LESSONS LEARNED FROM PERFORMANCE OF BUILDINGS DURING THE SEPTEMBER 18, 2011 EARTHQUAKE IN NEPAL

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ABSTRACT

The September 18, 2011 earthquake that occurred near the Nepal-Sikkim border had a moment magnitude (Mw) of 6.9. This shallow-focus earthquake lasted for about 30-40 seconds and affected several areas of Nepal, India, China, Bhutan, and Bangladesh. This paper presents lessons learned from the investigation of the performance of buildings in the earthquake affected areas in Nepal. Many non-engineered stone masonry, brick masonry, and reinforced concrete buildings suffered heavy damage, while engineered reinforced concrete buildings and buildings constructed with indigenous technology locally known as Centibera buildings, exhibited minor or no damage.

Keywords: Brick masonry; centibera; earthquake; Nepal; pounding; stone masonry.

1. INTRODUCTION

A moment magnitude (Mw) of 6.9 earthquake occurred in east Nepal near the Nepal-Sikkim border on September 18, 2011 at 18:25 local time. The epicenter (27.72°N, 88.06°E) of the earthquake was 272 km east of Kathmandu; the focal depth was 19.7 km. A peak ground acceleration (PGA) of 0.2g was recorded during the earthquake at a station in Siliguri, India [1]. Several areas of Nepal, India, Bhutan, Bangladesh, and China were subjected to strong shaking during the earthquake and widespread damage have been reported. Fatalities due to the earthquake were India-94 China (Tibet)-7, Nepal-6, Bhutan-1 [2]. The shaking was felt throughout eastern Nepal and some parts of central Nepal including the capital city Kathmandu. The Modified Mercalli Intensity (MMI) was VI in the towns of Taplejung and Phidim in eastern Nepal, V in Kathmandu and IV in Bhaktapur. In Nepal, the earthquake displaced 12,301 persons of 4,851 families, while 6,435 houses were damaged, 11,520 houses were partially damaged, and 3,024 houses suffered only minor damage. In Ilam District alone, the earthquake led to the complete damage of 2,141 houses and partial damage of 4,115 houses.
A reconnaissance survey was carried out from October 12 to October 19, 2011 by a joint team from Tokyo Institute of Technology, Japan and Institute of Engineering, Pulchowk Campus, Nepal to assess the extent and nature of damage caused by the earthquake in Nepal. Thorough investigations were carried out in the severely affected densely populated towns viz. Bhaktapur, Ilam, Phidim (Panchthar District), and Taplejung (Figure 1). The damage information of remote villages with widely dispersed houses in the affected region was collected from the local authorities and organizations. This paper presents a comprehensive overview of the performance of buildings in the earthquake-affected areas. Damage in Sikkim, India have already been reported in [2] and [3] however, the investigation of the damage in Nepal has not been reported yet. In this paper lessons learnt from the investigation of the performance of buildings in earthquake affected areas in Nepal are reported.
2. EXPERIMENTAL PROGRAM

Nepal is a country with a diverse geographical setting varying from low lands in the southern part, to high mountains including the world’s highest peak Mount Everest (el. 8,848 m) in the north. One third of the Himalayan arc, which marks an active plate boundary between the Indian and Eurasian plates, lies in northern Nepal and is a source of major seismicity in the area (Figure 2). The presence of numerous active faults in Nepal shown in Figure 3, clearly highlights the seismic hazard in this Himalayan nation [4].

In the past, Nepal has experienced only two devastating earthquakes in the last century. A magnitude 8.1 earthquake occurred in January 1934, with epicenter (26.50°N, 86.50°E) close to Nepal-India border region [5]. The Kathmandu Valley experienced intensities of IX-X in the MMI scale. A total of 8,519 persons were reported dead in Nepal, out of which 4,296 persons died in Kathmandu alone [6]. A magnitude 6.8 earthquake occurred in August 1988, with epicenter (26.755°N, 86.616°E) in eastern Nepal [5]. The MMI estimated in Kathmandu was VII-VIII and at least 721 people lost their lives in Nepal due to this earthquake [7].

Figure 3. Active faults in and around Nepal Himalaya [4]

Figure 4. Seismic hazard map of Nepal showing bedrock peak ground horizontal acceleration contours in gals for 500 years return period (National Seismological Center, Nepal, 2011)

The Seismic hazard map produced by the National Seismological Center of Nepal shows the design-level PGA of near the epicentral region of the September 18, 2011 earthquake.
3. DAMAGE TO NON-ENGINEERED BUILDINGS

Buildings that are constructed using traditional and indigenous techniques, without any or little involvement of qualified architects and engineers, can be considered as non-engineered buildings [8]. The traditional and indigenous techniques are inspired by the observation of buildings during past earthquakes and engineering judgment. Depending on the use of materials and construction technology, non-engineered buildings can be divided into two categories. The non-engineered buildings constructed using locally available materials, following local tradition and culture and requiring skillful craftsmanship of traditional technology, are designated as first category. Load bearing masonry wall buildings, stud-wall and brick-nogged constructions in wood are typical examples of the first category of non-engineered buildings. The second category of the non-engineered buildings refers to urban type masonry construction or a traditional look construction which does not use local materials and does not adopt traditional craftsmanship. Composite construction using combinations of load bearing walls and piers in masonry, reinforced concrete, steel or wood, are examples of the second category of non-engineered buildings. During the field survey, the damage to both categories of non-engineered buildings were observed and are explained below.

3.1 Traditional stone masonry buildings

Traditional stone masonry buildings are mainly constructed of random rubble stone masonry, in which rough stones are piled up without any mortar or with mud mortar. Such buildings are constructed based on traditional techniques using locally available material and labor. Stone masonry buildings are common in most of the villages in Nepal, due to easy availability of construction material and associated low cost. Seismic forces are ignored while constructing these buildings. The stone masonry buildings are characterized by heavy mass, very low strength compared to the mass density and brittle nature of failure. The absence of reinforcements and poor quality of mud mortar or no mortar, leads to buildings that fail in brittle manner, without allowing for energy dissipation and providing no warning to the occupants before collapse during seismic events.

One or two storied stone masonry buildings are very common in Ilam, Panchthar and Taplejung districts, were closer to the epicenter of the earthquake (Figure 1). Typical wall thickness of stone masonry was 450 mm. Although the walls were thick, almost all of the stone masonry buildings, which were surveyed, suffered damage ranging from several cracks to complete collapse. Some of the stone masonry buildings contained timber frames, however, due to their smaller sizes and poor connections, the presence of timber frames could not contribute effectively to control the damage to the buildings. During the survey, it was observed that low quality of construction, presence of unsupported long slender walls, large openings in walls and improper connection of walls at the corners, were the main reasons that caused damage to the buildings. An example of the severe damage observed during the survey is shown in Figure 5, where a school building in Ilam had completely collapsed. The low quality of mortar and absence of supporting walls to the long stone wall resulted in the collapse of another school building at Cheplung, Panchthar district (Figure 6). The large openings provided in the walls drastically reduced the stiffness of the school
building and led to the complete destruction of the building in Taplejung (Figure 7). Examples of poor connection between the walls at the corners of the buildings are shown in Figures 8 and 9. One of the problems in the traditional construction technology of stone buildings, is the improper connection between the stones at the inner and outer layer of the wall. No proper interlocking is provided between these two layers and this usually leads to the delamination and bulging of the walls as shown in Figure 10.

Figure 5. Rubble of the collapsed building in a village school building in Ilam

Figure 6. Collapse of school building at Cheplung Panchthar District

Figure 7. Collapse of school building in Taplejung

Figure 8. Collapse of stone masonry wall in timber framed building

Figure 9. Collapse of stone masonry building

Figure 10. Schematic of delamination and bulging of stone masonry wall due to absence of interlocking between layers
Insufficient or no provision of bond stones and weak mud mortar are the reasons for the delamination of stone layers. During the survey in many stone masonry buildings, delamination was observed and an example is shown in Figure 11. In addition, out of plane bending and overturning of walls was also common in many buildings (Figure 12).

3.2 Traditional brick masonry buildings
The traditional brick masonry buildings in Nepal are 3 to 4 story high with a sloped roof at the top as shown in Figure 13 [9]. The walls of the buildings are constructed using fired bricks or fired and sun dried bricks in mud mortar. The thickness of the brick wall in typical traditional residential buildings varies from 360 mm to 600 mm. The floors are constructed using wooden beams, above which wooden planks are placed in the direction perpendicular to the beams and a thick mud layer is used to provide the smooth surface of the floor (Figure 14(a)). The sloped roofs are also constructed similar to the floors but with a layer of roof tiles provided on top of the mud layer (Figure 14(b)). Such type of buildings are very common in the old cities of Kathmandu Valley. The traditional brick masonry buildings are characterized by its heavy mass. Since the bricks are laid on the mud mortar, these structures possess very low strength and exhibit a brittle nature of failure resulting in sudden collapse, giving occupants inadequate time to escape during seismic events. The performance of these buildings is usually better than those of stone masonry buildings, however, these buildings cannot be considered as seismic resistant buildings unless proper retrofitting techniques are implemented.
Some of the traditional brick masonry buildings located in the Bhaktapur city, which is about 272 km away from the epicenter suffered heavy damage. The old city of Bhaktapur consists of houses constructed in blocks of 5-10 buildings sharing common walls. Although minor to major cracks were present in several buildings in the area, the numbers of collapsed buildings were few. It was noted that several buildings had experienced permanent out-of-plane deformation of walls. In some of the buildings, diagonal cracks in masonry walls starting from corners of walls and lintels and interface between windows/doors and walls were observed. Besides, typical forms of damage observed in the traditional brick masonry buildings were (a) vertical cracks on walls along the mortar joint at the common face between two adjacent buildings and (b) out of plane failure of walls. In Figure 15, buildings with vertical cracks on wall along the mortar joint, at the common face between two adjacent buildings can be clearly seen. Many buildings in the locality had façade made of fired bricks whereas the side walls were made of sun dried bricks as shown in Figure 16. Due to improper interlocking between the fired brick walls and sun dried brick walls, the sun dried brick walls had collapsed in the out of plane direction. The out plane failure of brick walls can also be observed in Figure 17.
3.3 Traditional infilled timber framed buildings, and Centibera buildings

Following an indigenous technique, locally known as Centibera, buildings are constructed with stone masonry walls up to the plinth level or the first floor, on top of which walls comprised of wooden frames together with woven bamboo mesh and thin layer of cement mortar plaster or plaster composed of a mixture of mud, cow dung and rice husk are built (Figure 18). Typically Centibera buildings are 1 or 2 story high. Such buildings are common in eastern Nepal. Due to light weight and closely spaced timber studs, the buildings are more capable of resisting seismic loads compared to stone or brick masonry buildings.

During the field visit, it was found that in Centibera buildings, there were no cracks (Figure 19), while in the brick masonry buildings close to the Centibera building, many cracks were visible in the masonry walls. The presence of closely spaced timber studs and woven bamboo mesh prevented the propagation of cracks, that helped in elimination of out of plane failure of walls.
3.4 Infilled reinforced concrete (RC) framed buildings

Within the past few decades, many brick masonry infilled reinforced concrete framed buildings have been constructed in many cities in Nepal without any intervention of engineers or architects. The buildings have been constructed based on the experience of local contractors but without any concept of seismic resistant design. Very small cross sections usually 230 mm × 230 mm sized columns and 230 mm × 400 mm beams are very common in these buildings. The number of 12 mm diameter longitudinal rebars in columns and beams varies from 4-8 and shear rebars are provided with a spacing of 300 mm. The thickness of exterior infill brick walls is 230 mm and that of interior infill walls (partition walls) is 100 mm. Low grade cement mortar of mix ratio 1:6 cement/sand is used to build the walls. Because of low seismic resistance, the buildings are very vulnerable to large earthquakes.

There are many infilled RC framed buildings in Kathmandu Valley but being very far from the epicenter, these buildings did not suffer any damage during the earthquake. However, in many infilled RC buildings in eastern Nepal, particularly in Ilam, Panchthar and Taplejung districts, many cracks were observed in infilled brick masonry walls. One of the common features of damage was the separation of brick walls from the adjacent RC frames. In a building located at Ilam as shown in Figure 20, the cracks along the junction of RC frames and walls can be seen. Also an inclined crack initiating from the corner of the door opening was also visible. A building in Taplejung also exhibited shear cracks in the exterior infilled brick masonry wall (Figure 21). A shear crack that propagated from a small opening in an exterior infilled brick masonry wall is also shown.

Figure 18. Centibera construction technique

Figure 19. No cracks in the building constructed using Centibera

Figure 20. (a) Cracks at the junction of brick wall and RC frame and (b) Shear crack on brick wall

Figure 21. Shear crack in exterior infilled brick masonry wall
3.5 Seismic pounding between stone masonry structure and RC framed structures

In Phidim Bazar, a collapse of a stone masonry building due to structural pounding was also observed. When the survey team reached the site, the demolition of the damaged stone masonry building was in progress. Figure 22(a) shows the three buildings without any gap between the adjacent buildings. The white colored demolished building is the stone masonry building. The configuration of the buildings is shown in Figure 22(b).

The stone masonry building was constructed first 20 years ago, while the RC building 1 was 7 years old and the RC building 2 was recently built. The stone masonry building had 2 stories and the other adjacent buildings were 3 storied buildings. The provisions of steel rebar band in the stone masonry wall (Figure 22(c)) and RC tie beams on top of walls (Figure 22(d)) were the peculiar features of this masonry building. During the entire field survey, in no other stone masonry buildings such provisions were observed. However, being constructed with mud mortar and attached to the other two RC buildings, the stone masonry building could not withstand the seismic load and the impact loads from the adjacent buildings. During the earthquake, the second floor walls and the roof of the masonry building completely collapsed, dumping the rubble on the first floor slab. Due to excessive load, some of the RC tie beams failed in flexure. A permanently deflected beam with many flexural cracks at the mid span of the beam is clearly visible in Figure 22(d). A permanent gap of about 5 cm between the stone masonry building and RC building 1 can be seen in Figure 22(e), though there was no gap before the earthquake.

RC building 1 also suffered heavy damage. The brick masonry infill wall at the third floor had completely collapsed. Hence, only the bare frame is visible at the third floor in Figure 22. In most cases, shear cracks are formed in one direction of masonry walls, although, in RC building 1, shear cracks were found in all the four orthogonal walls of the building as shown in Figure 22(f). It is concluded that the shear crack in one direction of wall was due to the earthquake load and that in another direction was attributed by the shear force due to the structural pounding between the buildings. In the first floor rooms of the RC building 1, shear cracks were clearly visible in all the surrounding four walls as depicted in Figure 23.
Figure 22. Collapse of stone masonry building due to structural pounding in Phidim Bazar, Panchthar District (a) collapsed stone masonry building with the two adjacent RC buildings (b) building configuration (c) steel rebar band provided in the stone masonry wall (d) flexural cracks on RC beam supported by stone masonry walls (e) residual gap between stone masonry building and RC building 1 and (f) shear cracks on both the orthogonal infill brick masonry walls of RC building
Significant amount of cracks had developed in the slabs of RC building 1 and RC building 2 (Figure 24) as a result of structural pounding between RC building 1 and RC building 2. Also, the structural pounding caused the formation of shear cracks at the beam-column joint (Figure 25) and a beam of RC building 2 (Figure 26). Hence, the damage to these three buildings shows a good example of structural pounding and also illustrates the vulnerability of buildings to structural pounding, if the provided gap between the adjacent buildings is insufficient.
4. SUMMARY AND RECOMMENDATIONS

The magnitude 6.9 Nepal-Sikkim earthquake which occurred on September 18, 2011 caused widespread damage to rural buildings in eastern Nepal. Nonetheless, the effect of the earthquake on the urban infrastructure of the country was insignificant. The areas mostly affected by the earthquake were remote and poor villages, where buildings had been constructed without considering the effects of earthquake lateral loads. Even in the major towns of Mechi zone which comprises of Taplejung, Panchthar, Ilam and Jhapa districts, many reinforced concrete (RC) buildings had been built using design thumb rules without following any earthquake resistant design code. Since people in rural areas affected by the earthquake are farmers, when the earthquake occurred at 18:25 most of the people were not inside their homes. Hence, while more than 6,000 buildings were damaged completely, the casualties were not proportional to the structural damage.

Most of the buildings which suffered severe damage in Bhaktapur in the Kathmandu Valley were made of brick masonry with mud mortar and had been constructed before the building statutes of using seismic design codes were enacted in Bhaktapur Municipality. It is noted that at the present time all the municipalities of Nepal require seismic design of buildings using either the Indian Seismic Code IS: 1893 or the International Building Code (IBC) or any other standard code of practice, but satisfying the minimum requirements of the Nepal National Building Code (NBC). However, most of the buildings in the country have been designed either prior to the enforcement of building laws or have been influenced by poor implementation of the laws. Thus, a high seismic hazard exists throughout the major municipalities of Nepal.

One to two story load-bearing stone masonry buildings which are widely used in the villages of eastern Nepal were found to be heavily damaged in Ilam, Panchthar, and Taplejung districts. Weak mortar joints and structural irregularities were identified as a triggering factor for the heavy damage. The buildings which used timber frames suffered less damage, compared to load-bearing stone masonry buildings. Typical buildings in the epicentral region of Taplejung district, where the first story is stone-masonry and the upper story is timber-framed, suffered less damage due to the light weight of the upper story.
of Centibera for walls in timber-framed buildings was recognized as a promising technology for low-cost housing. Modern RC buildings suffered negligible damage with few exceptions. Typical damage to RC buildings includes separation of masonry walls from main frame, diagonal cracks propagating from the corners of lintels, and pounding-induced cracks.

Not only in the villages of Nepal but also in the villages of many other countries in Asia such as India, Pakistan, Iran, etc., adobe construction is abundant. Such adobe construction may suffer similar type of damage during seismic events and hence engineering societies, administration and NGOs working in these countries should pay attention to minimize the losses to properties and loss of lives. Since Nepal lies in an earthquake prone region, the following recommendations are provided to increase the seismic safety of buildings based on the observations made during the field investigation:

- Many existing buildings in remote villages require immediate cost-effective ways of retrofitting, using locally available materials such as timber and bamboo.
- Timber-framed masonry construction in the first story and timber-framed Centibera construction in the upper story appears to be a promising technology for the construction of new seismic-resistant buildings in the villages.
- All the structures in the major towns of eastern Nepal should be carefully investigated for the assessment of their seismic safety and appropriate retrofitting measures should be taken for seismically vulnerable structures.
- Government authorities should ensure that only seismic-resistant structures are designed and constructed, especially bridges, hospitals, and school buildings, in major towns such as Ilam, Phidim, and Taplejung.

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