquake (photos by B. Li)

In addition to the relative strength and stiffness of the infill wall with respect to the bounding frame, the interface between the infill wall and the frame is another factor affecting the interaction of the two. If the infill is stiff and possesses higher strength (e.g., solid clay bricks), then it can damage the surrounding frame, as shown in Figure 4(a). However, if there is no connection between the frame and the infill wall, then the infill wall can be damaged due to its brittle behavior. In the latter instance, the frame may experience only minor damage, because the infill wall does not transfer significant force, despite having high stiffness and strength (Figure 4(b) and (c)).

(a) Moderate damage to RC frame and URM infill wall

(b) URM infill wall damage and negligible RC frame damage

(c) URM infill wall damage and minor RC frame damage

Figure 4. Frame-infill wall interaction – Wenchuan earthquake (photos by B. Li)

Figure 5 shows a five-story building, the third story of which collapsed during the 2009 L'Aquila earthquake. It can be observed that the column sizes throughout the building are small and therefore the infill walls had significant contributions to the story stiffness. In low- to medium-rise URM infilled RC buildings without vertical stiffness or strength discontinuities, first story infill walls are anticipated to be damaged first, since earthquake shaking subjects them to the highest shear forces. However, under bidirectional loading, upper-story infill walls can fail due to the combination of out of plane (OOP) and in plane (IP) effects. Infill walls of the third story of the building in Figure 5 likely failed under the OOP/IP interaction. It can also be observed that some of the fourth story infill walls also failed, while infill walls of the other (first, second, and fifth) stories remained intact. Once the infill walls failed, a "soft" third story formed. It is speculated that the presence of stronger beams relative to the columns led to the formation of hinges at both of the column ends, which led to the collapse of the third story as a result of increasing deformations.

Figure 5. Story collapse due to infill failure – L'Aquila earthquake (photos by K. Mosalam)

Figure 6 shows damage to a corner joint damage from the L'Aquila earthquake. The photos show that the upper portions of infill walls on both sides of the joint failed. These infill failures clearly affected the degree and nature of damage to the corner joint. If the infill walls had not failed, then they would have transferred additional shear forces from both building sides to the column by compression strut actions. Moreover, these additional forces on the column would have reduced the shear forces acting on the corner joint. It can be observed that the joint is poorly detailed due to the lack of sufficient transverse reinforcement. Even then, it may have been possible to reduce the earthquake damage to the joint by spreading the damage to the column had the infill walls not failed.

Figure 6. Joint failure due to infill damage – L'Aquila earthquake (photos by K. Mosalam)

As it is stated previously, for low to medium rise URM infilled RC buildings without vertical stiffness or strength discontinuities, first story infill walls are expected to be damaged first leading to the formation of weak and soft stories during ground shaking. Figures 7 and Figure 8 show two buildings, the first story of which failed in the Kocaeli and Haiti earthquakes, respectively. While the first two stories of the building in Figure 7 failed completely, damage to the upper four stories was limited (note the unbroken glass windows in those stories). Similarly, while the first story of the building in Figure 8 failed, there was no damage visible in the upper stories.

The significant stiffness of the infill walls with respect to the framing system might have played a role in these failures. The brittle fracture of the first and second story infill walls in Figure 7, or of only the first story infill walls in Figure 8, prior to columns' flexural yielding would have overloaded the non-ductile first and second story columns in Figure 7, or the first story columns in Figure 8, in shear, likely resulting in the observed gravity load failure.

Figure 7. First two stories collapsed building – Kocaeli earthquake (photos by K. Mosalam)

Figure 8. First story collapsed building – Haiti earthquake (photos by E. Fierro)

Primary Reference

Mosalam, K.M. and M.S. Günay, (2012) “Chapter 23: Seismic Analysis and Design of Masonry-Infilled Frames," in Structural and Geotechnical Engineering, S.K. Kunnath, Editor, Encyclopedia of Life support Systems (EOLSS) Publishers, Oxford, UK.

Photo References

B. Li (2008) Wenchuan earthquake, China.

E. Fierro (2010) Haiti earthquake.

K. Mosalam (1999) Kocaeli earthquake, Turkey; (2009) L’Aquila earthquake, Italy.