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PERFORMANCE OF MASONRY AND CONCRETE BUILDINGS DURING M7.8 GORKHA (NEPAL) EARTHQUAKE OF APRIL 25, 2015

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Abstract

The rapid urbanization has led to construction activities that often ignore long-term concerns of safety in extreme natural events such as earthquakes. These vulnerable structures add to the seismic risk of the region and have been responsible for losses and damages caused during the earthquake events.

The M7.8 earthquake of 25th April, 2015 was a significant event in the long seismic history of the Eastern Himalayas which caused more than 8000 casualties, widespread destruction of residential, commercial and cultural heritage structures, surface fissures and landslides in the western and central regions of Nepal. It was followed by a strong aftershock of M7.3 after 17 days of the main event which caused further damages. These events provided a unique opportunity to study the vulnerability of the built environment and re-assess the risk exposure of the region which is undergoing rapid urbanization without adequate preparedness for seismic safety. A field trip was undertaken by the authors covering the affected regions of Nepal and adjoining Indian states of Uttar Pradesh and Bihar.

This paper discusses the general observations in the earthquake-affected regions, with special emphasis on the seismic performance of masonry and concrete buildings in the Kathmandu valley region. The level of damage was consistent with the intensity of shaking experienced; however, some structures suffered dramatic collapse which could have been mitigated by good earthquake resistant practices. Widespread damage was observed in unreinforced masonry and reinforced concrete structures which lacked adequate lateral strength and seismic load resisting features. Lack of engineering input was evident from the poor structural and geometric configuration of the buildings and non-compliance with the building codes, which aggravated the seismic vulnerability of these structures. Cultural heritage structures, such as temples and palaces, were severely affected, as many of them were reduced to rubble. Since the maximum shaking intensity on Indian side was between V and VI, most structures did escape serious damage, but they continue to remain vulnerable for future design level earthquakes. Despite the knowledge of the high seismicity of the Himalayan region, the present lack of preparedness is unacceptable and it is necessary to implement good earthquake resistant practices to minimize losses in future earthquakes.

Keywords: Seismic vulnerability; Earthquake effects; Unreinforced masonry; Reinforced concrete frame

1. Introduction

Nepal and the neighboring regions suffered a major earthquake on 25th April, 2015 which was followed by strong aftershocks even after a fortnight of the main event. The earthquake killed more than 8000 people, destroyed about half a million buildings completely and disrupted the road network in the mountainous terrain by surface ruptures and landslides. This paper aims at providing a brief overview of the earthquake and its effects on built environment especially masonry and concrete buildings, as observed in the affected areas of Nepal and adjoining Indian states of Uttar Pradesh and Bihar during the field trip undertaken by authors from May 3-9, 2015 traversing over 2200 km (visited towns are marked in Fig. 1).

The M7.8 earthquake of April 25, 2015 struck at 11:41 am IST (11:56 am local time) with its epicenter located in Gorkha district (28.15°N 84.7°E) in central Nepal, about 80 km NW of the capital Kathmandu (Fig. 1). This event occurred as the result of thrust faulting on or near the Main Himalayan/Frontal Thrust (MFT) interface between the Indian plate and the Eurasian plate [1]. The strong aftershock of M7.3 occurred on 12 May 2015, 17 days after the main shock, which was located at about 80 km NE of Kathmandu (Fig. 1). In Nepal, the earthquake caused unprecedented loss of life and devastation. A large part of the northern India, especially eastern Uttar Pradesh, Bihar and north Bengal, also experienced moderate shaking during these earthquakes.

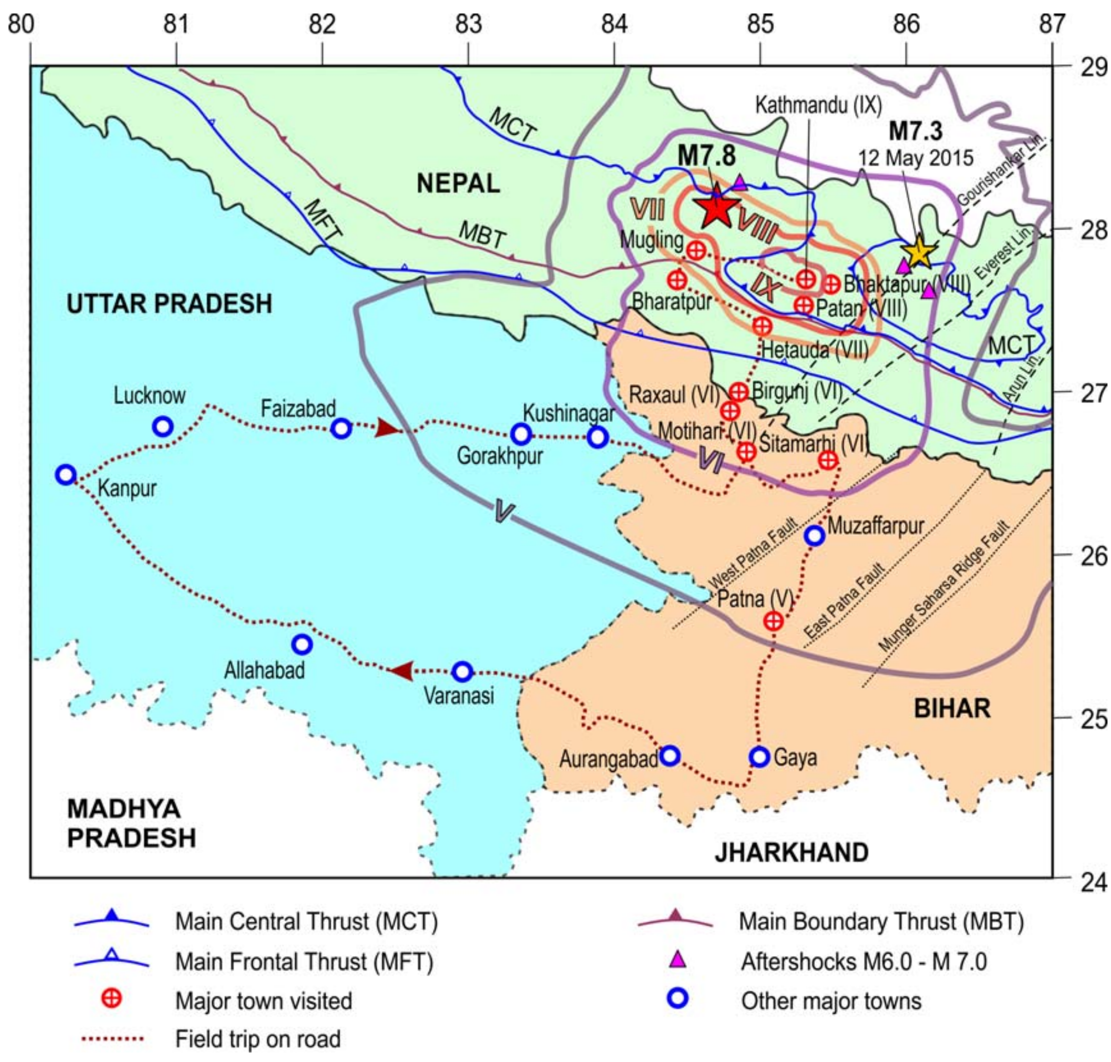
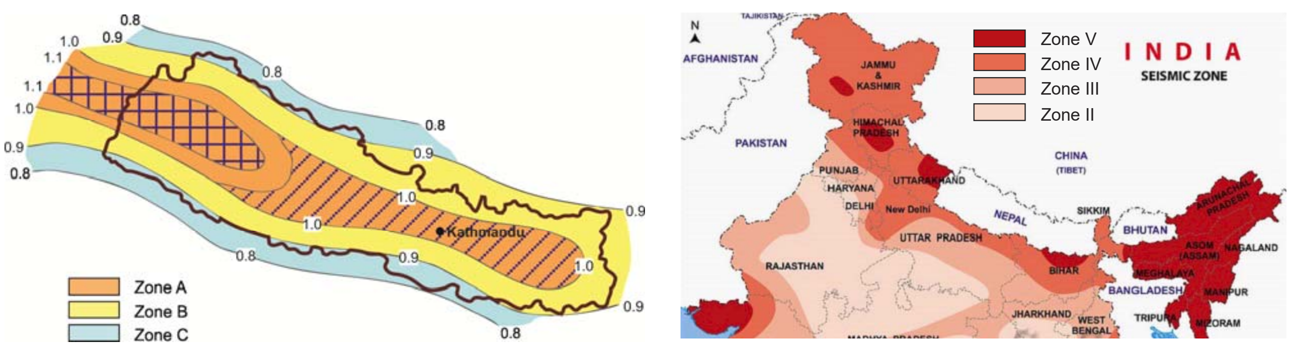


Fig. 1 – Location of epicenter of the earthquake and its aftershock, Main Central Thrust (MCT), Main Boundary Thrust (MBT), Main Frontal Thrust (MFT) and the towns visited in Nepal and India

2. Seismological Setting

The Himalayan region is one of the most seismically active regions in the world producing significant number of earthquakes of M8.0+ magnitude in the past. The largest M8.1 event, known as the 1934 Nepal-Bihar earthquake caused widespread damage in Nepal and Bihar, and around 10,000 fatalities were reported. The M7.8 earthquake was not completely unexpected in the Central Nepal region, as several studies had indicated the likelihood of earthquakes of magnitude greater than 8.0 based on the slip deficit estimation and accumulation of strain energy in the region. This has been anticipated in early 1990's and confirmed by recent studies [2-4].

As shown in Fig. 2, major part of Nepal including Kathmandu lies in zone A on the seismic zoning map of Nepal [5, 6] whereas the districts of north Bihar adjoining the Nepal border lie in zones IV and V on Indian seismic zone map [7]. The seismic zone A of Nepal is equivalent to the most severe Indian seismic zone V liable to shaking intensity of IX on the MSK scale. The ground motion of the main event was earlier available only from the USGS station KATNP in Kathmandu [8]. Only recently, strong ground motion data from four other stations, KTP, TVU, PTN and THM located within the Kathmandu valley have been published [9]. All stations were located at soft soil site, except KTP which was located on a rock site. The reported values of peak ground acceleration (PGA) and velocity (PGV) ranged from 0.15 to 0.24 g and 52 to 107 cm/s, respectively (see Fig. 3a for acceleration and velocity time histories recorded at USGS station). The highest value of PGA was recorded at KTP station situated on a rock site, whereas higher ground velocities were registered at stations located on a soft soil. This is noteworthy as peak ground velocity is better correlated with the damage statistics of mid-to high-rise buildings and it could have played a significant role in the unexpected level of damages in many structures [10].

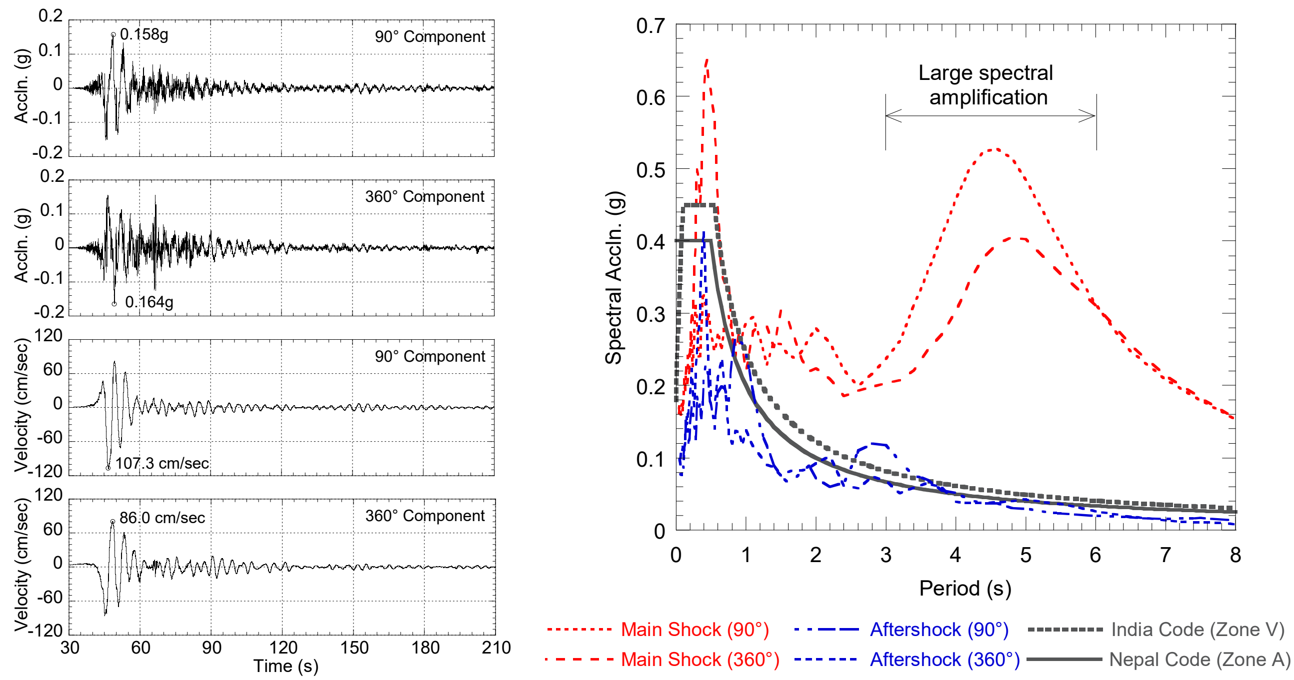


(a) (b)

Fig. 2 – Seismic zone maps: (a) Nepal, and (b) northern and eastern part of India

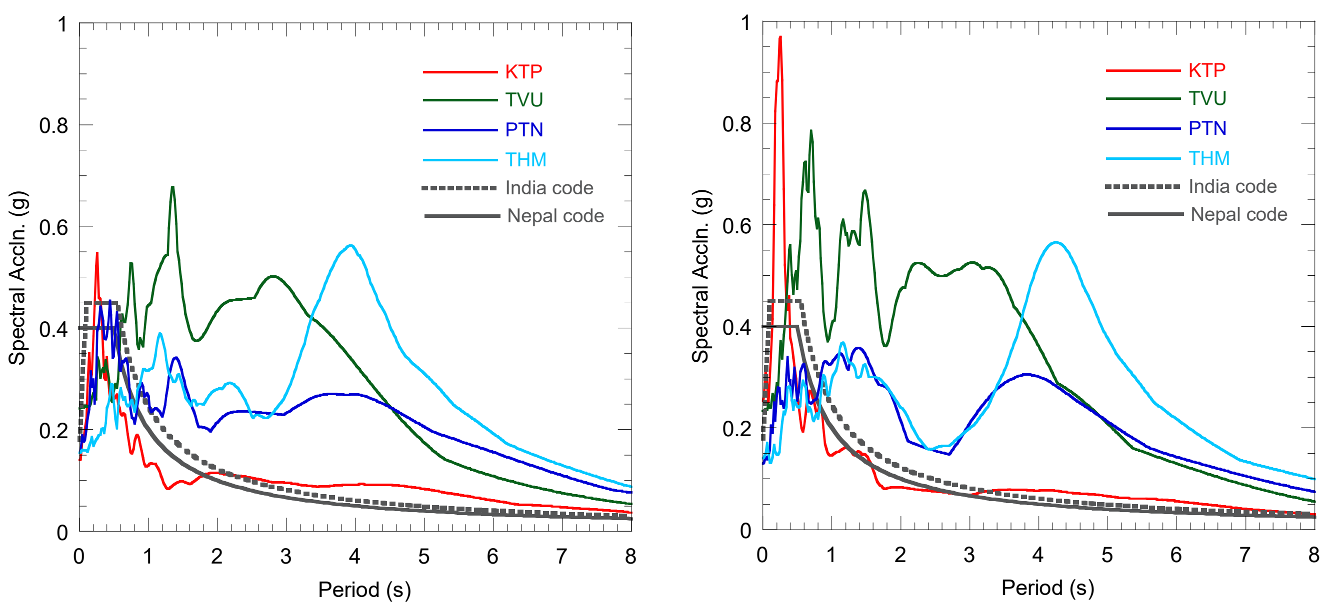
In Figs. 3(b) and 4, acceleration response spectra of the recorded motions are compared with the code prescribed elastic design response spectrum corresponding to zone A of the Nepal seismic code and the zone V of the Indian seismic code for the design basis earthquake (DBE) in soft soil site. It is clear that in the acceleration-controlled regime (i.e. short period range which is typical for low-rise unreinforced masonry and infilled RC frame construction), the ground motion has higher acceleration demand than the code-expected demand in the most severe seismic zone.

Geologic studies show that the Kathmandu valley is covered by thick semi-consolidated quaternary sediments with a maximum depth of 550 m in the central part of the valley [11]. An earlier study on local site amplifications due to unconsolidated quaternary sediments of Kathmandu valley has indicated that the resonant frequencies were in the range of 0.5 to 8.9 Hz with the maximum amplification occurring at 2 s in the central lacustrine area [12]. Thus, in recorded ground motion an unusually higher spectral amplification was observed in a range of 2 – 6 s (0.17 to 0.50 Hz), except at the KTP station, which was located on the rock site. Further, the response spectra obtained for the M7.3 aftershock of 0.087g PGA recorded at USGS station (Fig. 3b) shows a similar amplification at 3 s period, which confirms the influence of the soft soil basin in the seismic ground motion of the valley. Similar basin effect has been observed in past few earthquakes including the notable 1985 Mexico City earthquake. The valley surrounded by four mountains is also susceptible for focusing of seismic waves.



(a) (b)

Fig. 3 – (a) Acceleration time histories for the main shock of the 25 April 2015 event recorded at Kathmandu, and (b) Comparison of 5% damped acceleration response spectra of recorded ground motions of main shock and M7.3 aftershock with the Indian and Nepalese seismic code specified elastic design response spectrum for the design basis earthquake in soft soil site



(a) (b)

Fig. 4 – Comparison of 5% damped acceleration response spectra of recorded ground motions of main shock at KTP (rock site), TVU (soil site), PTN (soil site) and THM (soil site) with the Indian and Nepalese seismic code specified elastic design response spectrum for the design basis earthquake in soft soil site: (a) N-S component, and (b) E-W component

The contour map of dominant period of ground of the Kathmandu region is shown in Fig. 5 (redrawn after Paudyal et al. [12]). Various places where major damage was observed (marked by triangular shape) and the locations of five strong-motion accelerometer (SMA) stations (marked by star shape) are indicated in the Fig. 5. These dominant period contours provide some valuable information which can be correlated with the observed damage. The old unreinforced masonry buildings in Nikosera (marked as 3 in the Fig. 5) generally fall under the acceleration sensitive region of the spectra with a period range of 0.1 to 0.6 s which closely matches with the dominant period of ground of the affected region (0.11 to 0.80 s). Similarly, the failure of the Dharahara tower (12), 203 feet tall unreinforced masonry tower could also be related to the long period dominance in the central region (1.30 to 2.05 s). The USGS station KATNP (13) also lies in the central area of the valley with long period dominance; hence, the record from this station cannot be used as a representative data for the entire Kathmandu valley. Thus, for better understanding of the seismicity of the region, strong motion stations should be set up at numerous locations.

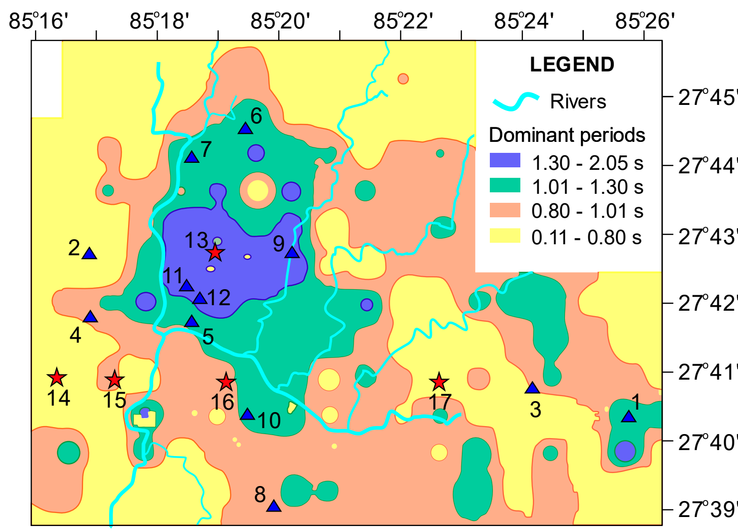


Fig. 5 – Variation of dominant period of ground of the Kathmandu valley [12]. Various places where major damage was observed (1: Bhaktapur Durbar square, 2: Sitapaila, 3: Nikosera, 4: Kalanki bus stop, 5: Teku road, 6: Parkview Horizon apartments, 7: Gongbu new bus stand: 8: Cityscape apartments, 9: Kalopul, 10: Patan Durbar square, 11: Kathmandu Durbar square, 12: Dharahara tower) and location of SMA stations (13: USGS KATNP station, 14: KTP station, 15: TVU station, 16: PTN station, 17: THM station).

The period of multi-storey RC buildings can be approximated as 0.1N, where N is the number of storeys. Hence, buildings of 10 to 20 storey height possess fundamental time period in the range of 1 to 2 s, which is the predominant frequency in the central region of the valley. The period of 14 storeys Parkview Horizon building (6), which suffered major damage to the masonry infills, falls dangerously close to the dominant period range of 1.01 to 1.30 s. Thus, the development of new high-rise buildings should be regulated based on the study of soil profile and its properties. The construction of buildings along the banks of river such as in Kalopul (9) and along banks of river Bishnumati near Gongabu Bus stand (7), Machha Pokhari also led to severe damage.

3. General Observations

In the April 25, 2015 earthquake, the Kathmandu valley experienced intensity IX shaking on MSK scale, which left many buildings and temples in ruins. The regions around Kathmandu reported an intensity of VII in Nepal. Isoseismals of main earthquake event are presented in Fig. 1. These isoseismals were generated based on the observations during the field visit and intensity map reported by USGS [1]. Though Kathmandu is about 80 km away from the epicenter, it experienced a shaking intensity higher than the regions around the epicenter. From the structural damage evaluation, it was found that the damage was concentrated in few pockets of the

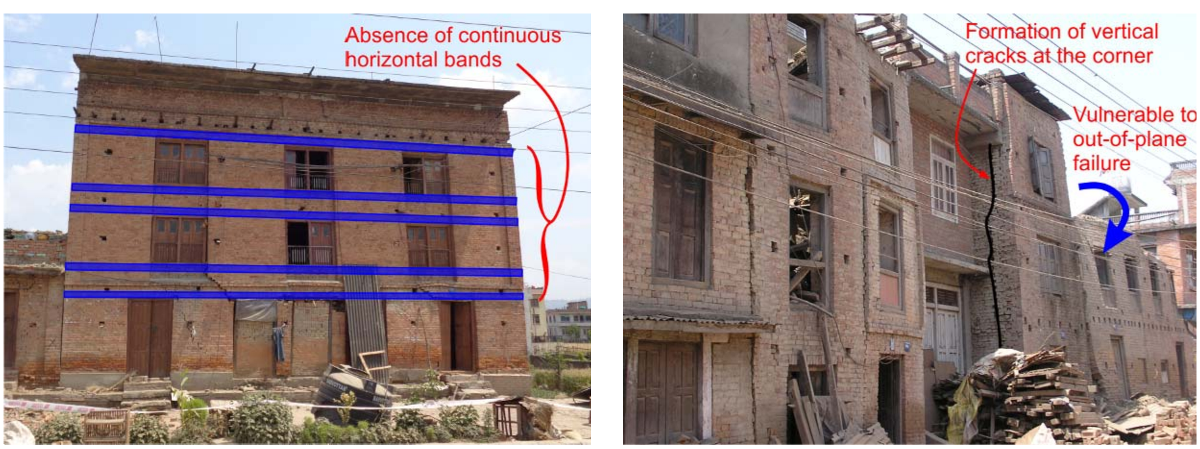
Kathmandu valley such as Khadka Gaon, banks of Bishnumati River in Machha Pokhari. The cultural heritage structures suffered extensive damage during this earthquake. Especially the historical temples and palaces in the urban centers of Kathmandu, Bhaktapur and Patan suffered severe damage.

In India, the maximum shaking intensity of VI was observed in some parts of northern Bihar. Due to the low intensity of shaking (less than VI), even poorly built structures did escape serious damage during this event. However, some damages were reported in *kaccha* houses (non-engineered masonry buildings constructed from stone/bricks and mud mortar) in Sitamarhi district, north Bihar. In addition, few instances of collapse of free-standing masonry walls were also reported in parts of Bihar and Uttar Pradesh. A great majority of buildings affected in the northern region of Bihar are not constructed as per the Indian code of practice and the structural deficiencies inherent in their construction make them highly vulnerable to severe damage under expected shaking intensity of IX (corresponding to Zone V). This region had already witnessed the maximum shaking intensity of X on Mercalli scale during M8.1 1934 Nepal-Bihar earthquake which caused widespread damage in north Bihar districts and liquefaction of soils extending from Motihari to Sitamarhi to Madhubani (a slump belt 300 km long and 60 km wide) [13].

4. Seismic Performance of Masonry and Concrete Buildings

4.1 Unreinforced Masonry (URM) Structures

Unreinforced masonry buildings were the most prevalent building type before masonry infilled RC structures became popular in Nepal. Many 50-60 year old unreinforced masonry buildings in Bhaktapur were severely damaged not only due to their deteriorated strength but also due to their inherent structural defects. The box-like action achieved by integrating peripheral walls in unreinforced masonry buildings is an important earthquake resistant feature. The provision of continuous horizontal bands at different levels of the building helps in maintaining structural integrity with all walls and floor diaphragms acting together as a single unit under lateral loads. However, in most of the collapsed buildings, it was observed that there were no horizontal bands connecting the wall units (Fig. 6a). The cross walls in this type of construction were simply butt jointed and had no interlocking features which resulted in their separation by the formation of vertical cracks at the corners (Fig. 6b). However, as per the present Nepal National Building Code [14], at the junction of two or more walls, reinforcement in the form of timber or steel should be provided to integrate the box action for the peripheral walls. Due to the absence of positive connection between the walls at corners and at T-junctions, these walls behaved as free-standing slender walls subjected to large out-of-plane seismic forces due to their heavy mass which often exceeded their capacity. Thus, these separated walls were vulnerable to out-of-plane collapse and many failed during the shaking.



(a) (b)

Fig. 6 – Typical URM construction in Nikosera: (a) Absence of continuous horizontal bands, and (b) formation of vertical cracks at corners which resulted in separation of cross wall from main wall

Though the out-of-plane failure of walls in unreinforced masonry buildings was more common, the in-plane damage by step-type diagonal cracks in masonry walls extending to the full storey height was also observed which further reduced the out-of-plane strength of walls and increased the risk of out-of-plane collapse (Fig. 7a). From the failure pattern of building shown in Fig. 7b it can be observed that the in-plane damage was followed by out-of-plane collapse. Closely spaced large openings are detrimental to the seismic performance of masonry structures, which was also observed in the partially collapsed URM buildings in Bhaktapur (Fig. 8a) and provision of openings of irregular sizes is also not a good earthquake resistant practice (Fig. 8b).

(a) (b)

Fig. 7 – URM buildings failures in Nikosera: (a) Collapse of three storey unreinforced masonry building, and (b) combined in-plane and out-of-plane failure of the wall

(a) (b)

Fig. 8 – (a) Partial collapse of URM building with large openings, in Nikosera, and (b) typical view of the residential building with too many opening placed haphazardly near Kathmandu Durbar Square

According to the mandatory rules of thumb of Nepal building code, for URM buildings built with mud mortar [14], the height of the wall should be less than eight times the thickness of the wall, openings should not be closer than 600 mm and compulsory timber or RC horizontal bands, collar bands and diagonal bands at the corners have to be provided in such buildings. However, it has been observed that many URM structures do not abide by such mandatory guidelines.

Traditional structural elements observed in the cultural heritage structures which survived in the earthquake, are proven examples for the resilience provided by seismic resistant features in building construction. The old masonry buildings, especially heritage structures which survived in this earthquake, were provided with the continuous timber bands at each storey levels. In addition, in the *dega* temples, wide timber bands were provided on the top of openings which act as lintels for carrying the loads from the upper storeys (Fig. 9a). The roof was connected to the walls by means of wooden pegs which enhance the box action of the building (Fig. 9b). The sloping/ overhanging timber roof was supported by aesthetically carved timber struts which also act as structural members enhancing the rigidity of the floor/roof (Fig. 9b). However, it seems that this knowledge of earthquake resistant features was somehow lost during the last few decades leading to the poor seismic performance of the URM buildings. The lack of earthquake resistant features in these masonry structures could also be due to high cost and non-availability of structural timber in Himalayan regions. The use of material other than timber, such as precast RC and steel members, for confining masonry should be investigated for wider application [15].

(a) (b)

Fig. 9 – Good construction practice in URM buildings of Bhaktapur Durbar Square: (a) provision of wide timber bands over the top of openings, and (b) connection of floor/roof and walls using timber struts and wooden pegs

4.2 Concrete Buildings

In the past five decades, there has been a widespread conversion of traditional Newari houses and unreinforced masonry buildings to masonry infilled reinforced concrete (RC) structures in the Kathmandu valley. Many such RC buildings in Kathmandu suffered varying degree of damage, ranging from moderate damage to complete collapse during this earthquake. Presence of inherently poor construction features significantly added to the seismic vulnerability of these structures. These buildings though built with better construction materials were incapacitated in resisting seismic forces due to the lack of proper professional engineering consultation resulting in poor design details, ignorance of good earthquake resistant practices for RC construction, and poor workmanship. The devastating earthquake of M6.4 in 1988 led to the development of Nepal National Building Code (NBC) with the support of United Nations Development Programme, which was published in the mid 90's [16]. The code was recommended as advisory for buildings in rural areas and mandatory for all public buildings and residential buildings in municipalities where building permit process exists. However, during this field visit, the authors observed numerous violations of codal provisions in the urban built environment, highlighting serious lack of enforcement of the code which is a familiar state of affairs in many regions where the general governance is weak. Substantial number of building collapses or damages could have been averted by complying with the building code provisions. The RC structures in Kathmandu valley can be broadly classified into engineered and non-engineered construction. The non-engineered low-rise buildings, popularly referred as pillar construction, suffered severe damage and complete collapse in many cases. The engineered constructions, though escaped with minor to moderate damage, were deficient in earthquake resistant features similar to the non-engineered construction.

Buildings with open ground and weak storeys are infamous for their poor behaviour in the past earthquakes and this event was not an exception. Many open ground storey buildings collapsed completely due to soft/weak storey mechanism (Fig. 10). Buildings which were partly used for commercial purposes collapsed, often with pancaking of floor slabs, due to open ground and intermediate storeys in the absence of infills. The collapse of these buildings was primarily triggered by the formation of soft/weak storey mechanism due to the inadequate wall area, small sizes of RC frame members and poor reinforcement detailing at critical locations.

(a) (b)

Fig. 10 – Open ground and weak storey failures (a) Four storey buildings in Sitapaila, Kathmandu and (b) Building with basement near Kalopul, Kathmandu.

For non-engineered buildings built by mid-level technicians, the Nepal building code specifies Mandatory Rules of Thumb for RC buildings with and without masonry infills [5, 17]. These documents provide ready to use dimensions and details of structural and non-structural elements, guidelines for the selection of site, the plan of building, the location of wall openings and their details, etc. However, the observed damages reveal the lack of awareness of such provisions among the public. Extensive damage in many houses were caused by the absence of confining members/columns at the critical locations such as at the intersection of walls, areas adjacent to door openings and at the outer periphery of the building (Fig. 11). Complying with the mandatory requirement of horizontal RC bands at the lintel and sill levels of openings could have reduced the extent of damage to infill walls in many buildings (Fig. 11b). The walls projecting outside the framing elements failed in the in-plane and out-of-plane directions due to the absence of the integrating effect of RC bands with the frame elements under lateral loads (Fig. 11c). There were also damages due to poor site selection such as sloping ground, landfills, and riverbanks.

Large multi-storey commercial buildings and residential apartments which were supposed to be the engineered construction, design and built under professional guidance also suffered extensive damage though they did not collapse completely. The damage to the masonry infill walls such as large diagonal cracks in masonry panels and cracks at the frame-masonry interface was very common in these high-rise structures (Fig. 11d). The projection of walls outside the framing elements is widely prevalent in the rapidly urbanizing valley region driven by need to utilize the space to its maximum. However, these slender projecting walls when not positively connected or integrated with the building frame become extremely vulnerable to collapse along both in-plane and out-of-plane directions as observed in 15+ storey buildings in Kathmandu and Lalitpur. Moreover, such high-rise buildings weakened by the damage to infills posed serious danger to neighboring buildings in densely built areas in the event of a strong aftershock ground motion. Diagonal shear cracks in masonry piers near openings were commonly observed in the wall panels where the continuous horizontal RC bands were not provided.

Vertical irregularity in buildings leading to discontinuous load transfer path is not preferred for ensuring good performance of buildings under seismic forces. The codal provisions also prohibit extending the floor area in upper storeys beyond the ground plan area. However, there are many buildings in the study region, where upper storeys are supported on long cantilever slab or beams (Fig. 12a). Buildings with aspect ratio (such as

Fig. 11 – Various structural defects in newly constructed buildings: (a) absence of column at the intersection of two walls, (b) damage to the wall panel due to absence of confinement all around openings, (c) projection of masonry wall beyond the column grid line, and (d) damage to masonry infills in mult-storeyed buildings

Fig. 12 – (a) An example of RC building with upper storeys supported on long cantilever slab or beam, and (b) a building with very large length to width ratio (L/B)

length to width ratio and height to width ratio) much larger than the code prescribed value of three were surprisingly common in the region (Fig. 12b). Such configurations are generally weak in resisting lateral forces and buildings with such plan and vertical irregularities which did escape with minor damage this time are likely to suffer severe damage in case of stronger shaking expected in the design level earthquake. Many buildings in the worst affected areas were built very close to each other and in many cases with almost no gap between them as they extend upto property lines. Pounding of such buildings either led to chain of collapses involving surrounding buildings or left them leaning out of plumb (Fig. 13).

An overview of the seismic performance of RC buildings suggests that some of the key features that contributed to the poor performance of the structures include the following; (a) inadequate size and poor reinforcement detailing of the RC frame members, (b) poor beam-column connection details, (c) weak and slender brick masonry partition walls, (d) extended floor plans in upper stories supported on cantilevered beams and slabs, (e) open ground and soft/weak storey, (f) large vertical and horizontal plan irregularities, (g) discontinuity in lateral load resisting system, (h) lack of soil investigation etc. Many of these poor construction features were also responsible for the widespread damage to RC buildings in Sikkim during the M6.9 India-Nepal border earthquake of September 2011 [18].

(a) (b)

Fig. 13 – (a) Collapse of intermediate storey due to pounding of adjacent building, and (b) collapse due to extension of the upper storey plan beyond the column grid lines which created vertical irregularity

5. Conclusions

The damage to built environment and number of casualties due to Himalayan earthquakes has been rising proportionally with the growth of population and the spread of settlement in vulnerable areas. The seismic vulnerability of various building typologies was exposed during this event. While most of old masonry structures including the heritage temples suffered partial to complete collapse, well-constructed RC frame structures performed well with minor cracks. However, dramatic collapse of many RC frame structures was observed due to the poor construction practices such as open ground storey, inadequate size and poor reinforcement detailing of columns, poor geometric configuration of the buildings, insufficient spacing between adjacent buildings, projection of walls beyond the column lines, weak and slender masonry infill walls, lack of proper site investigation for constructions on sloping ground, etc.

On the Indian side, even the poorly constructed buildings escaped from damage as they experienced a low intensity of shaking, but they remain extremely vulnerable under greater levels of shaking expected in future design level earthquakes. The high population density in the northern Bihar and similar flaws in building construction practices as seen in Nepal increase the seismic risk in this region to unacceptable levels. This trend may lead to a large-scale disaster as evidenced in the M8.1 1934 earthquake, if the growing seismic risk is not mitigated by promoting the awareness on seismic safety and the earthquake resistant construction practices. Despite the available knowledge base, it is unfortunate that the society is not adequately prepared due to lack of its implementation and, therefore, it is important that the regulatory authorities controlling building construction urgently begin enforcing strict compliance of seismic codes in the interest of public safety.

6. Acknowledgements

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