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# Lessons learned from damage of the owner-built RC frames in the 2015 Nepal earthquakes

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## *Abstract*

The 2015 $M_w$-7.8 Nepal Earthquake and its aftershocks caused great loss of lives and severe damage to buildings. A team of 22 professors from China Earthquake Administration was sent for an extensive field investigation on the damage of buildings and lifelines. As part of the research efforts, the study presents the observation results and quantitative analyses on damage of the own-built reinforced concrete (RC) frame structures, which are widely adopted in the urban or sub-urban areas throughout Nepal. The frames are constructed of slender RC columns, RC beams and masonry infill walls, and exhibited much better seismic performance than most of other types of buildings, such as the stone, soil, masonry or wooden buildings. However, a lot of owner-built RC frames were still severely damaged or even collapsed. Lessons must be learned from the damaged buildings for facing the future earthquakes. First, beside RC frames, traditional structural systems with a good integrity was examined and introduced. Second, Typical structural features of the Nepal owner-built RC frames are demonstrated. Third, a few collapsed or severely damaged RC frames are selected for a detailed analysis, and factors that caused severe damage are summarized based on a quantitative field investigation. The results show that the key reasons that may cause the collapse of these buildings include slope sites, failure of foundation, pounding of neighboring buildings, and damage accumulation of earthquake series. Proposals for the improvement of design and constructions are presented.

*Keywords: RC frame, Nepal earthquake, field investigation, RC frame, damage mechanism*

## 1. Introduction

2015 $M_w$7.8 Gorkha earthquake and its strong aftershocks caused extensive damage to Nepal and its adjacent countries with great loss of lives, a lot of collapsed buildings including historical buildings, extensive landslides and many blocked roads. The epicenter, time and magnitude of the major earthquakes are shown in Fig.1. Five aftershocks with a magnitude over 6.0 occurred within twenty days after the main shock, and the most devastating aftershock was $M_w$7.3 aftershock on May 12. These earthquakes occurred along the major fault line where the Indian Plate is diving underneath the Eurasian Plate.

A team of twenty-two professors and researchers was set up by China Earthquake Administration, and sent to Nepal for a comprehensive field survey forty days after the main shock [1]. There were generally two objectives: (1) to evaluate seismic damage and economic loss for better proposals on reconstruction assistance; (2) to learn lessons from the effects of the earthquakes for minimizing future disasters. The survey last for fifteen days and the investigated contents include buildings, lifelines, geological hazards, shelters and reconstruction plans. Fig.1 shows the investigated districts that are indicated by grey color. These districts are close to the epicenter regions and the country boundary between China and Nepal.

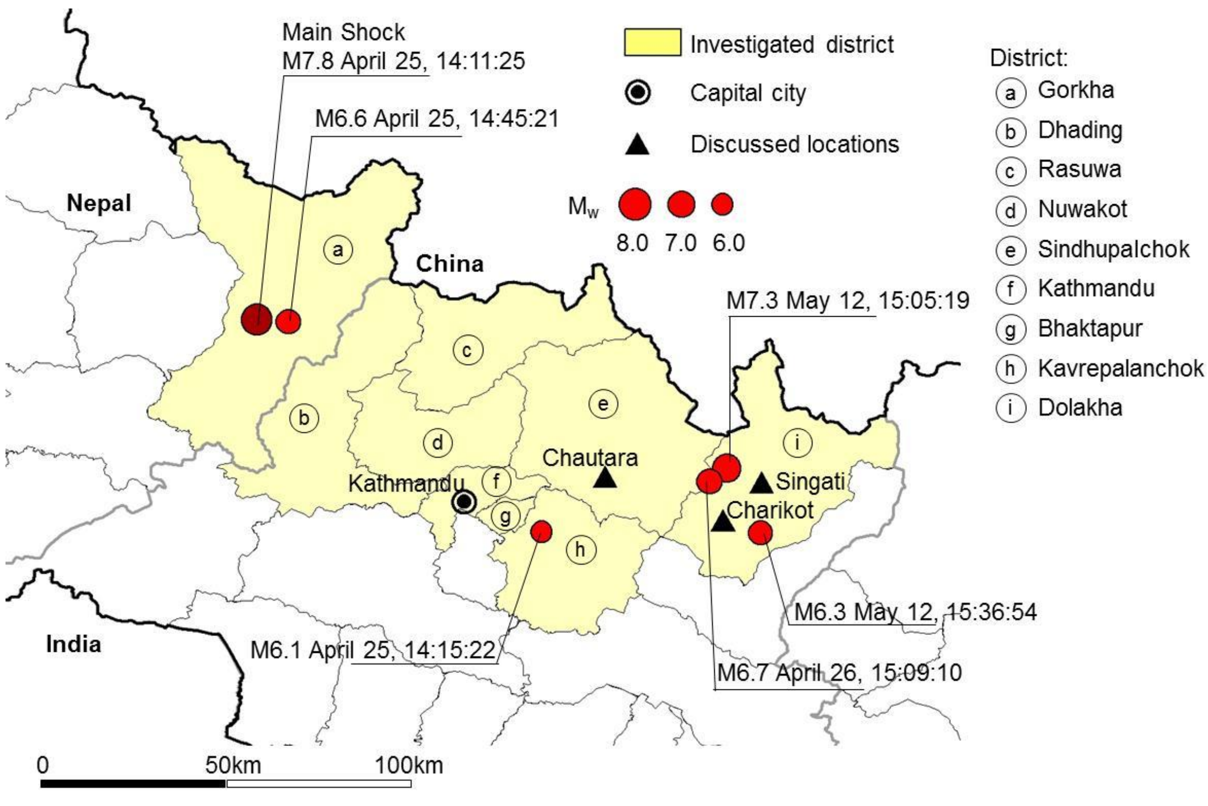


Fig. 1 – Earthquake sequence and investigated districts

As reported, the earthquake killed nearly 9000 people, and injured three times as many in Nepal and its adjacent countries, such as China, India and Bangladesh. The casualty was primarily due to the collapsed buildings, most of which were not well engineered. A detailed examination was conducted on the damage of buildings, particularly for the owner-built RC frames. The owner-built RC frames in Nepal have a few special features that are worth further studying. First, although the RC frame exhibited significantly better integrity and seismic performance than other owner-built buildings, such as unreinforced masonry buildings, random rubble masonry buildings, adobe buildings strengthened with timber floors and roofs [2], severe damage of RC frames were observed in Chautara Municipality, Charikot Municipality and Singati, as indicated in Fig.1. Second, they are usually built with a few common construction conventions based on the experience of local workers, and are widely used in the urban and sub-urban areas. Third, compared with the regularly designed RC frames, the owner-built RC frames [3] might present different seismic behavior with small component sections, simple connection details and poor construction quality. In this study, a quantitative investigation on the severely damage owner-built RC frames in Chautara and Charikot are performed and lessons for improving the owner-building buildings are presented.

## 2. Overview of the damaged buildings

Before the 2015 Nepal earthquakes, researchers [3, 4] had investigated the seismic performance of the RC frames in Nepal, and stated that the owner-built RC frames were deemed to have insufficient strength, limited duration, lack of ductile detailing and poor construction. It is observed from the field investigation that the owner-built RC frames usually presented significantly better seismic performance than other types of structures. As an illustration, Fig. 2 shows an overview of the buildings along the main street in Jalbrie, which is a village in Sindhupalchok. The RC frames in the photos are indicated by arrows. The RC frames survived and presented minor damage, while other buildings, which are constructed of brick, stone, adobe or wood, were all severely damaged or collapsed. These severe damaged buildings are not engineered, generally lack of integrity and connection detailing against seismic loads, and are widely used in the rural area. It might be most effective way of mitigating the earthquake disaster to improve the performance of the RC frame by learning lessons from the damaged RC frames, and to promote the structural system by keeping its traditional simple form.


Fig. 2 – Difference of damage degree between various types of structures (at Jalbire, a village in Sindhupalchok)

In the field investigation, the authors tried to give more attentions to the well survived non-engineered buildings in the vicinity of many collapsed buildings. Besides the RC frames, another type of structure that was not engineered at all was also found relatively effective for collapse prevention. Fig. 3(a) shows the global view of the entire building and Fig. 3(b) shows the local details inside this building. This is also one of the traditional type of buildings with a few special features: (1) wood is used extensively to form the frame the buildings, including roof system, floor system and columns; (2) The walls are constructed of stone and soil, and strengthened by wood members; (3) According to the quantitative investigation, the story height of the building is about 2.0 meters, and the span of wood beam is also about 2.0 meters or less, which are quite small. Note that the masonry pattern shown on the wall is not real masonry but painted decoration lines on the surface. Compared with the collapsed random rubble masonry buildings and adobe buildings, this structural system present a better integrity, and might be of some value for further study to build economic earthquake-resistant rural resident buildings.


(a) (b)

Fig. 3 – Wood strengthened stone-soil structure (at Pangdang, a villige in Sindhupalchok District)

## 3. Quantitatively investigation on the failure of RC frames

The owner-built RC frames are widely used in the urban or sub-urban areas. The damage to these buildings was limited in most of the investigated districts. In order to extend our understanding on the failure mechanism of the structural system, more attentions were paid to the severely damaged or collapsed RC buildings, many of which were found in Chautara Municipality, Charikot Municipality and Singati. There might be a few reasons for the phenomenon. First, these locations are close to the damageable strong aftershocks, as shown in Fig. 1 and full of RC frames, as shown in Fig. 4. Second, the municipalities are built on a slope, where the behavior of the RC structures is more complicated and construction quality is more difficult to control. Discussions on the failure mechanism of the RC frames are made as follows based on the field quantitative investigation.

Fig. 4 – Full of owner-built RC frame in the Charikot Municipality

### 3.1 About the dimension details of the structures

According to the on-site measurements, the dimensions of the owner-built RC frames in Nepal are quite special compared to the conventional RC frames, which are designed by the code. The story number usually ranges from two to six, and sometimes can even reach eight. The story height generally ranges from 2.4 to 3.0m, and the larger span of a frame from 2.8 to 4.0m, which indicate that the spans and heights are usually much smaller than the conventional frame. The size of member section are also quite small, e.g., a typical size of beam section is 240 x 340 mm (width x depth), and a typical side length of column ranges from 230 to 300 mm. The reduced size of frame and its members makes the building more economical, although a case study by the reference [4] shows that such frames may present large deformation responses than the structure designed by Nepal Building Code (NBC).

### 3.2 Collapse mechanism and discussions

A lot of RC frames are built on a sloping site in Charikot and Chautara. The slope effects would induce more collapse risk of the buildings. According to the investigation, RC frame buildings are more likely to have two potential weak stories. Taking the building in Fig. 5 as an example, the two weak stories are indicated by Location A and Location B. The bottom story where B is located is likely to become a weak story, because the lateral stiffness has a sharp change from the foundation to the bottom floor. Location A is also a critical location to collapse due to the significant stiffness change due to the enhancement of the street ground to the bottom story. For the case in Fig. 5, Collapse initiated from location A because of lack of infill walls at the story facing to the street. The collapse was finally caused by the failure of columns at the weak stories, which indicate the slab composite effects are very strong, and the design to realize "strong column, weak beam" seems quite difficult to achieve.

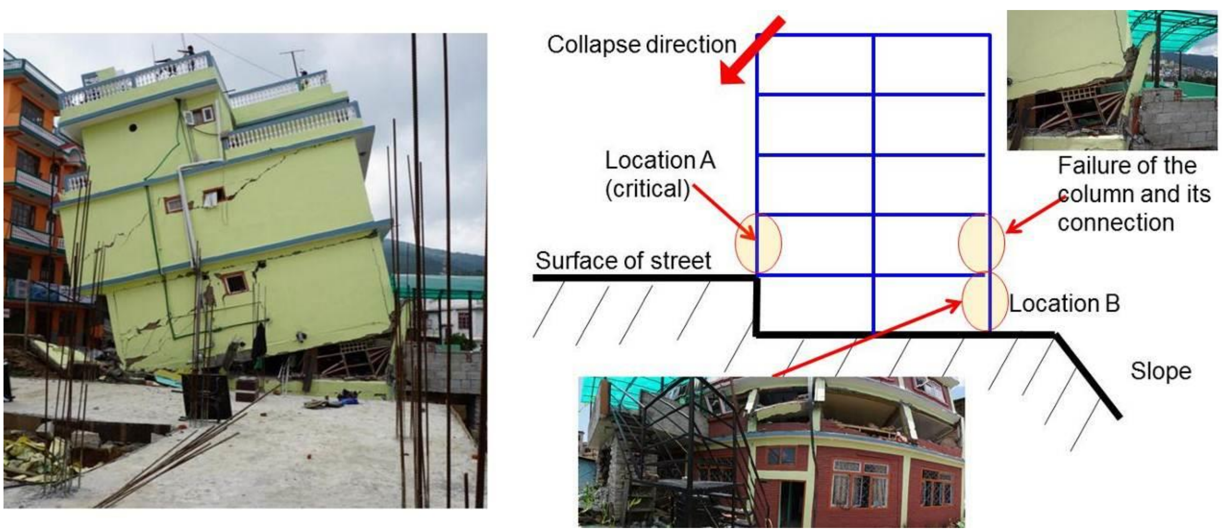


Fig. 5 – Building collapse due to slope effects (in Charikot)

Fig. 6 shows another two collapsed buildings. Failure initiated from the ground floor or foundation (similar to Location B in Fig. 5) rather than from the upper story that faces to the street. Hence, either of the buildings inclined to the downhill direction. The sloping site effects sometimes are combined with the failure of foundation. The building in Fig. 6(a) had no basement, and was inclined due to the failure of downhill side column bases and their foundations. The building in Fig. 6(b) collapsed due to the weakness of downhill side columns, as the location B in Fig. 5. As the street-side columns at the bottom story were restrained by the retaining walls, the bottom story is not likely to vibrate into the street side.


(a) (b)

Fig.6 – Building collapse to the downhill direction (in Chautara): (a) collapse with the failure of foundation; (b) failure of the gound column on the downhill site.

Poundings of different types between adjacent buildings were widely observed in the field investigation. Fig. 7 shows three types of poundings between four buildings, which triggered a different failure mode for each of the buildings. Buildings A and B originally touched each other before the earthquakes. After the earthquakes on May 12, Building A exhibited minor damage at the infill walls of the first story, while Building B collapsed due to a complete failure at the first story, as shown in Fig. 8(a). Building B was originally 1.0 m away from its neighbor Building C. The lateral deformation of Building B and C was too large to avoid the pounding between them. In the end, they crashed each other at the top stories, which triggered a global collapse of building C, as shown in Fig. 8(b).

It is pointed that building C was at very high risk to suffer a global failure. As shown in Fig. 7, building C had five stories with a total height of 14 m, but only had total width of 4.0 m, which was quite narrow. Unfortunately, the building was also located at the edge of a 2.0-meter-high platform. Furthermore, as building C fell down from the platform, the column at the top of building C crashed into the second floor of the building D, and penetrated its infill walls, as shown in Fig. 9.

It is can be concluded from the systematic collisions between the neighboring buildings that the distance between the adjacent buildings is one of the key parameters related with the failure mode. Seen from the case in Fig. 7, the interval between two buildings should be either small enough to work together or large enough to avoid collision. Also seen from Fig. 7, slope sites or weak neighboring buildings can also increase the pounding risk. Flexible connections or materials (like wood or rubber) can be used between the buildings with a high risk of severe collision, like the case between Buildings B and C.

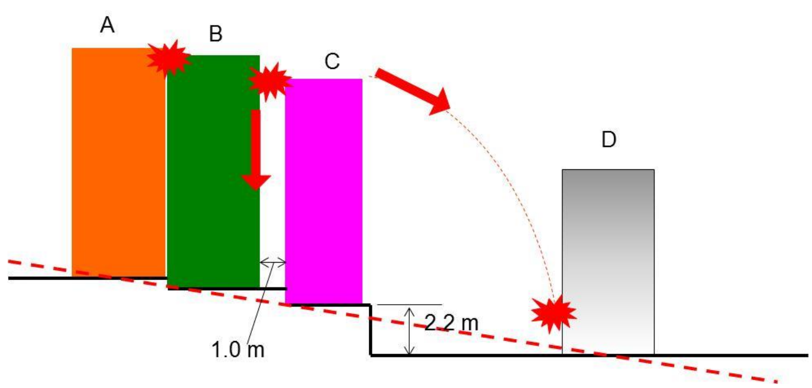


Fig.7 – Collisions between four buildings


(a) (b)

Fig.8 – Interaction between the buildings: (a) Buildings A and B; (b) Buildings B and C

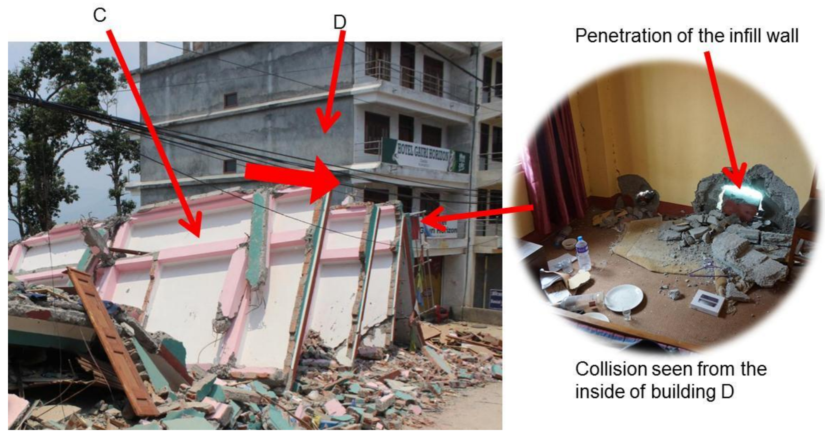


Fig.9 –Interaction between Buildings C and D

A few very strong aftershocks occurred after the main shock, and most of the structural collapses of RC frames occurred in the May-12 aftershocks, so it is evident that the collapse of buildings would be related to some extent with the damage accumulation under the earthquake sequence. One of the examples is the five-story RC frame in Chautara, as shown in Fig. 10. The building was severely damaged with a large residual drift at the first story after the main shock, but did not collapse at all. When the strong aftershock on May 12 occurred, the first story of the building was destroyed completely, and collapsed to the ground with a vertical displacement of about -2.0 m. It is quite difficult to quantify which was more fatal, the effects of damage accumulation or the strong motion on May 12. In either Chautara or Charikot, most collapsed RC frames were observed in the aftershocks. Although most of the owner-built RC frames were not designed by the code, a lesson is learned from the phenomena that more considerations are required for the seismic design on how to face the damageable strong aftershocks.

## 4. Summary and conclusion

Trying to learn lessons from the 2015 Nepal earthquake, more attentions are paid in the field investigation to the traditional buildings with a good integrity and RC frames with severe damage. With respect to the traditional buildings, a type of wood strengthened stone masonry building system, which presents relatively good seismic performance, is introduced. Compared with other traditional owner-built buildings, the RC frames survived and presented relative minor damage. Typical failure patterns of the owner-built RC frames in Chautara and Charikot are performed and lessons on slope sites, failure of foundation, pounding of neighboring buildings, and damage accumulation of earthquake series are summarized.

Beside the poor construction quality and inappropriate detailing, slope sites effect and pounding between adjacent buildings and weak foundation are also important reasons to cause severe damage or even collapse to the owner-built RC frames. Two potential weak locations of the RC frames with the slope site effect are investigated and demonstrated with the real cases. The distance between the adjacent buildings is one of the key parameters related with the failure mode, and slope sites or weak neighboring buildings can further raise the pounding risk. Flexible connections or materials (like wood or rubber) are proposed between the buildings with a high risk of severe collision.

Numerical simulation is under way based on the investigation data to address the following three issues, the slope site effects, pounding effects and damage accumulation of the earthquake sequence.


(a) (b)

Fig. 10 – Collapse related with the cumulative damage of the earthquake sequence: (a) states after April 25 earthquakes (photo from the building owner); (b) states after May 12 earthquakes (in Chautara)

## 5. Acknowledgements

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