

The Behaviour of RC Frames with Masonry Infill in Wenchuan Earthquake

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The Wenchuan Earthquake, with a moment magnitude of 7.9 (reported by USGS), occurred in Sichuan Province in China on May 12, 2008. As of July 2, 2008 69,195 people were killed, 373,606 injured, 18,389 missing, 5 million homeless and 79,852 rescued. A team of eight researchers from Melbourne and Hong Kong, including the first-named author, visited China in late June-early July 2008 to visit the cities of Chengdu, Dujiangyang, Yingxiu and Mianyang to investigate the effect of this earthquake. A common form of construction in the affected area is that of reinforced concrete frames with masonry infill. A PhD research project is currently being undertaken at the University of Melbourne on the behaviour of this type of construction when subjected to seismic loads. This paper focuses specifically on observations made on this type of construction during the visit to Sichuan with identification of damage and of key failure modes. This will be related to the damage and failure modes observed in past earthquakes and in experimental work; hence placing the observations from the Sichuan earthquake into the context of previous reconnaissance and research.

Introduction

In late June and early July, about 50 days after the occurrence of the Wenchuan Earthquake a group of eight researchers from Australia and Hong Kong visited Sichuan province to observe the damage to infrastructure in the four cities of Chengdu, Dujiangyan, Yingxiu and Mianyang. Figure 1 shows the map of Sichuan Province, the epicentre and fault of the Wenchuan Earthquake and the cities that were visited.

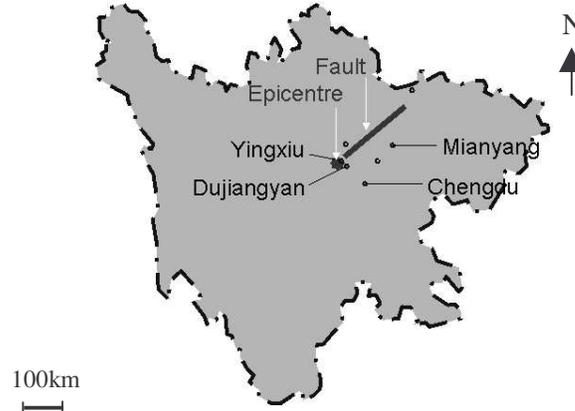


Figure 1: Map of Sichuan province (Su 2008).

The seismic characteristics and ground motion parameters of the Wenchuan Earthquake can be found elsewhere (e.g. Zifa 2008, Su 2008, Kafle et al. 2008, CSIN 2008 and USGS 2008). Table 1 shows the intensity of the ground motion at the four cities visited.

Table 1: The Wenchuan Earthquake intensity at different cities (Kafle et al. 2008)

City	Intensity (MMI)	Distance from the epicentre (km)	Distance from the fault (km)
Chengdu	VI- VII	80	80
Mianyang	VII	145	60
Dujiangyan	VII-IX	20	20
Yingxiu	XI	≈ 0	≈ 0

Generally, the buildings in Chengdu were intact. Some minor damage, mostly in the form of cracks in the veneer and/or plaster could be observed. In Mianyang, crushing in the veneer tiles or masonry walls (and/or panels) could be observed along with a few examples of building collapse. In Dujiangyan, building collapse could be observed in all parts of the city, however, the city was in full operation at the time of visit. The city of Yingxiu was heavily damaged and the emergency services still had a presence in the city.

One of the common forms of construction observed in all four cities was RC ties and RC frames with masonry infill panels. These include a range of 5-storey to high-rise buildings. According to information gathered from local engineers, it is a common practice in the region to construct a relatively substantial one-storey RC frame (with/without infill panels) at the ground level and build the upper storeys, up to 5 storeys, from masonry materials in the form of walls restrained by vertical and horizontal RC ties that are effective axially but not flexurally stiff. The ties are square RC elements (generally with the same thickness as the wall) that have a small longitudinal bar in each corner.

A comprehensive report on the general damage observed can be found in Kafle et al. 2008. Within the following sections, the damage to the RC frames and/or ties with masonry panels has been singled out and discussed in more detail.

Damage to the infill-frames

The behaviour of infill-frames under lateral loads has been studied since the 1950s. The structural interaction between the infill and frame leading to a variety of modes of failure has been investigated by several researchers including Mehrabi 1994, Angel 1994 and Crisafulli 1997. Although some seismic design codes consider the interaction between the infill and frame (Hemant et al. 2006, FEMA 306), in actual design practice such structural interaction is usually ignored. The damage to the buildings after the Wenchuan earthquake can be partly attributed to such ignorance in design and partly to the low quality of construction that is discussed in this section.

One of the most common types of damage to the mid-rise buildings was a “soft-storey” effect. Generally, soft-storey buildings experienced plastic hinges at the ends of the columns (at the soft-storey level) including buckling of the longitudinal reinforcing bars, crushing/spalling of the concrete core and cover and excessive yielding of stirrups. The masonry panels were mostly intact or lightly-damaged on other levels (Kafle et al. 2008). The soft-storey effect has been extensively studied in previous research (e.g. Rodsin et al. 2004 and Wilson et al. 2005). The damage in the buildings with a bare frame at one (first) storey and infill-frames at other (upper) storeys concentrates mainly at the storey where the frame is not filled (strengthened) with infill panels. This potential soft-storey mechanism needs to be recognised in the design to ensure that it cannot occur. Some examples of plastic hinges in soft-storey buildings are shown in Figure 2.



Figure 2: Examples of plastic hinges at the level of soft-storey in Dujiangyan

Figure 3 shows an example of a building with a soft storey at the second storey. This building is an example of an RC frame with infill panels at the first storey and RC ties with infill panels at upper storeys. Since the arrangement of the infill panels is similar at all storeys, the second storey (with RC ties) will be weaker than the first storey (with RC frame). Figure 3c shows the x-pattern crack in the masonry infill at the soft storey level which resulted in separation between the masonry units and mortar and crushing of the masonry material (the horizontal crack is not caused by the earthquake; electric cables, considered as valuable materials, were pulled out after the earthquake). Figure 3d shows diagonal cracks in the infill panel at the third storey (above the soft-storey) along the soft-storey direction. The damage at this level is substantially less than that of the soft-storey.

Figures 4a and 4b show two perpendicular infill panels at the ground level of a building with an RC frame. In both cases the infill experienced tension (diagonal) cracks and masonry crushing at upper corner. The column at the corner detached from the beam as

the result of insufficient reinforcement overlap. Figure 4c shows another infill panel with the same mode of failure where the masonry crushing at the corner is more severe. In Figures 4a and 4c the separation between the infill panel and frame can be observed indicating the relative residual displacements between the infill and frame.

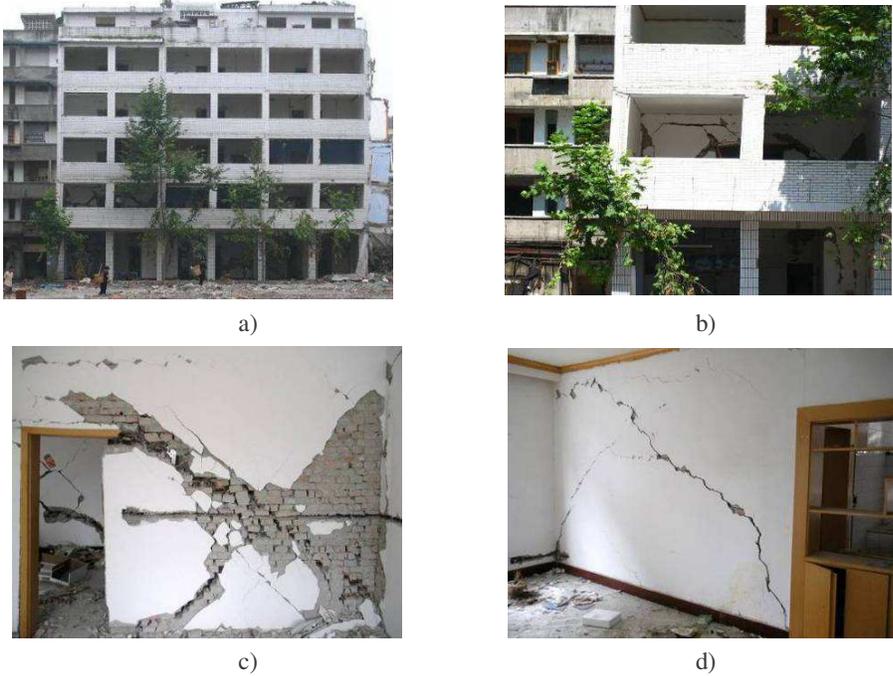


Figure 3: An example of a soft-story building in Dujiangyan.

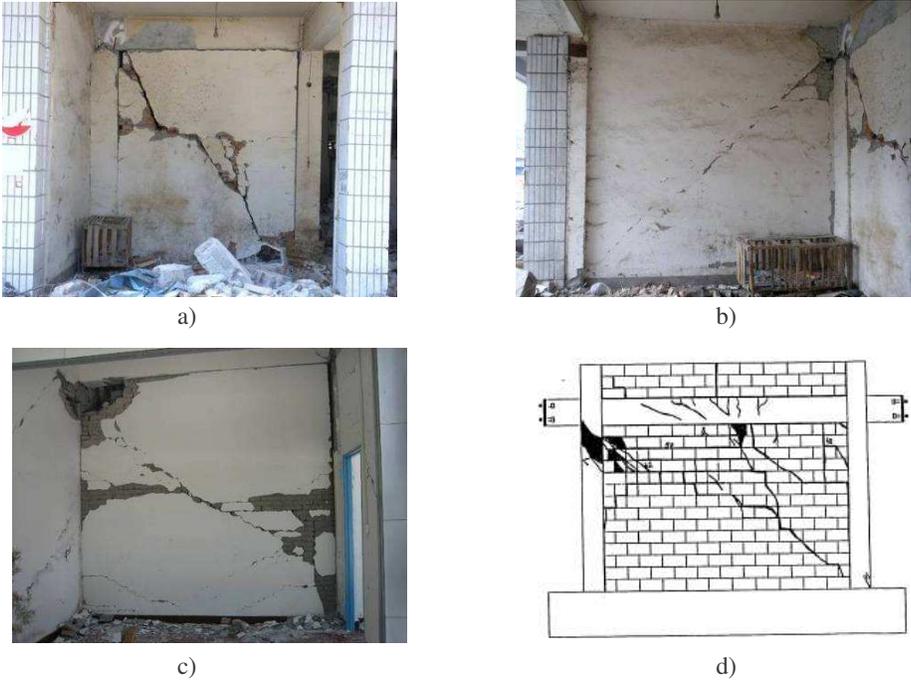


Figure 4: Different failure patterns in masonry infill panels in Dujiangyan.

It is to be noted that in the case of Figure 4a, where the panel is in the direction of the strong component of the earthquake, the diagonal crack spread through both the mortar

and bricks accompanied by the bed-joint crack in the mid-height, whereas in Figure 4b the diagonal crack was mainly in the plaster. The patterns of failure shown in Figures 4a and 4c are similar to what was observed by Mehrabi (1994) when a non-ductile (weak) RC frame with solid masonry units was tested (Figure 4d). Figure 5 shows how the structural behaviour of a bare frame is different from an infill-frame. The corner crushing of the masonry shows that the strut action completely developed in the infill-frame and the compressive stress in the masonry exceeded the ultimate strength of the material. The strut action in the infill-frame has been extensively studied (e.g. Mehrabi 1994, Crisafulli et al. 2000 and FEMA 306).

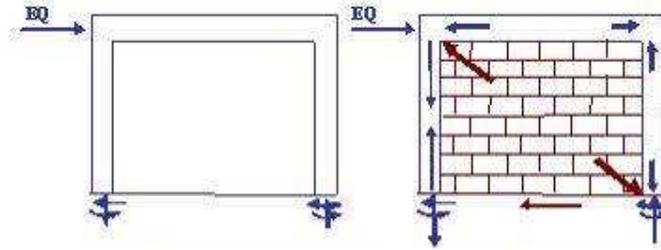


Figure 5: Comparison between the actions in a bare-frame and infill-frame.

Another example of a damaged RC structure with masonry infill is shown in Figure 6. The x-pattern (tensile) cracking of the masonry resulted in shear cracks in the top and bottom of the column as can be seen in Figure 6b. The collapse of the masonry infill is due to a combination of out-of-plane instability and in-plane degradation. It can be seen in panels along two perpendicular directions. Some other cases of out-of-plane failure of infill panels were observed. In addition to the one shown in Figure 6c, two other examples of such failures are shown in Figures 7a and 8. In all these cases the beams have long spans and there is not sufficient contact between the frame and infill to develop the arching effect in the infill which is important in providing the out-of-plane stability of the infill panel (Angel 1994). Such separations between the frame and infill may be as the result of panel shrinkage, constructional issues or in-plane loads and deformations as shown in Figure 6d (Paulay et al. 1992).

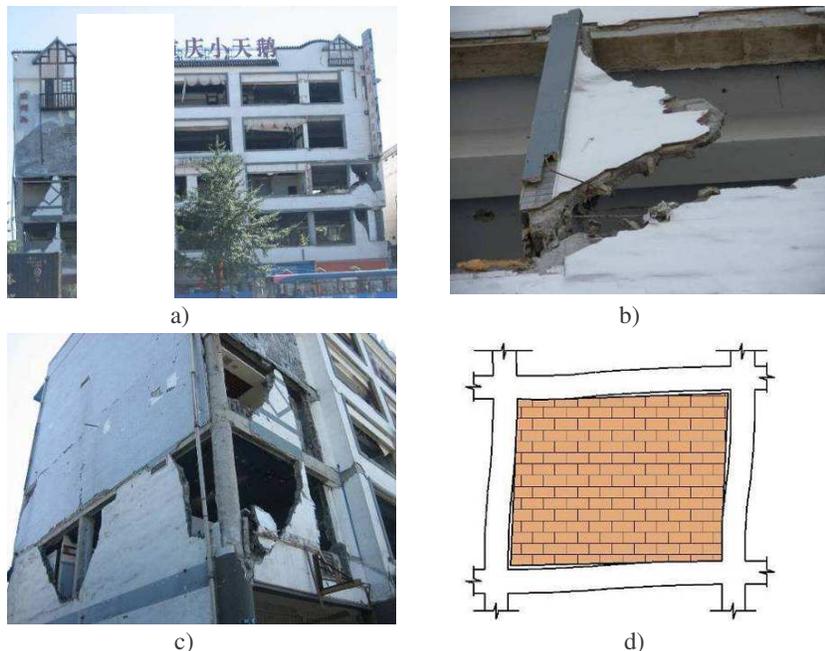


Figure 6: An example of a damaged RC structure with masonry infill in Dujiangyan.

Based on the results of tests on masonry walls in two-way bending (for which the behaviour can be similar to infill panels) conducted by Griffith et al. (2007), it can be seen that masonry walls can exhibit substantial out-of-plane displacement capacity and hence more ductile behaviour than is conventionally expected. It is shown that the maximum out-of-plane displacement for the walls reaches approximately the wall thickness. Figures 8 and 9 show examples of good out-of-plane stability of an infill panel in soft-storey buildings. Figure 8 shows how the lack of connectivity between the beam and infill has resulted in arching effect which is mostly developed horizontally between the columns only.

In Figures 7b, 7c and 7d, corner crushing of the masonry is shown which is an in-plane mode of failure and implies that a centric strut action developed well in the infill-frame. However, the damage to a limited length of the column on top which is in the form of concrete cover spalling and x-pattern cracks (shown in Figure 7b) indicates that the centric strut action changed into an eccentric strut action after crushing of the masonry at the corner of the panel. This resulted in a short column effect which is more common in the frames with partial infill panels in which the frame is not completely filled with the masonry. This effect is depicted in Figure 7e.

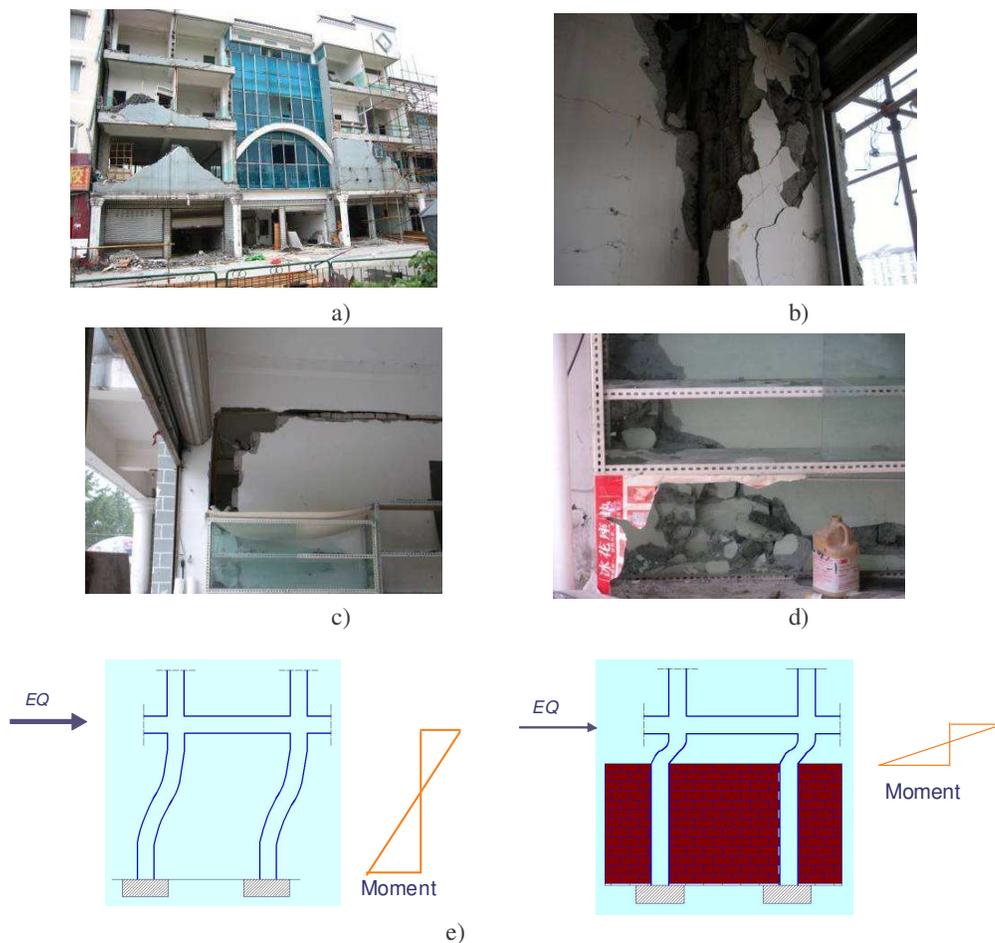


Figure 7: An example of different damage types in an RC frame with masonry infill in Dujiangyan.



Figure 8: Soft-storey building in Yingxiu and the separation between the infill and frame.

Figure 10 shows a good example of the difference between the behaviour of bare- and infill-frames under gravity and seismic loads. As shown, every other frame is filled with masonry except the two adjacent bare frames at one end of the building. All of the columns in the bare frames at the ground level experienced plastic hinges at top and bottom, whereas columns of the frames with infill were relatively undamaged. The formation of plastic hinges at the ends of the columns in the bare frames resulted in spalling and crushing of the concrete and hence the reduction in the axial capacity of the columns. Following on from this, there was a large vertical displacement that occurred at the top of the two adjacent bare frames.



Figure 9: Out-of-plane stability of the infill-panel in a soft-storey building in Dujiangyan.



Figure 10: The effect of infill panels on the structural behaviour under the combination of gravity and lateral loads in a 9-bay frame in Dujiangyan including 7 transverse infill-frames and 2 bare-frames.

It is to be noted that regardless of the mode of failure and structural system of a building, in some cases in Dujiangyan, intact and totally-collapsed buildings were less than 10 meters apart. This can possibly be attributed to the differences in the design and construction detailing, the configuration of the structure and differences in live loads. As shown in Figure 11, inadequate stirrup spacing, inappropriate aggregate size in concrete, insufficient length of reinforcing-bars anchorage/overlap, low quality of workmanship in the masonry infill panels and using different types of masonry units in a panel are of such examples of low quality of construction. Moreover, in some areas of Dujiangyan, a certain type of 6-storey residential apartment with RC ties with masonry infill was consistently damaged and/or suffered complete collapse. Based on the information gathered from the local people, the construction drawings approved by the city council

for these apartments were 4-storey and it has been during the construction that two extra floors were added to the buildings by the contractors without the council approval.

Closing remarks

Masonry infill panels in RC frames and ties have been widely used as a structural system in the four cities of Chengdu, Dujiangyan, Yingxiu and Mianyang. The damage to such structures after the Wenchuan Earthquake has been reported and various types of damage have been discussed here. In Yingxiu and Dujiangyan and in some cases in Mianyang, some buildings had collapsed totally. In the remaining buildings, the different patterns of damage can be categorised as follows:

- a) Damage to the masonry part of the infill frames:
- Cracks in/spalling of plaster and veneer tiles, (A)¹ (recognized as minor damage although could be dangerous in the form of falling debris);
 - Masonry crushing as the result of strut-action, (D, Y);
 - Masonry shear (bed-joint) and tensile (diagonal) cracks (D, Y);
 - Separation between the masonry infill and the frame (D, Y);
 - Masonry out-of-plane collapse in the frames with long spans (D, Y).



Figure 11: Examples of masonry units, masonry construction and concrete quality.

- b) RC components:
- Crushing of the concrete core in RC columns/ties (D, Y);
 - Spalling of the concrete cover in RC frame members (mostly columns) (D, Y);
 - Buckling of longitudinal reinforcing bars in soft-storey buildings as the result of inadequate stirrup spacing (D);
 - Shear cracks/failure of RC columns and beams in soft-storey buildings (D, Y);
 - Flexural failure of beams/slabs (D, Y);
 - Non-uniform settlement of columns as a result of non-uniform arrangement of masonry infill panels (D);
 - Short column effect (D).

¹ A, C, D, M and Y: damage observed in ALL four cities, Chengdu, Dujiangyan, Mianyang and Yingxiu respectively.

The damage to buildings is mainly attributed to low quality of construction, improper design and the severity of the ground motion. It was observed that in some cases the structural interaction between the frame and infill improved the seismic behaviour of the integrated infill-frame structure relative to the poorly-detailed frame acting alone. The modes of failure observed in different infill-frames were similar to those observed by researchers in their experimental studies. Although with proper application of current structural/earthquake engineering knowledge in design and construction the damage to buildings can be reduced, there is clearly a need for practical design procedures that consider the structural interaction between the infill panels and frame members.

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