Journal of Advanced College of Engineering and Management, Vol. 4, 2018

STRUCTURAL FAILURE ANALYSIS OF EARTHQUAKE AFFECTED BUILDINGS IN GORKHA (NEPAL) EARTHQUAKE 2015 IN KATHMANDU VALLEY

Deepti Adhikari[1], Ashmita Gautam[2]

[1,2]Advanced College of Engineering and Management, Kupondole, Lalitpur, Nepal.

[1]Email Address: deeptia101@gmail.com

Abstract

The major earthquake in April 25, 2015 of Mw 7.8 and aftershock of intensity Mw 7.3 on May 12, 2015 has caused not only a substantial death toll and huge economic losses, but also heavy damage to many buildings. This paper outlines the common observed damage patterns of different types of buildings in Kathmandu valley induced by the earthquake and their constructional deficiencies..We visited Department Of Urban Development and Building Construction (DUDBC) of Nepal Government, and Nepal Society for Earthquake Technology (NSET) and got various information regarding structural damages caused by Gorkha earthquake. After acquiring knowledge on this topic through internet and from NSET and DUDBC, the structural failure analysis of buildings affected during the earthquake in Kathmandu Valley was done by photo observation. Both unreinforced masonry buildings and reinforced masonry structures suffered low to heavy destruction. The construction and structural deficiencies were identified to be the major cause of failure, however local soil amplification, foundation problems, liquefaction associated damages and local settlement related damages were also significantly observed during this earthquake and reported in the paper. The Gorkha earthquake sequences delivered unprecedented opportunity to augment the understanding on seismic performance of the buildings. This paper is also motivated to point out the faintness in the past to current constructional practice of buildings, provide preventive measure and convey awareness to stake holders for future safer building construction practice.

Keywords: *Gorkha earthquake, damage patterns, reinforced concrete structure, unreinforced masonry buildings, constructional deficiencies*

1. Introduction

The Gorkha earthquake of Magnitude Mw 7.8 on April 25, 2015 and its major aftershock of magnitude Mw 7.3 on May 12, 2015, shook Kathmandu valley and its neighboring districts heavily causing 8,219 human casualties (MoHA, May 13, 2015) and huge loss of property. The spatial distribution of aftershocks, which extended 150 km to the east of the epicenter, suggests that the rupture propagated from west to east, thus producing severe destruction in Kathmandu, at approximately 80 km southeast of the epicenter. Around 755,549 residential buildings, 4000 government offices, and 8200 school buildings were damaged due to this earthquake [1]. An immediate post-earthquake reconnaissance done by several governmental and non-governmental sectors showed that damages in reinforced concrete buildings in the urban areas were mostly due to poor construction quality, low concrete strength, non-seismic detailing in beam–column joints, and local site effects. Most of the masonry buildings in the villages nearby main shock epicenter were also affected. Most of the lives lost in the past earthquake was due to collapsing of buildings constructed using traditional materials like brick, stone, adobe and wood. Those buildings were not particularly earthquake resistant or engineered buildings. However, in the last few decades, the use of reinforced concrete has significantly increased, especially in the urban areas of Nepal.

There can be various reasons that lead to the design of building: by proper analysis, design and detailing with respect to safety, economy, stability and strength. The verification of quality of design of the various structural components of a building before construction and quality control of work during construction is very important. The non-reinforced buildings should also be designed according to specific building codes and parameters so that the risks posed by catastrophic disasters could be minimized. The studies related with earthquake demand the structures to be stronger and safer. The earthquake, being inevitable natural catastrophe, safe design should hold the paramount importance as loss of lives and properties are unpleasant because of worst scenarios it can create. In this paper, effort is focused on determining the earthquake induced damages to different designs of buildings in Kathmandu Valley and to point out the deficiencies in constructional practices of buildings that were followed and which still prevail.

1.1 Seismicity of Gorkha Earthquake

The first earthquake struck at 11:56 AM local time (06:11 UTC) with an epicenter located 77 6kilometers (48 miles) northwest of Kathmandu at a shallow depth of 15.0 kilometers (9.3 miles). The second earthquake struck at 12:50 PM local time (07:05 UTC) with a shallow epicenter located 18 kilometers (11 miles) southeast of Kodari, on the southwestern flanks of Mount Everest, also at a depth of 15.0 kilometers (9.3 miles)[2].

Ground shaking from the first earthquake lasted for two minutes according to local reports and was felt as far away as New Delhi in India, Lahore in Pakistan, Lhasa in Tibet, and Dhaka in Bangladesh. Minimally 379 aftershocks rattled Nepal and the surrounding region with magnitudes 4.0 or greater in the months after the event, including five which registered above magnitude-6.0. The European Space Agency's satellite Sentinel-1A used imagery obtained before and after the earthquake to determine that the maximum land deformation occurred only 17 kilometers (11 miles) from Kathmandu which explained the catastrophic levels of damage experienced in that area.

The earthquake's slip – defined by the United States Geological Survey (USGS) as relative displacement of formerly adjacent points on opposite sides of a fault, measured on the fault surface – occurred over an area roughly 2,600 to 5,200 square kilometers (1,000 to 2,000 square miles) across a zone that included the cities of Kathmandu and Pokhara in one direction and nearly the entire Himalaya mountain width in the other. It is estimated that as much as 3.0 meters (10 feet) of northern India's Bihar state slid beneath Nepal in a matter of seconds.

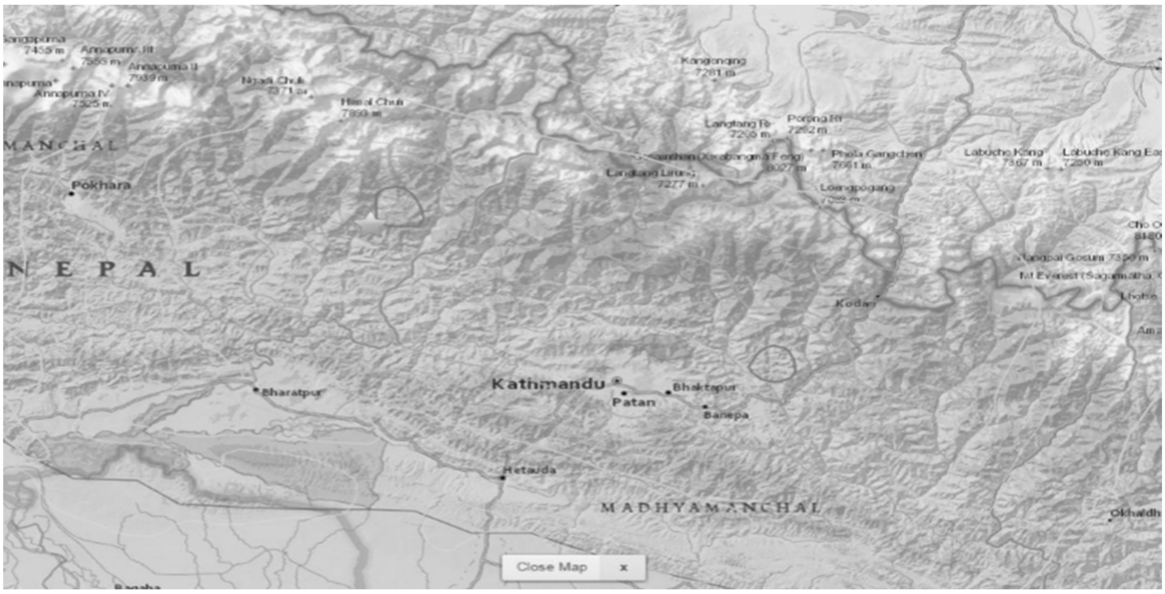
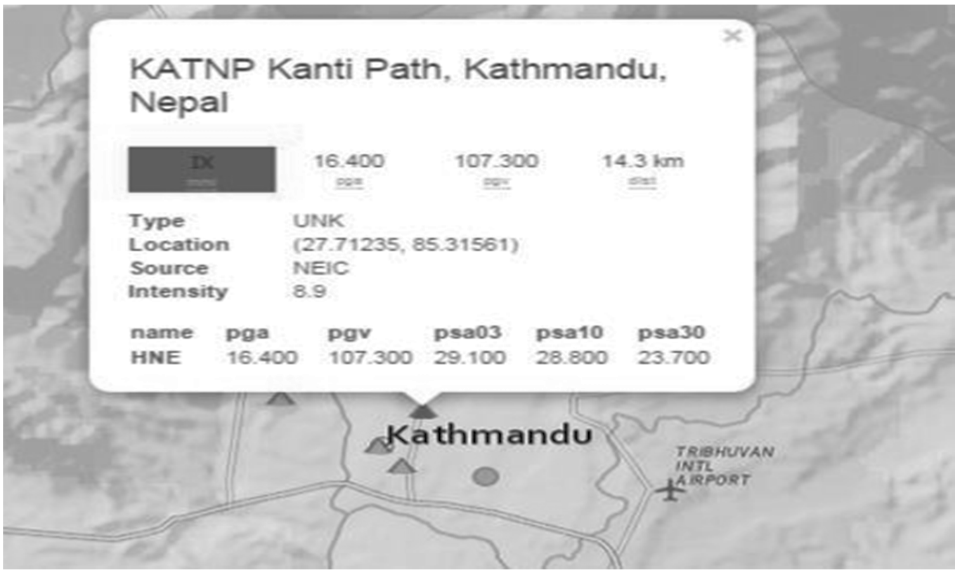


Fig. 1: Map showing the location of the epicenter propagation of the rupture towards Kathmandu. (Source: USGS)

1.2 Ground Motion Record

The ground motion is divided in to three components, two horizontal components and one vertical component. The recorded PGA at the station was 0.16g, while the derived PGA in Kathmandu valley was 0.73g. The derived maximum PGA is 1.32g in Sindhupalchowk district, which suffered the maximum structural damages and casualties due to the shaking. As per UBC 97, the design PGA is 0.44g in Kathmandu valley [2].



KATNP Kanti Path, Kathmandu, Nepal

IX 16.400 107.300 14.3 km

Type	UNK
Location	(27.71235, 85.31561)
Source	NEIC
Intensity	8.9

name	pga	pgv	psa03	psa10	psa30
HNE	16.400	107.300	29.100	28.800	23.700

Fig. 2: Showing the Recorded PGA at the Kantipath Station. (Source: USGS)

1.3 Geological Features of Kathmandu Valley

The manner in which the ground responds to an earthquake is a result of the earthquake rupture process, the path that transfers energy between the source and the surface, and the response of the shallow materials below the ground surface. In addition, the topography of the site and the geological irregularities produced by a basin could induce significant changes in the ground shaking. The region is defined by a geological feature where considerable thicknesses of sediments have deposited over the bedrock for a long geological time period. These deposits are geologically younger than the underlying bedrock. Such compositional/structural differences influence (amplify) the ground motion characteristics of earthquakes.

Kathmandu is located on a basin which is filled with Quaternary fluvio-lacustrine sediments that are more than 600 meters thick (Figure 3). It is important to highlight that the geometry of the Kathmandu basin is similar to the Mexico City basin which amplified the ground motion during the 1985 Michoacán earthquake, resulting in an enormous death toll (more than 30,000) and vast damage in Mexico City. The observed ground motion, as well as the pattern of damage in the Kathmandu Valley, indicates that the presence of the basin significantly modified the ground motion. A seismic micro zonation study in Kathmandu, conducted by Paudyal et al. (2012), indicated that the dominant period in the valley ranges between 1-2 seconds. Therefore, the ground would carry significantly stronger energy with period between 1 and 2 seconds due to the resonance effect. Hence, buildings whose frequencies coincide with the resonance frequencies of the valley would be subjected to stronger earthquake forces. From the field survey, it was observed that the tall buildings (above 10 stories), whose resonance period is between 1 and 2 seconds, responded to the earthquakes strongly (more damage) compared to the lower height engineered buildings in the vicinity [3].

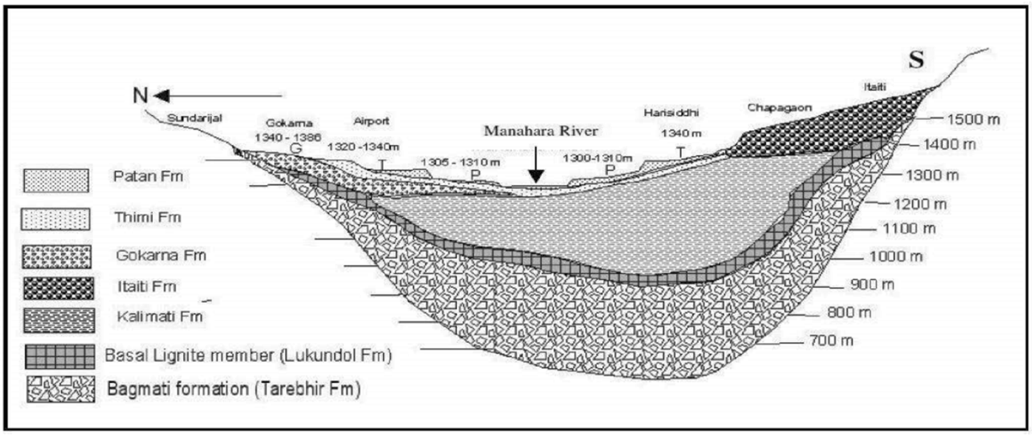


Fig. 3: Cross section map of the Kathmandu Valley and a schematic geological cross-section along N- S (after Sakai, 2001).

1.4 Property Effects of Gorkha Earthquake

Residential

Extensive catastrophic damage to property was reported throughout central Nepal, including in Kathmandu and throughout the Kathmandu Valley. Hundreds of thousands of buildings collapsed throughout Nepal as a result of the earthquakes, and the combined total of houses destroyed stood at 605,254. A further 288,255 were partially destroyed.

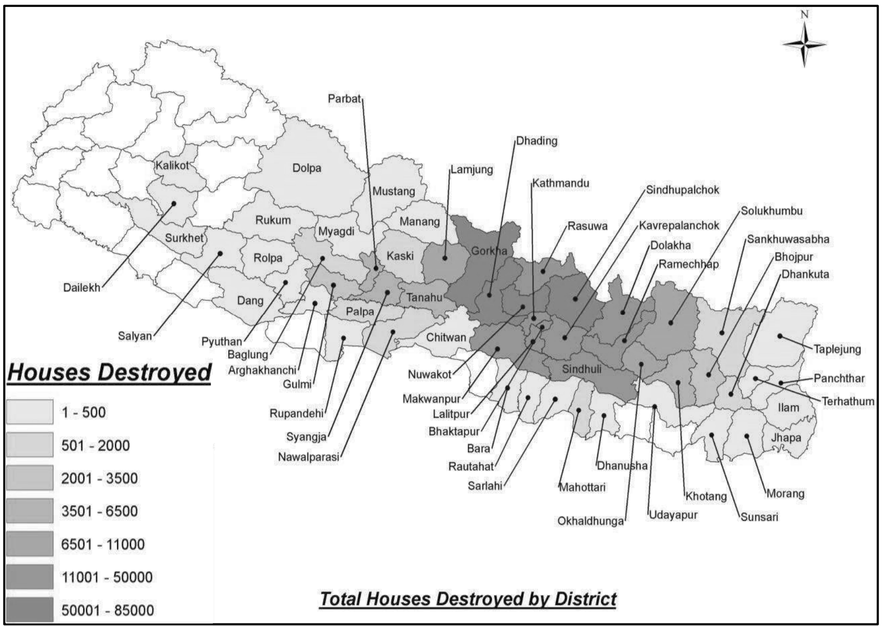
A 2011 report from Nepal's Central Bureau of Statistics revealed that almost 42 percent of houses had outer walls constructed of brick or stone masonry with mud mortar, almost 29 percent had walls constructed from brick or stone masonry with cement mortar, one-fifth had bamboo walls, and the remaining 5 percent had walls comprised of wooden planks. However, nearly 10 percent of homes in Nepal had reinforced cement concrete pillar foundations. This figure rose to more than 28 percent when only urban areas were taken into consideration. Buildings with reinforced cement concrete foundations and structures have a more rigid composition and are therefore more resistant to the forces applied when earthquakes occur. Building collapses in Kathmandu were largely confined to unreinforced masonry and brick structures in the city's historic area, rather than modern buildings. The same 2011 census report indicated that there were roughly 4.63 million homes in Nepal. Given the nearly 894,000 residential and government homes that were damaged or destroyed, that means that approximately 1-in-5 homes were impacted by the April 12 and May 25 tremors.

The district of Dhading suffered the largest number of homes destroyed with 81,406. Nuwakot was second with a total of 75,577 homes destroyed, then Sindhupalchowk followed with 64,595. Kathmandu was the district with the largest number of homes damaged at 56,301 followed by Kavrepalanchowk (23,745), and Makawanpur (17,560). Fewer homes were destroyed (43,587) than damaged in Kathmandu which is perhaps not surprising given that it is the district containing Nepal's largest urban center – Kathmandu City. Most of the damage from the May 12 tremor was sustained in villages and towns to the east of Kathmandu. The village of Sankhu was flattened according to relief workers in the area. The tremor triggered landslides throughout the mountainous regions of the country including at least three major slides in Sindhupalchowk district[3].

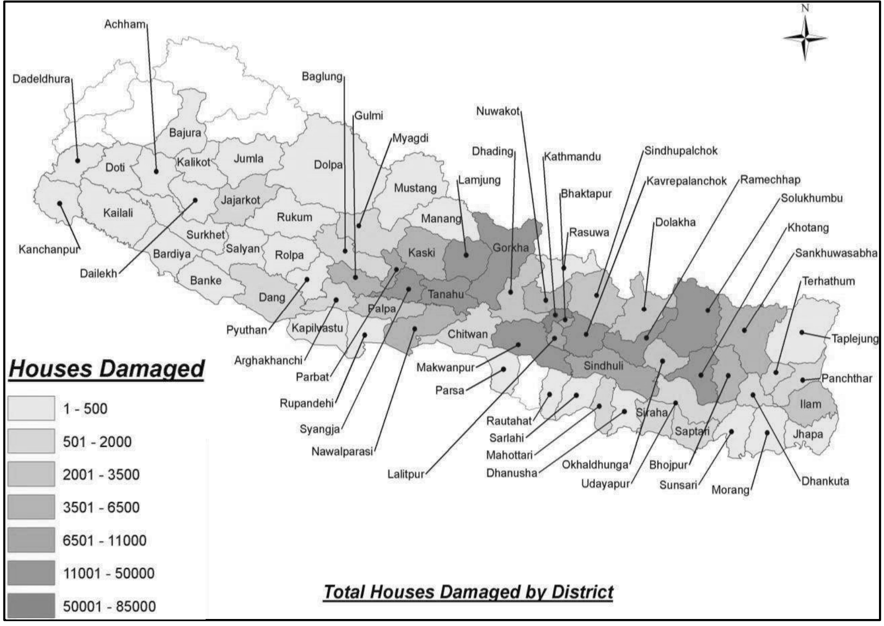
A full list housing impacts in Nepal is found in Appendix A.

Appendix A

(Source: Nepal Disaster Risk Reduction Portal & Impact Forecasting)



Total Houses Destroyed by District



Total Houses Damaged by District

1.5 Overview of Housing Construction in Nepal since 1934

Building construction in Nepal dates back to several thousand years, though the reminiscent of bricks from Buddha’s period are the most reliable sources. It could be said that before 2550 years, there used to be masonry construction system in Nepal. Most of the traditional settlements of Kathmandu valley are of around thirteenth century and the history of villages dates back to similar time. The adobe construction, wooden framed houses and rubble stone masonry constructions are more popular in villages of Nepal, meanwhile most of the urban and suburbs constitute majority fraction of stone or brick masonry buildings constituting around 20 % of reinforced concrete (RC) construction. So, it is obvious that 80 % of the buildings are non-engineered to poorly engineered stone or brick masonry constructions even in urban areas of Nepal; moreover, majority fraction of RC construction is also covered by non-engineered to pre-engineered construction as owner built houses[4]. The description presented by Brahma Shamsher Rana in his book ‘‘The Great Earthquake of Nepal’’ [Nepal ko mahabhukampa (in Nepali)] depicts the prevalence of widespread stone and brick masonry structures. Notably, the bricks were of both burnt and non-burnt clay units in absence of mechanized system. Similarly, the stone masonry houses in villages of Nepal were also reported in his work along with significant fraction of wooden framed structures in rural Nepal. The performance of masonry structures was noticeably inferior than the performance of wooden framed structures during 1934 earthquake due to construction technology, load concentration and structural binding as well as large number of masonry structures in comparison to wooden framed structures. In addition to this, masonry houses in Nepal are used at least by three generations without any strengthening measures, so during every earthquake in Nepal the older masonry structures claim enormous damage of life and properties. Similarly, during 1988 earthquake in Nepal building units were commonly of adobe, wooden framed, brick or stone masonry and very small number of RC structures [5]. The reconnaissance report presented by JSCE depicts the severity of damage in adobe and masonry houses in eastern and central Nepal with relatively insignificant damage in wooden framed and RC structures. Moreover, the masonry houses collapsed during the 1988 earthquake were primarily the survivors of 1934 earthquake [5]. Similarly, it is widely noted that majority of the collapsed masonry houses in rural as well as urban areas of Nepal were either the survivors of 1988 earthquake or even 1934 and 1988 earthquake [6]. After 1980s RC construction in Nepal has been mushrooming and surpassed any other construction types after 2000 in urban areas. However, in rural Nepal stone masonry, adobe and wooden framed structures are still being dominant construction types. The construction technology, construction materials, binding materials are not significantly changing in rural settlements of Nepal. In contrast, the urban housing stocks are nowadays constructed either following by-laws, mandatory rule of thumb as suggested by Nepal Building Code or well-designed structures with analysis and ductile detailing frameworks. After enactment of Building Code Act (1994) and legal enforcement in 2003, the urban housing construction has significantly progressed in terms of building composition and design based on seismic demand. Yet, the majority fraction of structures in Nepal are the ones constructed before enforcement of building codes, so structural vulnerability hasn’t been reduced significantly. In the other hand, however the Nepal Building Code suggests some strengthening techniques for rural construction, technology transfer and adoption of improvement mechanisms are largely lagging. Past studies have shown the vulnerability of buildings to be very high and predicted severe damages in case of strong to major earthquake in central and western Nepal [7–11]. Most of the RC buildings constructed after 1980 are of 2–6 stories with exception of a few 7–11 storied high rise structures. The trend of RC construction is being more popular than any other construction types though economic constraints, availability of construction materials and technology, lack of optimized design, lack in enforcement of building regulations are some of the loopholes that are degrading the quality of construction ultimately increasing vulnerability of buildings. Regarding other types of structures, it is obvious that older and nonengineered constructions are enhancing the vulnerability. With exception to some severe but localized damages in RC buildings, most of the damage was concentrated in masonry, and adobe constructions during 2015 Gorkha earthquake in Nepal. This earthquake also correlates with the severe damage of unreinforced masonry (URM) structures during 1934 earthquake [12] and also the damage patterns are similar for many urban fabrics and outskirts.

2. Earthquake Affected Buildings in Kathmandu Valley

2.1 Photo Observation

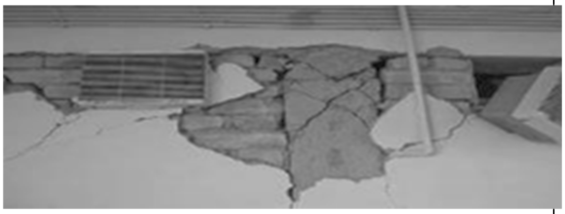
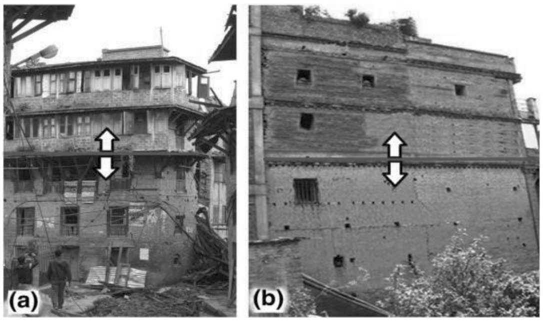


Fig. 1: Shear crack in column	Fig. 2: Buckling of column bars

	
Fig. 3: Separation of wall corner joint.	Fig. 4: Delamination on façade.

. (*Source :PDNA)*

	
Fig. 5: Reduction in thickness of wall with height.	Fig. 6: Mixed masonry: (a) mud and cement masonry; and (b) sun-dried and burnt brick masonry.

(*Source :NSET)*

Fig. 7: Mixed load-bearing element.

Fig. 8: Mixed floor system.

(*Source :NSET)*

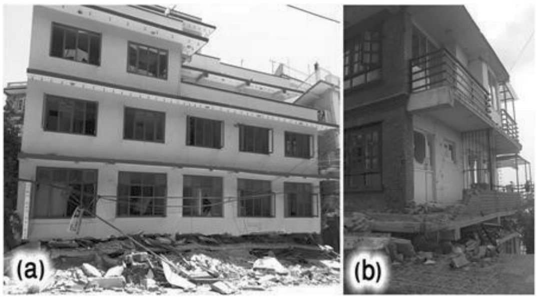


Fig. 9: Soft story failure: (a) commercial building at Mitranagar, Buspark, Kathmandu, ground floor collapsed; and (b) Green Valley Hotel, Nagarkot, Bhaktapur, intermediate floor completely collapsed

Fig. 10: Pounding effect: (a) commercial building at Mitranagar, Buspark, Kathmandu; and (b) commercial building at Milantole, Buspark, Kathmandu.

(*Source:NSET)*

Fig. 11: Private building damage due the ground rupture at Kausaltar, Bhaktapur.

Fig.12: Pancake failure: (a) residential building in Duwakot, Bhaktapur; and (b) residential building in Kamalvinayak, Bhaktapur.

(*Source :NSET)*

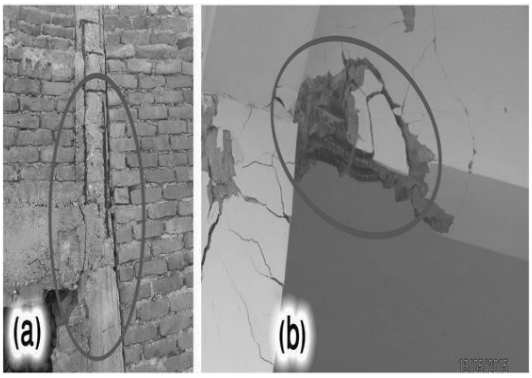


Fig. 13: Beam failure: (a) shear failure; and (b) flexural failure.	Fig. 14: Beam–column joint failure: (a) shear failure; and (b) brittle failure.

(*Source :NSET)*

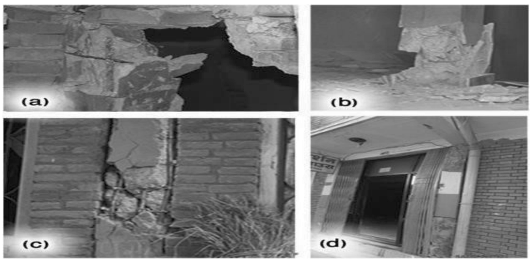


Fig. 15: Column failure: (a) shear failure; (b) flexural failure; (c) brittle failure; and (d) Buckling failure.	Fig. 16: Flexural failure of slab.

(*Source :NSET)*

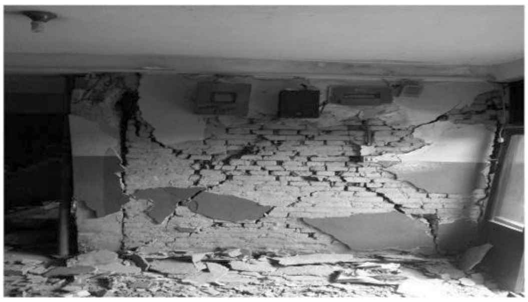


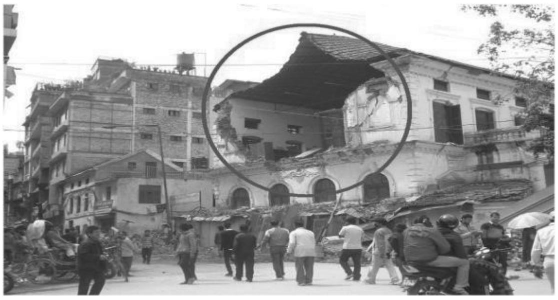
Fig. 17: Diagonal shear failure of infill wall.	Fig. 18: Water tank collapse.

(*Source :NSET)*

	
Fig. 19: Staircase failure.	Fig. 20: Parapet failure.

(*Source :NSET)*

	
Fig.21: Poor quality of construction materials.	Fig.22: Shear failure of building.

	
Fig.23: Tension failure of building.	Fig. 24: Out-of-plane failure of building.

(*Source :NSET)*

	
Fig. 25: Spandrel failure of building.	Fig. 26: Pounding effect between two buildings.

(*Source :NSET)*

	
Fig. 27: Torsion failure of building.	Fig. 28: Mixed failure mode of building.

(*Source :NSET)*

	
Fig. 29: Roof failure of building.	Fig. 30: Overturning of a 7 storey tall building in Kapan area, Kathmandu.

2.2 Damage and failure mode in RC buildings

Table 1: Damage and Failure of RC Buildings

Failure mode	Types of damages	Causes	Fig. no.
Soft story failure	Sinking of lower stories, sinking of intermediate stories	• Omitting infill masonry wall for parking, shopping, lobby, etc. purpose • Omitting infill masonry wall for architectural needs like creating big halls (even omitting middle column), irregular sizing of rooms, etc.	9
Pounding failure	Displacement, plumb out of the buildings, severe damage of the adjacent buildings, total collapse of the adjoining buildings	• Lack of gap between adjoining buildings • Stiffness different within the adjoining buildings • Floor height different between adjoining buildings, stiffness and mass irregularities • Excessive load transfer from higher buildings to lower height buildings • Drastic decrease in stiffness in the higher buildings from the roof level of lower building to top of higher building	10
Structural irregularity failure (plan and mass)	Overturning of massive floor, tilting of the building, separation of massive story from the building	• Relatively higher deflection of massive floor to other light floor • Stress concentrate in the floor level and ultimately may separate (poor ductile detailing in joints	
Failure due to ground rupture	Tilting or shifting of the building, structural elements damages or total collapse	• Built building in the poor soil strata • Build in the land pooling area • Lack of important of soil testing • Built in the fault area	11
Pancake	Total collapse	• Weak column–strong beam • Poor workmanships • Worst ductile detailing • Poor quality of construction material • Built for selling purpose	12

Table 2: Local Failures in RC Buildings.

Failure mode Types of Damages		Causes	Fig. no.
Beam failure Shear failure	Cracks developed at 45° angle normally), spallation of concrete at the middle or near the joints	• Stirrups provided in the Beams are not sufficient (spacing of rebar175 mm to 300 mm) • Rebar size that is used is of minimum diameter (5 mm to 7 mm) • Hoop provided is 90° with minimum hoop length (20 mm to 50 mm) • Stirrups are not placed correctly • Main rebar provided in the beam are not sufficient (using four bars of diameter ranging from 10 mm to 12 mm) • Overlapping length is minimum (usually 150 mm to 300 mm) • Overlapping location is also not appropriate (major problem) • Confinement reinforcement are not provided • Size of the beam is 230 mm by 230 mm (including slab thickness)	13a
Flexural failure	Crumble of concrete yielding of rebar, horizontal cracks near the joints		13b
Beam–column	Joints failure		
Shear failure	Cracks develop at the beam–column joint, crumble of concrete at the joints	• Lack of use of confinement rebar near the joints • Lack of use of confinement rebar inside the beam–column junction • Use of poor quality concrete	14a
Brittle failure	Separation of beam from column, crumble of concrete	• Adequate anchorage length of the beam is not provided (major problem) • Main bar provided in the beam and column is not sufficient • Extra bar that need to provide in the beam column joints are omitted	14b
Shear failure	Diagonal cracks of the column near joints and at the middle of the column, crushing of the column majorly near the joints	• Stirrups provided in the column are not sufficient (Single hoop). • Rebar size that is used is of minimum diameter (usually 5 mm to 7 mm) • Hoop provided is 90° with minimum length (20 mm to 50 mm)	15a

Flexural failure	Crumble of concrete, yielding of rebar, racks near the joints, formation of hinge (ultimate condition)	• Main rebar provided in the column are not sufficient (normally four bars of diameter ranging from 10 mm to 12 mm). • Overlapping length is minimum (usually 150 mm to 300 mm) • Overlapping location is also not appropriate (major problem) • Confinement reinforcement are not provided • Size of the column is 230 mm by 230 mm majorly • Orientation of the column is not appropriate	15b
Brittle failure	Separation of beam from column	• Adequate anchorage length of the column is not provided (major problem) • Main bar provided in the beam and column is not sufficient • Extra bar that need to provide in the beam column joints are omitted	15c
Buckling failure	Buckling of column, spalling of the concrete, bending of the rebar	• Due to slenderness of the column • Axial loads transfer to column is in the critical state	15d
Flexural failure of slabs	Cracks in concrete, sagging of the slab, delaminating of concrete covers	• Main rebar is not sufficiently layout • Meshing of the rebar is same for any kind of slab size • Thickness varies (100 mm to 175 mm) • Lack of proper detailing of the slab rebar • Poor concrete quality	16

Table 3: Non-Structural Damage of Buildings.

Failure mode	Types of damages	Causes	Fig. no.
Infill wall	Out of plan damage, crushing of wall diagonally or at toe and heel, shearing of bed joints, separation between the wall and the frame	• Lack of sill band and lintel band • Diagonal strut action • Due to strong infill surrounded by a strong frame • Weak joints and strong members • Strong infill and strong frame but vibrate differently	17
Water tank failure	Bare framed supporting polythene tank collapsed, formation of plastic hinges in the upper and lower edges of column	• Large inertia forces due to water tank mass	18
Staircase	Damage at the junction of the landing and the flight, sagging or drop down of the landing, total collapse	• Rebar detailing problems • Minimum use of main bar (8 mm to 10 mm) • Short column effect • Deck thickness varies from 75 to 125 mm	19
Parapet failure	Partial and totally collapsed	• No anchorage is provided • Built as secondary element with no proper design	20
Poor quality of materials	Cop-outs and spalling of concrete, material deteriorates effortlessly, breakage of corroded rods, loss in capacity of rods, corrosion can to spread to other parts, possibility of vanish of rods due to corrosion	• Pilling out/cop out the cover of the concrete in structural components • Breakage of the rod due to size reduction of rebar due to corrosion	21

2.3 Damage and Failure Mode of URM Buildings

Table 4: Damage and Failure Mode of URM buildings.

Failure mode	Types of damage	Causes	Fig. no.
Shear failure	Diagonal cracks at corner of openings and at center of wall segment	• Stress concentration at corners of windows and doors • Absent of sill and lintel band	22
Tension failure	Vertical cracks at the center, ends or corners of the walls	• Walls too high and too narrow • Openings too close to corners	23
Out-of-plane failure	End masonry walls failure, bulging of masonry wall, delamination of wall leaf	• Lack of structural integrity • Deficient bond at corners continuous vertical joints (wall to wall connection) • Flexible floor diaphragm • Trusting nature of sloping roof • Ineffective or lacking passing-through connections in multileaf masonry assemblages	24
Spandrel failures	Cracks between two openings one above the other	• Flexible floor diaphragm • Absent of sill and lintel band	25
Pounding	Cracks at the floor level, sway of buildings	• Lack of space between two buildings	26
Torsion and warping Failure	Larger damage occurs near the corner of the building, excessive cracking due to shear in all walls	• Unsymmetrical in plan and elevation of building • Imbalance in the sizes and positions of openings in the walls	27
Mixed mode failure	Partial collapse or total collapse	• Accumulation of in plane out of plane and corner effects • Corner buildings in row housing	28
Roof failure Overturning failure	Dislodging of roofing material, separation of roof truss from supports Sliding of the whole building	• Improperly tied roofing material • Lack of tie rod or tie beam • Weak support connection • Heavy roof material • Weak foundation design	29 30

3. Construction practices on buildings

Most of the buildings of Kathmandu valley are of two categories: (i) reinforced concrete buildings with burnt brick infill wall and (ii) unreinforced masonry buildings.

3.1 Construction practices of RC buildings

With the advancement of the construction materials, and its easy availability, reinforced concrete buildings have become the choice of many people. In major cities of Nepal, RC buildings with infill masonry wall are rampant. The building story varies from G + 1 up to G + 17 story height in Kathmandu valley. The high-rise buildings are mainly concentrated in Kathmandu, capital city of Nepal, and such buildings are very rare in other cities of Nepal. The residential RC buildings constructed in Kathmandu valley are normally in the similar construction practice. Most of these buildings are non-engineered design. The common practice of building home is that house owners have to submit architectural drawing maintaining all the criteria under architectural norm to the local government. If the architectural drawing meets all the criteria, the concern authority will approve the drawing and the house owners can proceed with the construction. The main lacking stuff here is the structural designing, ductile detailing and the working drawing. The concerned authority is not focusing in these things, although, these are the major issues that matters for building the earthquake resisting buildings. On other hand, some concerned authorities are limiting the norms and building codes in paper only and there is lacking in its implementation and supervision. In such situation, almost all reinforced concrete buildings are in the hands of the masons and they construct buildings according to their workability. Some of the poor practices that are common in construction of buildings are listed below.

1. In the commercial areas, the ground floors/basements are open for the purpose of shopping, parking, reception and lobby which are without infill walls, while the upper stories are divided into small rooms by using brick infill walls which may results in soft storey failure ;
2. In order to cover up maximum area, upper stories are constructed more in balconies. In such practices, floating columns from first storey are commonly observed in residential construction within as well as outside Kathmandu valley . This leads to buckling of the column of the ground floor due to lack of continuous load path during earthquake..
3. To increase the room size of the building there is a practice of extending the cantilever beams/slabs in the frontal façade of the building, in which ultimately the peripheral wall rest, probably in every story;
4. Modifications of the building horizontally (i.e. extension of rooms by demolishing of partition walls and structural elements like columns and beams, etc.) and vertically (i.e. addition of new story, water tanks, etc.) are common practice;
5. The building plans are normally square or rectangular shaped and its dimension varies with availability of land. The floor height ranges from 2.4 m to 3 m with 5 to 6 story level in general;
6. Beams are normally 2 m to 4 m (exceptional case N4 m) in span, owing to irregular column spacing. In many buildings, beam reinforcement consist of four longitudinal bars of diameter ranging from 10 mm to 16 mm. Transverse stirrup bars are usually 6 mm to 8 mm in diameter placed at a spacing of 100 mm to 250 mm and end of stirrups are usually terminated with 90° hook;
7. Columns are normally rectangular in cross sections with typical dimension 230 mm × 230 mm, and in some places 230 mm × 300 mm. Longitudinal reinforcement consists of four bars of diameter that ranges from 10 to 16 mm depending upon the mason. Transverse reinforcements

consist of a single loop of 6 mm to 8 mm diameter having 90° hooks spaced at 100 mm to 250 mm and terminated at the joints. The longitudinal reinforcement are spliced often just above the floor slab without sufficient lapping length. Use of special confinement rebar at the lapping section and near the beam and column joints, are totally avoided;

8. Slab thickness ranges from 75 mm up to 150 mm, which is casted monolithically with the beam. In some cases, slabs are directly casted in column without beam. The main reinforcement in slab is 6 to 8 mm diameter at a spacing of 150 mm c/c to 200 mm c/c in both directions; •Shallow isolated square footings are popular in foundation constructions. Normally its depth varies from 3 ft to 5 ft from ground level and the foundation mesh is of size 4 ft × 4 ft to 5 ft × 5 ft. Dowel rebar and confinement rebar are not used in column near footings;
9. Tie beams inter-connecting the footings are very rare in practice, and if constructed, it is normally of size 230 mm × 230 mm with four main reinforcement bar of minimum diameter of 10mm or 12 mm;
10. Integrity of infill wall with the column using lintel bands and sill bands is also very rare in practice;
11. Poor workmanship and poor construction materials are more common.

3.2 Traditional constructional practice of URM buildings

URM building construction is the predominant building type for traditional residential housing in the old cities of Kathmandu valley. These building structures might be considered as non-engineered structures, as their large majority were build prior to the existence of modern construction codes. Most of the traditional residential buildings were constructed with longitudinal and transverse direction masonry walls and these walls are the main load bearing system of the buildings. However, in case of row housings, there is only one directional load bearing system, i.e. façade and rear wall with intermediate wall or timber frames in between them to rest the floor joist along the span. The other walls constructed were only as a partition wall, with very little anchorage to the main walls, thus leaving a clean joint between perpendicular walls. Hence, corner walls easily separate during the earthquake jolts as shown in Fig. 3.

The thickness of the masonry walls ranges from 500 mm to 750 mm with three layers in a single cross-section. In façade of most of the traditional building, the outer face of the wall is made of fired clay bricks with smooth finishing and the inner face is made of sundried bricks. However, in the Nepalese traditional masonry wall construction practice, there is a lack of passing-through connections between the wall layers, as a result, delamination of the outer wall layer is predominant, as shown in Fig. 4. Moreover, in the case of multi-story buildings, masonry wall thickness is not uniform throughout the height. Wall thickness reduces from ground story to top as shown in Fig. 5, causing irregularities in elevation.

Horizontal structural systems, floors and roofs, were traditionally constructed using timber elements. Floor structures vary significantly between adjacent and apparently similar buildings. Timber joist floors are common, spanning in one or two directions in the older buildings, built using simple battens or joists upon which timber planks are laid. These in turn support the final floor finish. In the case of roof construction practice, most of all the roofs are one way predominantly sloped at around 10°. Construction of roofs is generally with timber rafter covered with tiles laid over mud mortar or metal sheet. These traditional construction practices of horizontal structural system show a vulnerable construction practice [16]. Since flexible floors and/or roofs offer no restraint to out-of-plane bending of walls, and absence of a ring-beam and heavy roofs increase inertial mass, these lead to a higher base shear.

In exception, many traditional buildings were modified in due time duration. Non-engineered modification includes cement mortar masonry being built above mud mortar masonry (Fig. 6a), burnt brick masonry being built above sun dried brick masonry (Fig. 6b), and RC or timber frame structure being built above masonry walls (Fig. 7). These modifications cause irregularities in elevation, which adversely may limit the structural performance to horizontal actions. Moreover, floor and roof constructions include RBC or RC floor. Unfortunately, many buildings consist of mixed floor system, i.e. timber joisted floor in lower few story, and RC or RBC floors in few story above (see Fig.8). Many houses have replaced their previous tile or metal roof with RC roof.

On the basis of, the above mentioned basic traditional technology features, it can be concluded that our ancestors have erected buildings following very simple construction rules and details, to comply with seismic resistance requirements. In addition, no engineered modification carried out is even worst with correspondence to seismic resistance requirement.

4. Conclusion

The RC, URM, random rubble construction and adobe construction were found to be the dominant construction systems of Nepal. This paper discusses about the damages in these types of buildings induced by the 2015 Gorkha earthquake. The damage patterns that were observed in RC buildings were beam column joint failure, short column damage, soft storey damage, lap splice damage, in-plane and out of plane failure and pounding failure. Similarly the modes of failure in masonry buildings were diagonal crack, out of plane collapse, multi- leaf wall failure and gable failure. Separation of diagonal walls and gable collapse was observed for adobe houses. The buildings were mainly destroyed in this earthquake because of the poor construction practices and structural deficiencies. It has been observed that the main causes of failures in RC buildings are soft storey, floating columns, mass irregularities, poor quality of construction materials, faulty construction practices, ground rupture, soil and foundation effect and pounding of adjacent structures. Similarly, the principal factors that influence damage to URM buildings are lack of integral action, lack of strong and ductile connections between walls, low tensile and shear strength of masonry, high in plane stiffness of wall, inadequate strength for out-of-plane forces, non-uniform rigidity distribution, low ductility and deformability capacity, heavy mass, foundation types, construction quality and non-engineered modifications. Similarly, in adobe constructions the leading cause of damage were binding and structural integrity, lack of tying members, heavy gable and roof construction. The seismic resistance capacity of masonry construction is relatively low in comparison to reinforced concrete construction.

Based on recognition damage survey, this paper highlights that traditional masonry constructions are highly fragile as well as the recent RC constructions in Kathmandu valley. This earthquake have shown that all the damage was noticeably concentrated into non-engineered or pre-engineered buildings with major flaws in construction or structural components. This proves that the construction technology that mostly prevail in Nepal is very poor and requires strict law to follow Nepal building code. In order to minimize earthquake induced damages in the future, building design should ensure adequate strength, stiffness, and high ductility. For a seismically active region like Nepal, engineered construction is the credible solution.

5. Recommendation for preventive measures

Buildings that suffered low to heavy damage during the Gorkha earthquake were found not to be following the by-laws and building codes properly. While no structure can be entirely immune to damage from earthquakes, the goal of earthquake resistant construction is to erect structures that can resist earthquake without collapse. Based on the different types of damage patterns observed and their associated constructional and structural deficiencies, this paper provides the following recommendations to reduce the effect of future seismic force on the buildings.

1. Failure of a column can affect the stability of the whole building, but the failure of a beam causes localized effect. Hence it is better to make beams to be the ductile weak link. This method of designing RC building is called the strong-column weak-beam design method. Columns should be stronger than beams and foundations should be stronger than columns. Connections between beams & columns and columns and foundations should not fail so that beams can safely transfer forces to columns and columns to foundations.
2. Geotechnical investigation is seldom done for residential buildings in Nepal. The selection of type of foundation should take into account various factors like soil strata, bearing capacity of soil, type of structure, type of loads, permissible differential settlement and economy.
3. Ductile detailing in RC members and the connection between structural component sshould be as per the code and its layout and workmanship should be strictly monitored by engineers. As shear failure is brittle, it must be avoided in designing RC buildings.
4. RCC bands such as gable band, roof band, lintel band, sill band, and plinth band and stitches should be provided in load bearing structures providing ductility as masonry buildings are brittle thus minimizing the damage.
5. The quality of the construction materials should be checked and the mixing and placement of concrete should be monitored by controlling the water cement ratio which is usually exceeded for achieving workability compromising the strength of concrete.
6. Shear walls - walls built for the sole purpose of adding lateral stability should be provided on the ground floor or basement to counter soft storey failure.
7. The trend of row housing should be discouraged and the built up area should be as per the code to prevent from pounding. As per Nepal building code, the height to breadth and length to breadth ratio should be restricted to less than 3.
8. The gross area of openings in infill walls should be restricted to 10% as provided by NBC.
9. All flexible structural elements such as beams, joist and rafters should be diagonally braced in masonry structures.
10. Clay is the most important component of the soil used in adobe construction which provides dry strength, however it also causes drying shrinkage of the soil. Controlled micro cracking of the soil mortar due to drying shrinkage is needed for strong adobe masonry construction. Straw and, to a lesser extent, coarse sand are additives that control the micro-cracking of the mortar due to drying shrinkage, and therefore improve the strength of adobe masonry.
11. A foundation made of concrete or brick masonry should be provide damp proofing for adobe walls.
12. A robust layout with limitation to only one storey should be implemented.
13. Integration of ring beam which ties the walls together and ensures that the building behaves like a box should be done for load bearing masonry walls.
14. Promote awareness to locals about the importance of an engineered building to minimize the damages induced by earthquake for a seismically active region like Nepal at different forums and media platform.

6. Recommendation for future studies

1. Conduct the research in a larger scale collecting information from different districts that were affected during the Gorkha earthquake.
2. To formulate measures to retrofit the existing buildings that suffered low degree of damage.

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