region and is often related to poor land-use practices. Further drought can deepen the effect of land degradation. Declining vegetation cover due to drought stress may enhance soil erosion and can lead to an irreversible loss of nutrients and subsequently desertification. Hence, modification of agricultural and water policies in the drought-affected areas may require additional national-level actions and measures to mitigate the drought-affected areas. While significant achievements have been made in post-disaster response and reconstruction, there are still challenges to reducing the risk of future disasters as the frequency and intensity of droughts and extreme weather events are expected to increase in the coming decades. Thus, disaster management is becoming difficult due to increasing population and climate change. The only way to reduce such disasters is to improve disaster and also better preparedness.

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ACKNOWLEDGEMENTS. We thank IMD Pune; Department of Agrometeorology, AAU, Anand; Department of Agriculture, Gandhinagar, and The Directorate of Economics and Statistics for providing meteorological and crop statistics data. We also thank Shiv Nadar University and NIT-Manipur for providing the necessary facilities.

Received 11 January 2015; revised accepted 10 August 2015

doi: 10.18520/v109/i11/2121-2126

Performance of residential buildings during the *M* 7.8 Gorkha (Nepal) earthquake of 25 April 2015

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The *M* 7.8 earthquake of 25 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 *M* 7.3 after 17 days of the main event which caused further damage. These events provided a unique opportunity to study the vulnerability of the built environment and reassess

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the risk exposure of the region which is undergoing rapid urbanization without adequate preparedness for seismic safety. A field trip was undertaken covering the affected regions of Nepal and adjoining Indian states of Uttar Pradesh and Bihar. This article discusses the general observations in the earthquake affected regions, with special emphasis on the seismic performance of residential structures in the Kathmandu valley region.

Keywords: Earthquake effects, reinforced concrete frame, seismic vulnerability, unreinforced masonry.

NEPAL and the neighbouring regions suffered a major earthquake on 25 April 2015, which was followed by strong aftershocks even after a fortnight of the main event. The disaster 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 communication aims at providing a brief overview of the earthquake and its effects on built environment, especially residential buildings, as observed in the affected areas of Nepal and adjoining Indian states of Uttar Pradesh and Bihar, during the field trip undertaken by the present authors during 3–9 May 2015 traversing over 2200 km.

The *M* 7.8 earthquake of 25 April 2015 struck at 11 : 41 am IST (11 : 56 am local time), with its epicentre located in Gorkha district (28.15°N 84.7°E) in the central Nepal, about 80 km NW of the capital Kathmandu (Figure 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 *M* 7.3 occurred on 12 May 2015, 17 days after the main shock, which was located at about 80 km NE of Kathmandu (Figure 1). In Nepal, the earthquake caused unprecedented loss of life and devastation. A large part of northern India, especially eastern Uttar Pradesh, Bihar and north Bengal, also experienced moderate shaking during these earthquakes.

The Himalayan region is one of the most seismically active regions in the world producing significant number of earthquakes of *M* 8.0+ magnitude in the past. The largest *M* 8.1 event, known as the 1934 Nepal–Bihar earthquake caused widespread damage in Nepal and Bihar, and around 10,000 fatalities were reported. The *M* 7.8 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 1990s and further confirmed by recent studies[2–7].

As shown in Figure 2, the major part of Nepal, including Kathmandu, lies in zone A on the seismic zoning map of Nepal[8,9], whereas the districts of north Bihar adjoining the Nepal border lie in zones IV and V on the Indian seismic zone map[10]. 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 recorded at USGS station KATNP (27.71N, 85.32E) in Kathmandu[11]. The reported values of peak ground acceleration (PGA) and velocity were 0.164 g and 107.30 cm/s respectively (see Figure 3 *a* for acceleration and velocity time histories). It should be

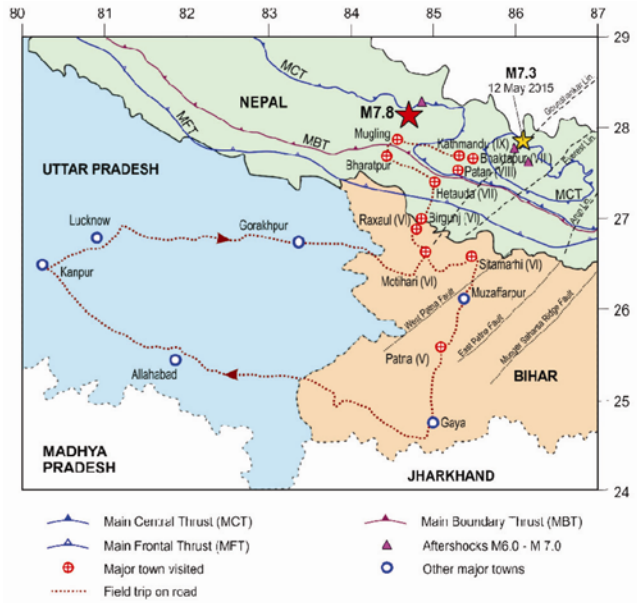

Figure 1. Location of epicentre of the earthquake and its aftershock, Main Central Thrust, Main Boundary Thrust, Main Frontal Thrust and the towns visited in Nepal and India.

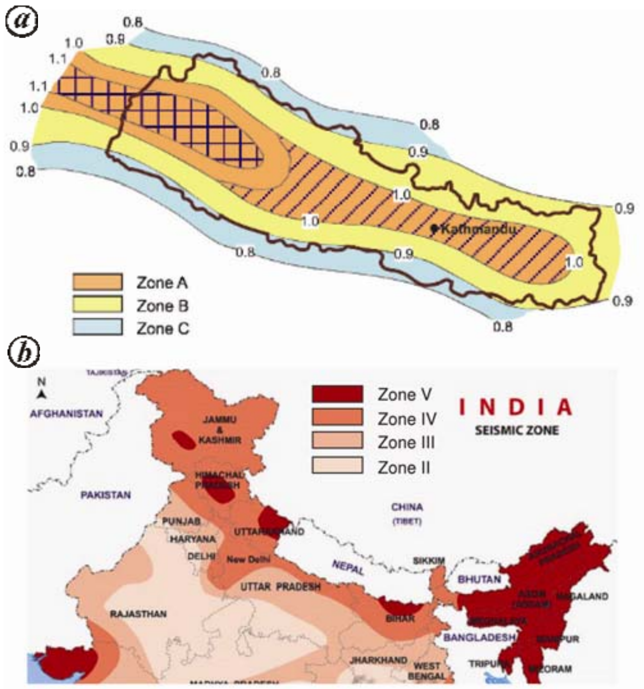

Figure 2. Seismic zone maps: (***a***) Nepal, and (***b***) northern and eastern parts of India.

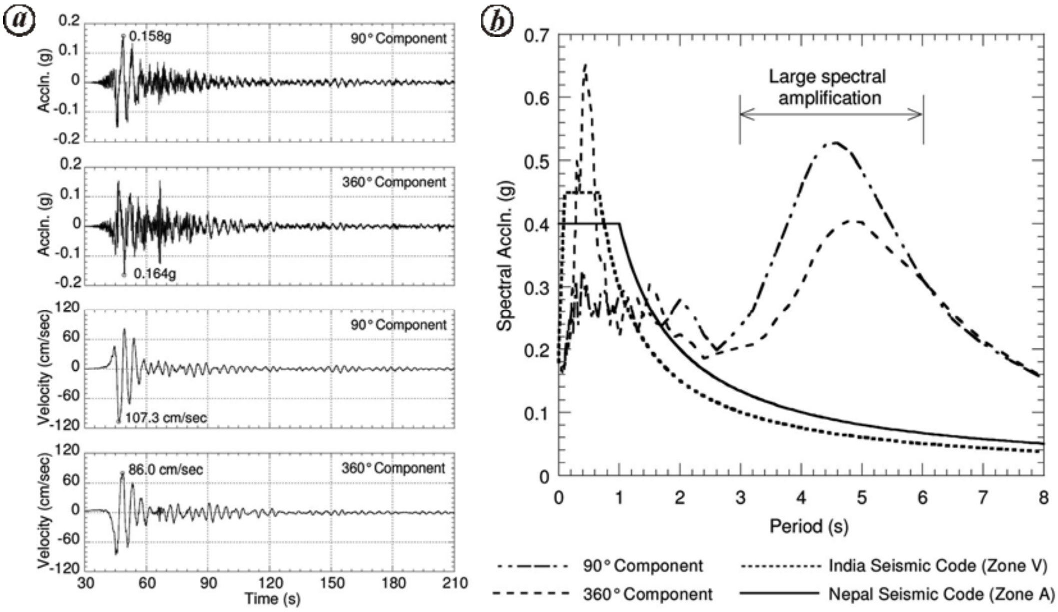

Figure 3. ***a***, Acceleration time histories for the main shock of the 25 April 2015 event recorded at Kathmandu. ***b***, Comparison of 5% damped acceleration response spectra of recorded ground motions with the Indian and Nepalese seismic code specified elastic design response spectrum for the design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

noted that the peak ground velocity is much higher than typically expected for the observed PGA of 0.164 g (ref. 12). 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 degree of damage to many structures[13].

In Figure 3 *b*, acceleration response spectra of the recorded ground motions are compared with the code-prescribed elastic design response spectrum corresponding to zone A of the Nepal seismic code and zone V of the Indian seismic code, for the design basis earthquake (DBE) in soft-soil site. The USGS global V_{S30} server indicates that the central part of Kathmandu valley has soft-soil deposits which are typically NEHRP site class D (V_{S30} between 180 and 360 m/s)[14]. 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[15]. 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 0.5 to 8.9 Hz, with the maximum amplification occurring at 0.5 Hz (2 sec) in the central lacustrine area[16]. However, in addition to the amplification at 0.5 sec (2 Hz), unusual higher spectral amplification was observed in the range 3–6 sec (0.17 to 0.33 Hz), which could also be due to the complex influence of underlying unconsolidated quaternary sediments in the basin. Similar basin effect has been observed in some of the past few earthquakes, including the notable 1985 Mexico City earthquake, where the ground acceleration was amplified by about 10 times at 2 sec period due to the presence of lake deposits, which resulted in large devastation even at a distance of 300 km from the epicentre[17].

During 3–9 May 2015, the present authors undertook a reconnaissance survey of the earthquake affected regions and visited (by road) major towns in Bihar (India) and Nepal (visited towns are marked in Figure 1). During the 25 April 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. Kathmandu, with a zone factor 1.0 according to the Nepal seismic code NBC 105, is expected to experience PGA higher than the recorded value[9]. Though it is about 80 km away from the epicentre, it experienced a shaking intensity higher than the regions around the epicentre. From the structural damage evaluation, it has been found that the damage was concentrated in few pockets of the Kathmandu valley such as Khadka Gaon, and banks of Bishnumati River in Machha Pokhari. Similar difference in site responses was observed in Los Angeles, USA during the 1994 Northridge earthquake and in Mexico City during the 1985 earthquake, due to the basin/site effect[18]. The extensive damage in few regions of Kathmandu valley can also be because of the amplification due to the soft-soil deposits, as observed in the response spectra of recorded ground motion (Figure 3 *b*). The valley surrounded by four mountains is also susceptible for focusing of seismic waves. There could be other factors which have resulted in concentrated damage, but due to the lack of sufficient number of ground motion records, the soil amplification and focusing effect cannot be proven currently. The cultural heritage structures suffered extensive damage during this earthquake. Especially the historical temples and palaces in the urban centres of Kathmandu, Bhaktapur and Patan suffered severe damage (Figure 4).

In India, the maximum shaking intensity of VI was observed in some parts of Northern Bihar, and since the intensity of shaking was small (less than VI), even poorly built structures escaped serious damage during this event; however, damages were reported in kaccha houses (non-engineered masonry buildings constructed from stone/bricks and mud mortar) in Sitamarhi district, north Bihar. In addition, damage to vulnerable, free-standing masonry walls was also reported in parts of Bihar and Uttar Pradesh. A great majority of buildings affected in the northern region of Bihar are not constructed according to the Indian code of practice, and the presence of serious structural deficiencies makes 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 *M* 8.1 1934 Nepal–Bihar earthquake which caused widespread damage in the north Bihar districts and liquefaction of soils extending from Motihari to Sitamarhi to Madhubani (a slump belt 300 km long and 60 km wide)[19].

Unreinforced masonry buildings were the most prevalent building type before masonry in filled RC structures became popular in Nepal. The traditional Newari type buildings were made of multi-leaf unreinforced masonry with the outer leaf made of fired clay bricks, neatly finished inner leaf of sun-dried bricks, and rammed earth or random bricks filled in the cavity with no interconnection between inner and outer leaf[20]. The walls were generally thick (450–750 mm), made of clay brick units with thin mud mortar and were unsupported over a large height. Many such 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 seismic 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

Figure 4. (***a***) Collapse of Dharhara tower in Sundhara, Kathmandu (27°42′3″, 85°18′42″). (Inset) Before earthquake (photo: Corbis Ian Trower). (***b***) Collapse of temples in Hanuman Dhoka, Kathmandu (27°42′14″, 85°18′29″). (Inset) Before earthquake (photo: Andrej Pauš).

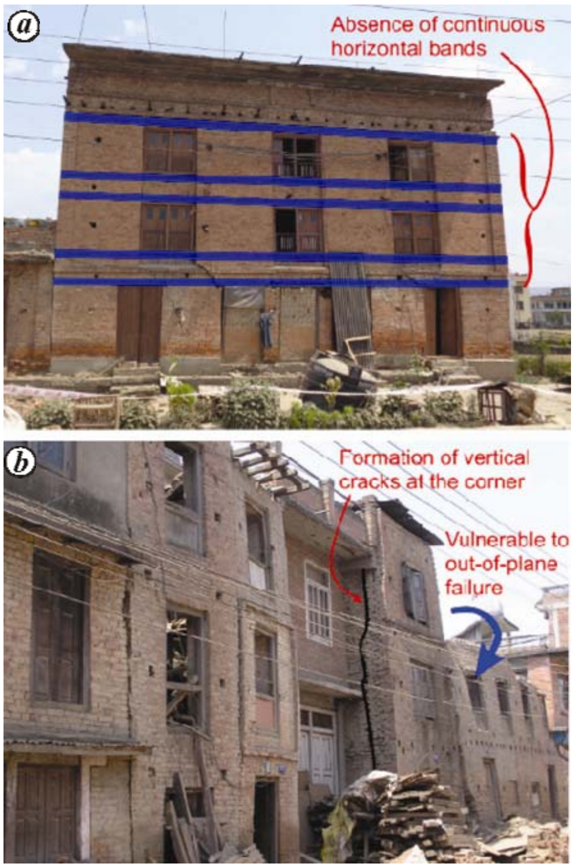

Figure 5. Typical URM construction in Nikosera (27°40′45″, 85°24′10″): (***a***) Absence of continuous horizontal bands, and (***b***) formation of vertical cracks at the corner which resulted in the separation of cross wall from the main wall.

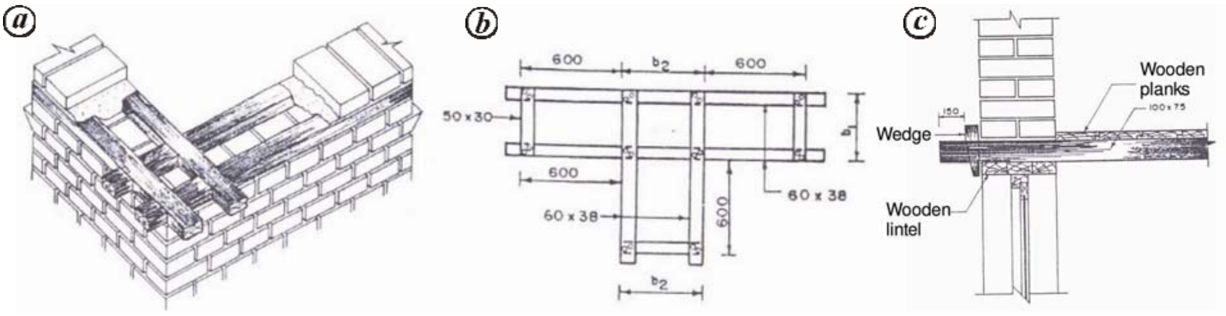

Figure 6. (***a***) Detailing of horizontal band with timber reinforcement at the corner. (***b***) detail of timber reinforcing at T-junction, and (***c***) example of use of wedge to anchor floor joist over lintel.

Figure 7. Typical out-of-plane failure of unreinforced masonry walls: (***a***) Failure due to absence of positive connection between the cross wall and main wall in Nikosera (27°40′45″, 85°24′10″), and (***b***) failure due to proper connection between floor/roof diaphragms and walls.

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 (Figure 5 *a*). 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 (Figure 5 *b*). However, according to the present Nepal National Building Code[21], 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 (Figure 6). Due to the absence of positive connection between the walls at the corners and at T-junctions, these behave 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 (Figure 7).

The floor and roof diaphragms were made of timber joists with timber planks and were embedded in the masonry (Figure 7 *a*). Wooden pegs were generally used to prevent the dislodgement of the roof from the wall in the Newari buildings as shown in Figure 6 *c*. However, as observed in Figure 7 *b*, the timber joists were simply embedded into masonry walls without provision of pegs. Consequently, they were incapable of holding the walls together resulting in tall, free-standing wall sections vulnerable to out-of-plane collapse. Some old masonry buildings, especially heritage structures which survived during this earthquake, were provided with the continuous timber bands at each storey levels. In addition, wide timber bands were provided on the top of openings, which acted as lintels for carrying the loads from the upper storeys (Figure 8 *a*). The roof was connected to the walls by means of wooden pegs which enhanced the box action of the building (Figure 8 *b*). The sloping/overhanging timber roof was supported by aesthetically carved timber struts, which also acted as structural members enhancing the rigidity of the floor/roof (Figure 8 *b*). However, it seems that this knowledge of earthquake-resistant features in unreinforced masonry was somehow lost during the last few decades leading to the poor seismic performance of these unreinforced masonry 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 the Himalayan region. The use of materials other than timber, such as precast RC and steel members, for confining masonry should be investigated for wider application[22].

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 (Figure 9 *a*). From the failure pattern of building shown in Figure 9 *b* it can be observed that in-plane damage was followed by out-of-plane collapse.

According to the mandatory rules of thumb for unreinforced masonry buildings built with mud mortar[21], 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. But it has been observed that many unreinforced masonry structures do not abide by such mandatory guidelines. 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 (Figure 10 *a*). Also, provision of openings of irregular size is not a good earthquake-resistant practice (Figure 10 *b*). In summary, the major reasons for collapse of these masonry buildings are: weak corners due to lack of interlocking between cross walls; poor connection of the floor/roof diaphragms with walls; heavy mass of the walls; weak masonry laid with mud mortar; multi-leaf wall with no through bonding, lack of horizontal bands, and closely spaced large openings.

In the past five decades, there has been a widespread conversion of traditional Newari houses and unreinforced masonry buildings to masonry in filled reinforced concrete (RC) structures in the Kathmandu valley. Many such RC buildings in Kathmandu suffered varying degrees 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 by 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 *M* 6.4 in 1988 led to the development of the Nepal National Building Code (NBC) with support of United Nations Development Programme, which was published in the mid 90s (ref. 23). The code was recommended as advisory for buildings in rural areas and

Figure 8. Good construction practice in traditional buildings of Bhaktapur Durbar Square (27°40′20″, 85°25′45″): (***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.

Figure 9. URM buildings failures in Nikosera (27°40′45″, 85°24′10″): (***a***) Collapse of three-storey unreinforced masonry building, and (***b***) combined in-plane and out-of-plane failure of the wall.

mandatory for all public and residential buildings in municipalities where building permit process exists. However, during the field visit, the present 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 poor. 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 of earthquake-resistant features similar to non-engineered construction.

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[8,24]. These documents provide ready-to-use dimensions and details of structural and non-structural elements, guidelines for the selection of site, the building plan, location of wall openings and their details, etc. However, it was observed that many recently constructed buildings violated the mandatory rules and suffered moderate to severe damage. Extensive damage in many houses was 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 (Figure 11). Complying with the mandatory requirement of horizontal RC bands at the lintel and still levels of openings could have reduced the extent of damage to infill walls in many buildings (Figure 11 *b* and *c*). The walls projecting outside the framing elements failed in the in-plane and out-of-plane directions due to absence of the integrating effect of RC bands with the frame elements under lateral loads (Figure 11 *d*). There were also damages due to poor site selection such as sloping ground, landfills and river banks.

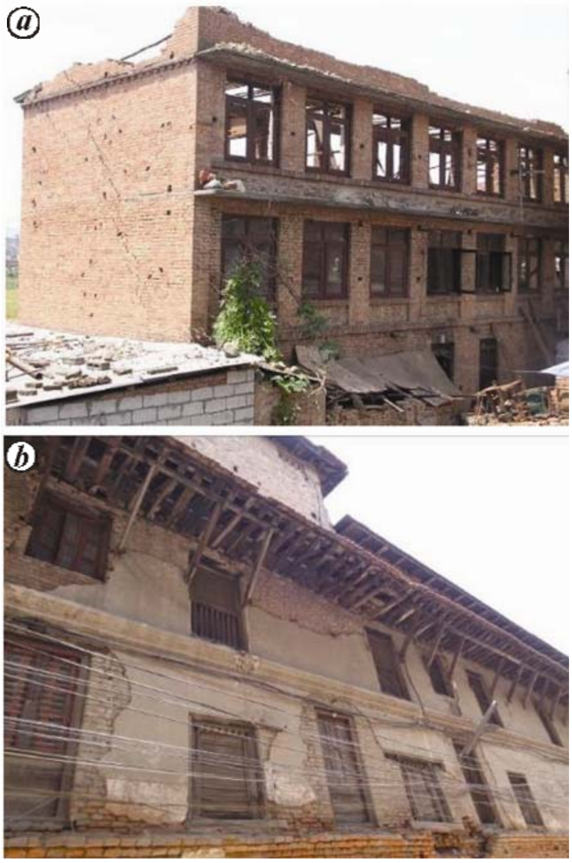

Figure 10. ***a***, Partial collapse of URM building with large openings in Nikosera (27°40′45″, 85°24′10″). ***b***, Typical view of the residential building with too many openings placed haphazardly near Kathmandu Durbar Square (27°42′14″, 85°18′29″).

Buildings with open ground storey are notorious for their poor behaviour during the past earthquakes and this event was no exception. Many open ground-storey buildings collapsed completely due to soft/weak storey mechanism. A residential building with open ground-storey in Sitapaila, Kathmandu which stood immediately adjacent to another building collapsed due to plastic hinge formation in the ground-storey columns and moved away laterally by about 3 m from the adjacent building (Figure 12 *a*). 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 (Figure 12). The collapse of these buildings was primarily triggered by the formation of soft/ weak storey mechanism due to the inadequate wall area, small size of RC frame members and poor reinforcement detailing at critical locations.

Large multi-storey commercial buildings and residential apartments which were supposed to be built under professional guidance also suffered extensive damage, though they did not collapse completely. Damage to the masonry infill walls such as large diagonal cracks in masonry panels and at the frame–masonry interface was common in these high-rise structures (Figure 13). The projection of walls outside the framing elements is widely prevalent in the rapidly urbanizing valley region driven by the need to utilize space to the 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 the 15+ storey buildings in Kathmandu and Lalitpur. Moreover, such high-rise buildings weakened by the damage to infills, posed serious danger to neighbouring 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 (Figure 13 *a* and *b*). Poor monitoring of the urban

Figure 11. Various structural defects in newly constructed residential buildings in Kadhka Gaon (27°41′43″, 85°15′53″): (***a***) Absence of column at the intersection of two walls. (***b***, ***c***) Damage to the wall panel due to absence of confinement all around the openings. (***d***) Projection of masonry wall beyond the column grid line.

development in the valley has led to conversion of many three-storey buildings to five- or six-storey structures, which have contributed in further increasing the seismic vulnerability of the valley.

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 (Figure 14 *a*). Buildings with aspect ratio (such as length to width ratio and height to width ratio) much larger than the code prescribed value of 3 were surprisingly common in the region[8] (Figure 14 *b*). 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 close to each other and in many cases with almost no gap between them as they extended up to property lines. Pounding of such buildings either led to a chain of collapses involving surrounding buildings or left them leaning out of plumb.

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 the upper stories supported on cantilevered beams and slabs; (e) open ground and soft/weak storey; (f) large vertical

Figure 12. ***a***, Open ground storey failure of four-storey building in Sitapaila, Kathmandu, (27°42′42″, 85°16′58″) and (***b***–***d***), pancake collapse of single and multiple floors of commercial and residential buildings (***b***, Machha Pokhari – 27°44′06″, 85°18′20″; ***c***, Sitapaila – 27°42′36″, 85°16′59″; ***d***, Kalanki Bus Stop – 27°41′47″, 85°16′54″).

Figure 13. Typical damage to masonry infill in tall RC frame buildings: (***a***) 17-storey apartment building in Patan (27°39′02″, 85°19′55″) and (***b***) 14-storey building in Kathmandu (27°44′21″, 85°19′27″).

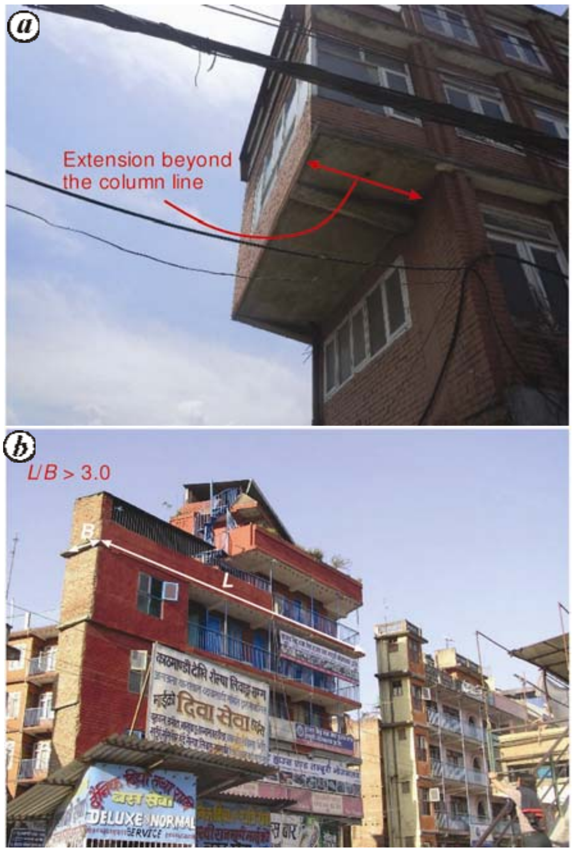

Figure 14. (***a***) An example of RC building with upper storeys supported on long cantilever slab or beam, and (***b***) a building with very large length to width ratio (*L*/*B*).

and horizontal plan irregularities; (g) discontinuity in lateral load transfer system; (h) lack of soil investigation. Many of these poor construction features were also responsible for the widespread damage to RC buildings in Sikkim during the *M* 6.9 India–Nepal border earthquake of September 2011 (ref. 25).

Damage to built environment and number of casualties due to Himalayan earthquakes have been rising proportionally with the growth of population and the spread of settlement to vulnerable areas. The seismic vulnerability of various building typologies has been exposed during this event. While most of the 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, and lack of proper site investigation for constructions on sloping ground.

On the Indian side, even the poorly constructed buildings escaped from damage due to the low intensity of shaking they experienced, but they remain extremely vulnerable for greater levels of shaking expected in future design-level earthquakes. The high population density in 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 *M* 8.1 1934 earthquake, if the growing seismic risk is not mitigated by promoting the elements of seismic safety and earthquake-resistant construction practices. Despite the available knowledge base, it is unfortunate that the society is not adequately prepared due to lack of implementation. Therefore, it is important that authorities controlling building construction urgently begin enforcing strict compliance of seismic codes in the interest of public safety.

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ACKNOWLEDGEMENTS. We thank the numerous individuals for their invaluable assistance during the field study, which was financially supported by Poonam and Prabhu Goel Foundation at IIT Kanpur.

Received 13 June 2015; revised accepted 31 July 2015

doi: 10.18520/v109/i11/2126-2136