Seismic vulnerability of vernacular Newari buildings in Nepal: observations and analysis of damage due to 1934, 1988, 2011, and 2015 earthquakes

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Abstract. This paper reports the seismic vulnerability of vernacular Newari buildings based on the damage observations during four major earthquakes (1934, 1988, 2011 and 2015) that struck Bhaktapur city. Some specific features that contributed to collapse prevention in traditional masonry buildings are also highlighted in this paper. In this paper, we have outlined the insights of each earthquake using forensic interpretations and the recommendations by various researchers after 1934 and 1988 earthquakes are compared in terms of their implementation. With the help of damage database recorded during 1934, 1988 and 2015 earthquakes, we have created damage probability matrices and empirical fragility functions for traditional masonry structures. The fragility functions and damage probability matrices derived in this study highlight that most of the vernacular Newari buildings are likely to be collapsed in the case of strong to major earthquakes.

1 Background

Since the recorded history of earthquakes in Nepal that affected Kathmandu valley; Bhaktapur city has been identified as the area that sustains severer damage than other neighboring towns. As systematic records of earthquake damage are available since the 19th century only, little is known about the devastating earthquakes historical earthquakes until 18th century. To this end, the available record of 1833 earthquake (M_L 7.7) can be considered as the more detailed one although it is not exhaustive. Bilham (1995) reported that 410 fatalities and more than 4000 buildings were recorded to be damaged in Kathmandu valley alone due to the 1833 earthquake. Following the 1833 earthquake, notable seismic events from 1834, 1917, 1934, 1936, 1938, 1952, 1953, 1954, 1958, 1959, 1962, 1964, 1966, 1970, 1972, 1973, 1974, 1984, 1986, 1987, 1988, 2007, 2011, 2014 and 2015 have affected Kathmandu valley (Rana, 1935; Gupta, 1988; Fujiwara et al., 1989); however, accounts of building damage are available for 1934, 1988, 2011 and 2015 earthquakes only. Recently, a magnitude 7.8 earthquake struck central on 25 April 2015. Together with notable aftershocks of 25 April 2015, 26 April 2015 and 12 May 2015, Gorkha earthquake destroyed l498852 buildings whereas other 256697 buildings were partly damaged (NPC, 2015). Consistently, Bhaktapur was the most affected town in Kathmandu valley during 2015 Gorkha earthquake. Bhaktapur is one of the oldest (13th century) town in

Kathmandu valley with unique row housing settlements and cultural constructions in the form of vernacular Newari buildings [locally called as '*Chhen*']. More than 80% of buildings in the historic town of Bhaktapur are the brick masonry in mud mortar constructions that are highly vulnerable to earthquake shaking due to lack of several seismic features which will be discussed in the following sections of the paper. Historical records of 1833 earthquake as depicted by Rana (1935) and Bilham (1995)

5 suggest the widespread damage of vernacular masonry buildings in Bhaktapur. Similarly, the accounts of Gupta (1988) and Fujiwara et al. (1989) highlight the consistent scenario of building damage in Bhaktapur; that is severer than the neighboring towns in Kathmandu valley. During 2011 Nepal-Sikkim border earthquake, some brick masonry buildings in Bhaktapur were damage whereas no notable damage was observed in other areas of Kathmandu valley. During Gorkha earthquake, Bhaktapur was the most affected town due to widespread collapse and partial damage of brick masonry buildings. This consistent damage

10 scenario confined to Bhaktapur motivated us to explore the underlying vulnerability of vernacular masonry buildings of Bhaktapur that could be useful in the case of future earthquakes. To fulfill this objective, we interpreted the damage occurrence for available records along with the field investigations performed after 2011 and 2015 earthquakes. Forensic analysis is used to highlight the underlying vulnerability of the vernacular buildings. To the best of authors' knowledge, seismic vulnerability of such vernacular buildings is not reported till now, so we present the detail accounts of forensically interpreted damage

15 scenario during several earthquakes. Moreover, seismic vulnerability of vernacular brick masonry buildings is outlined in terms of damage probability matrices and empirical fragility curves.

2 Vernacular Newari buildings in Bhaktapur

Bhaktapur is a densely populated medieval town situated 12 km east of Kathmandu (Fig. 1). Until 2014, nearly 18600 building were constructed within 6.88 km^2 area and more than 80% of the total buildings were the vernacular brick masonry ones.

20 Vernacular Newari buildings are unreinforced brick masonry buildings usually having three to four stories (Fig. 2). A shallow foundation of bricks is provided in vernacular buildings. The first story comprises large openings to run small businesses whereas the upper stories constitute lesser opening percentage. Vernacular buildings are generally rectangular and constructed usually in gently sloping terrain. The thickness of brick masonry wall varies between 250 and 600 mm (see Fig. 3). In the third and fourth stories, timber posts are also provided and wooden staircase is provided for vertical transportation. As shown in

25 Fig. 2, first floor is used for commercial activities; second floor is used for bedrooms; third floor is used for living rooms; and the fourth floor is used as kitchen. In general, box gable roof is provided in vernacular masonry buildings, meanwhile, roofing material is dominantly the roof tiles. Upper stories are usually provided with depressed and projected windows whereas the lower stories comprise dormer or lattice windows. Fig. 3 shows a typical section of vernacular brick masonry building that comprises mud mortar, brick layer, wooden plank and timber beam. Two types of wall partitioning can be observed in

30 vernacular buildings: either throughout masonry wall or wooden planks guided one.

3 Seismic performance of vernacular Newari buildings during major earthquakes

3.1 Bihar-Nepal earthquake

The 1934 Bihar-Nepal earthquake is the strongest earthquake (M_W ~8.4) in the modern history of Nepal. The epicenter of the earthquake was in eastern Nepal and the effect of earthquake was observed throughout Nepal and northern India. Rana (1935)

5   reported the focal depth to be ~24-40 miles taking into consideration of public opinion. Rana (1935) reported that the effective shaking was of 2-3 minutes and whereas the total shaking was felt for around 8 minutes. Furthermore, Rana (1935) noted that the shaking was initially horizontal and then circular. Vertical shaking was also reported to be dominant by Rana (1935) during Bihar-Nepal earthquake. Rana (1935) estimated the ground peak ground velocity in the range of 285-345 cm/s, although this estimation comes from Rana's own experience, however, such figures depict strong ground shaking during the earthquake.

10   Although, the epicenter of the earthquake was nearly 150km east of Bhaktapur, severe damage was occurred in Bhaktapur. Such intense damage was attributed to site characteristics of Bhaktapur (alluvial deposit), construction technology, building population and vulnerability of building stocks. Reports of building damage due to Bihar-Nepal earthquake are presented in the following section.

3.1.1 Reported building damage in Bhaktapur

15   In total, 6224 residential buildings were damaged due Bihar-Nepal earthquake (Rana, 1935). More than 177 heritage structures were also damaged due to the earthquake. The most common failure mode was reported to be the combination of in plane and out of plane mechanism as shown in Fig. 4a. Apart from this, poor binding among the masonry units can be observed in damaged wall section. Fig. 4b depicts the collapse of heavy gable wall as contemporary practices were based on homogenous walls throughout the building.

20   Rana (1935) reported that the damage range was between 40-100% for various settlements within the town and outlined the causes of damage as: a) multistoried buildings; b) buildings with higher opening percentage; c) structural pounding in case of row housing; d) buildings constructed with low quality bricks (unbaked ones) ; e) improper bonding between the brick units; f) load concentration in the upper stories and gable; g) poor site selection and foundation problem (unleveled); h) buildings undergone with incremental construction; i) projections; and j) lack of integrity between the orthogonal walls.

25   Pictures of damage taken by Rana (1935) confirm that the buildings in the corner of row housing settlements were damaged more than the standalones. This may be due to combination of vulnerability as well as additional lateral load imposed by other structures.

The description presented by Rana (1935) also considered some of the improvement measures for post-earthquake reconstruction as: a) use well dried and proper dimension bricks with smooth finish for construction; b) Oil mixed and dried

30   bricks "*Chiga: appa*" is better than other brick types; c) do not construct more than a story with raw bricks; d) use light roofing; e) limit the height of vernacular buildings to 51 ft.; f) mix cow dung for improved mortar quality; g) use timber posts rather than brick pillars; h) avoid river banks, land plots beside the ponds for construction; i) provide timber band "*Nas*" in in masonry

walls; j) reduce weight of gable portion; k) provide sufficient masonry wall in between the openings; l) lime as mortar is superior than mud mortar or mud with cow dung; m) determine building height and foundation depth per the quality of construction materials.

3.2 Udaypur earthquake

5   After the 1934 earthquake, Bhaktapur was hit by several moderate earthquakes until 1988, however, notable structural damage was not reported. Udaypur earthquake (M_W 6.8) occurred in 1988 ~150 km southeast of Kathmandu. During this earthquake, Bhaktapur was the most affected town in Kathmandu valley. The Modified Mercalli Intensity (MMI) for Kathmandu valley was assigned to be V and peak ground acceleration was estimated to be ~20-50 gals (Fujiwara et al., 1989). The maximum MMI intensity for Bhaktapur was estimated ~7.40 whereas neighboring towns Kathmandu and Patan were assigned to 6.67

10   and 6.57 maximum intensity respectively by Fujiwara et al. (1989). Gupta (1988) and Fujiwara et al. (1989) reported that most of the damaged buildings were the survivors of the 1934 earthquakes.

3.2.1 Reported building damage in Bhaktapur

During Udaypur earthquake 274 buildings collapsed and other 1477 buildings observed partial damage throughout Bhaktapur district. Due to lack of statistical records in localized scale, exact scenario of damage distribution is not possible to outline;

15   however, the descriptions provided by Gupta (1988), Fujiwara et al. (1989) and Dixit (1991) suggest that the town of Bhaktapur was the most affected. Fujiwara et al. (1989) has reported that the houses partly damaged during 1934 earthquake were used without any repair and the damage was intense in such structures. The construction practices as highlighted by Gupta (1988) and Fujiwara et al. (1989) reflect that there were no indications of the improved construction practice per the recommendations of Rana (1935) after the 1934 earthquake. Gupta (1988) and Fujiwara et al. (1989) identified the causes of building damage

20   in Bhaktapur as: a) buildings situated in sloping ground (Fig. 5); b) building constructed using mud-mortar; c) buildings constructed up to four to five stories in brick masonry without any earthquake resistant provision (Fig. 5); d) structural pounding (Fig. 6); e) poor quality of construction material for foundation; f) poor mortar quality; g) separation of masonry units due to shrinkage in mud-mortar; h) marginal construction in corner joints and joints occurring in between different walls within the diaphragm; i) non-dried clay bricks used in walls; j) lack of diaphragm action due to improper timber joists; k)

25   heavy gable construction and roofing (Fig. 7); l) heavy masonry wall (thickness ~500 mm); m) in-plane and out-of-plane mechanisms (Fig. 8); n) improper opening placement (Fig. 9); and o) cantilevered projections.

Following their field investigation, Fujiwara et al. (1989) recommended some measures for earthquake resistant constructions as: a) lower the overall building weight by avoiding the brick topping on floor level and replacing the heavy roof by corrugated iron sheets or thatch; b) restrain the gable wall along with the main structural walls below it so that a matchbox type

30   construction could be developed that assures better structural integrity; c) place horizontal bracing for roof and floor slabs and also provide diagonal bracing at the corners; and d) improve mortar quality.

3.3 Sikkim-Nepal border earthquake

The Sikkim-Nepal border earthquake (M_W 6.9) affected primarily eastern Nepal but few cases of vernacular masonry damage in Bhaktapur were observed during the field reconnaissance. The earthquake occurred ~270 km east of Kathmandu valley at a focal depth of 19.7 km (USGS 2011).

5   During the field investigation, it was known that the damaged buildings were the ones already partially damaged due to 1988 Udyapur earthquake. Although the accelerometric records in Kathmandu valley show low peak ground acceleration (~0.05g), some of the buildings in Bhaktapur sustained partial collapse and some others sustained partial damage. Interestingly, some of the already bulged buildings due to the 1988 Udaypur earthquake remained unaffected in some locations of Bhaktapur. Notably, two cases of out of plane wall collapse were observed (Fig. 10a) in Bhaktapur. In addition, one case of structural

10 pounding was noted probably due to sharp variation in dynamic properties among the adjoin buildings (Fig. 10b). Damages in heavy gable wall (Fig. 11a), cracks on masonry walls especially at corner region (Fig. 11b), and damage in heavy roof (Fig. 11c) were identified other observed damage modes during the field reconnaissance. Since1934, the construction strategy was not found to be changed as the similar failure modes and construction materials and technology were observed during field reconnaissance.

15 ### 3.4 Gorkha earthquake

The 2015 Gorkha earthquake (M_W 7.8) affected the ancient Bhaktapur town heavily that can be roughly compared to the damage occurred during 1934 earthquake. The epicenter of Gorkha earthquake was located ~78 km N-NE of Kathmandu valley in Barpak village of Gorkha district. Several factors like local amplification and construction technology responsible for structural damage and the accounts of building damage in regional scale are presented by Gautam et al. (2016) and Gautam

20 and Chaulagain (2016). In the case of Bhaktapur, almost 80% building stocks were the vernacular Newari houses and most of remaining buildings were the substandard RC buildings (for details see: Chaulagain et al. (2013). During Gorkha earthquake, relatively lower value of PGA and short duration of shaking may have altered the damage scenario and hence previous loss estimation models depicted by Chaulagain et al. (2016) was not able to represent the actual damage scenario.

3.4.1 Report of building damage in Bhaktapur

25 Although the intensity of earthquake in Kathmandu valley was generally VIII, some areas of Bhaktapur like; Golmadhi, Suryamadhi, Jela, Byasi were destroyed; that leads in greater than VIII intensity. In the follwoign section of the manuscript, we have assigned IX intensity for Bhaktapur to derive the fragility functions. local scale. Fig. 12 depicts the major collapse locations within Bhaktapur; destroyed settlements are highlighted by large red bubbles. Apart from this, slight, minor and heavy damages were observed in all parts of the town. The major damage locations were towards the eastern fringe of the town

30 and the settlements located on the sloping ground. The summary of component-wise failure modes is presented in Table 1.

3.4.2 Seismic features in vernacular Newari buildings

During field investigation, apart from the widespread damage, significant survival cases were also identified. We observed that the buildings consisting some specific features were either lowly damaged or undamaged when compared to the buildings without such features. We observed that, the features highlighted in Table 2 effectively contributed in collapse prevention and in many cases life safety should have been facilitated by such components too. Table 2 outlines the identified seismic features in vernacular Newari buildings of Bhaktapur.

4 Construction of DPM and fragility functions

Seismic vulnerability of buildings is either presented in terms of damage probability matrices (DPM) or fragility functions (Elnashai and Di Sarno, 2000). Many researchers have formulated fragility functions for buildings worldwide using either analytical (e.g. Hassan and Sozen, 1997; Erberik and Elnashai, 2004; Rota et al., 2010; Parisi and Sabella, 2017), empirical (e.g. Sabetta et al., 1998; Yamazaki and Murao, 2000; Rossetto and Elnashai, 2003; Gautam, 2017), hybrid (e.g. Kappos et al. 2006; Kappos and Panagopoulos, 2010) or expert opinion (e.g. ATC, 1985; ATC, 1996) approaches. To the best of authors' knowledge, fragility functions for traditional Newari buildings do not exist, however their vulnerability is important due to their large population in major urban centers of Kathmandu valley. To address the lack of vulnerability functions or DPM, we have created DPM as well fragility functions using the database of 1934, 1988 and 2015 earthquakes. To create the DPMs, we first defined the mean damage ratio (MDR) for three intensity levels. The mean damage ratio (MDR) at given intensity level (I) can be calculated as:

$$MDR(I) = \Sigma_{DS} \, P(DS,I) \times CDR(DS), \tag{1}$$

Where *MDR(I)* is mean damage ratio at given intensity; *P (DS, I)* is the damage state probability of defined building type; and *CDR(DS)* indicates central damage ratio corresponding to the damage state DS. The damage state probability P (DS, I) can be calculated as below:

$$P\,(DS,I) = \frac{N(DS,I)}{N(I)}, \tag{2}$$

Where $N(DS, I)$ denotes the number of buildings in damage state DS; and $N(I)$ indicates the total number of buildings subjected to the earthquake event. DPMs for VIII, IX and X intensity levels were derived based on the damage data available from historical accounts. The DPMs for traditional masonry buildings is presented in Table 3. The DPMs were subsequently converted into fragility functions by as shown in Fig. 21.

The database was taken from Rana (1935), Gupta (1988), Fujiwara et al. (1989), NPC (2015) and some news outlets. To create fragility functions, we considered peak ground velocity (PGV) as intensity measure (IM) that was estimated from the Modified Mercalli Intensity (I_{MM}) using the correlation proposed by Wald et al. (1999) as:

$$I_{MM} = 3.47 \log(PGV) + 2.35, \tag{3}$$

The estimated peak ground velocities from each of the earthquake were employed to calculate the lognormal distribution parameters as intensity measures (IMs). Several previous studies confirm the lognormal distribution as the representative statistical distribution (e.g. Porter and Kiremidjian, 2001; Beck et al., 2002; Pagni and Lowes, 2006), accordingly we use the lognormal distribution in this study. Two-parameter lognormal cumulative distribution function used to define the fragility functions can be written as:

$$F(C|IM = x) = \Phi\left(\frac{\ln(x/\varepsilon)}{\beta}\right), \tag{4}$$

Where $F(C|IM = x)$ indicates the probability that a ground motion with $IM = x$ will cause the given damage state (minor, severe, collapse); $\Phi(\cdot)$ is the standard normal cumulative distribution function; ε is the median of the fragility function; and β is the logarithmic standard deviation. A summary of the estimated lognormal distribution parameters for minor, severe and collapse damage states is also presented in Table 4 below. Fragility functions for three damage states are derived from the damage data of 1934, 1988 and 2015 earthquakes as shown in Fig. 22.

5 Construction of DPM and fragility functions

Our observations and forensic analysis has led us to conclude that the vernacular Newari buildings are likely to be severely damaged in the case of strong to major earthquakes (MMI≥VIII). Due to lack of periodic strengthening and repairs after the earthquakes and unrelenting use, vulnerability of vernacular buildings in Bhaktapur is very high that may lead to collapse even at moderate shaking. We have presented the damage modes from four earthquakes (1934, 1988, 2011 and 2015), and forensic interpretations confirm that there is not substantial change in the traditional construction practices between 1934 and 2015. The damage probability matrices and fragility functions created from the damage data depict that the collapse damage state is more likely than any other in the case of strong to major earthquakes and that may drastically increase the fatality rate. The upshot of this is the possibility that the damage in Bhaktapur will be greater than any other areas if the vulnerable structures are not strengthened immediately. This research has underlined the importance of identification of local seismic features that could effectively downscale the building collapse. The most important limitation of this research lies in the use of empirical database to create fragility functions, so future studies should develop analytical models to create analytical fragility functions. This is the first step towards enhancing the understanding of seismic vulnerability of vernacular Newari buildings and further work needs to be done to establish possible low cost strengthening solutions as well as retrofitting strategies.

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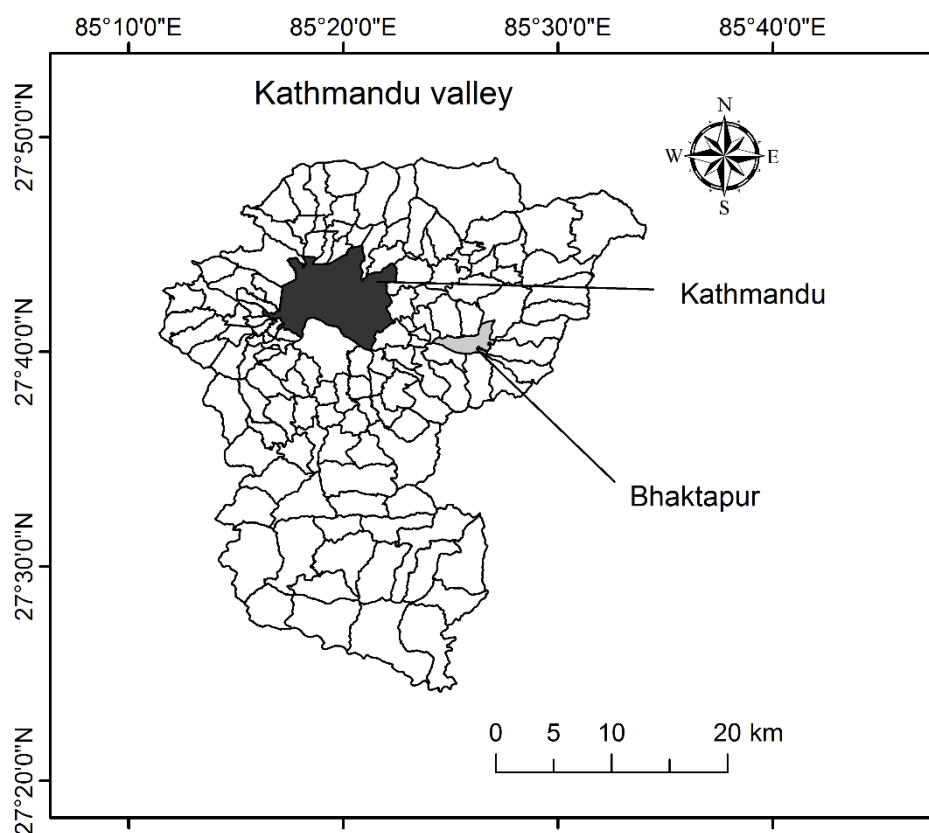
Figure 1: 1 Location of Bhaktapur in Kathmandu valley.
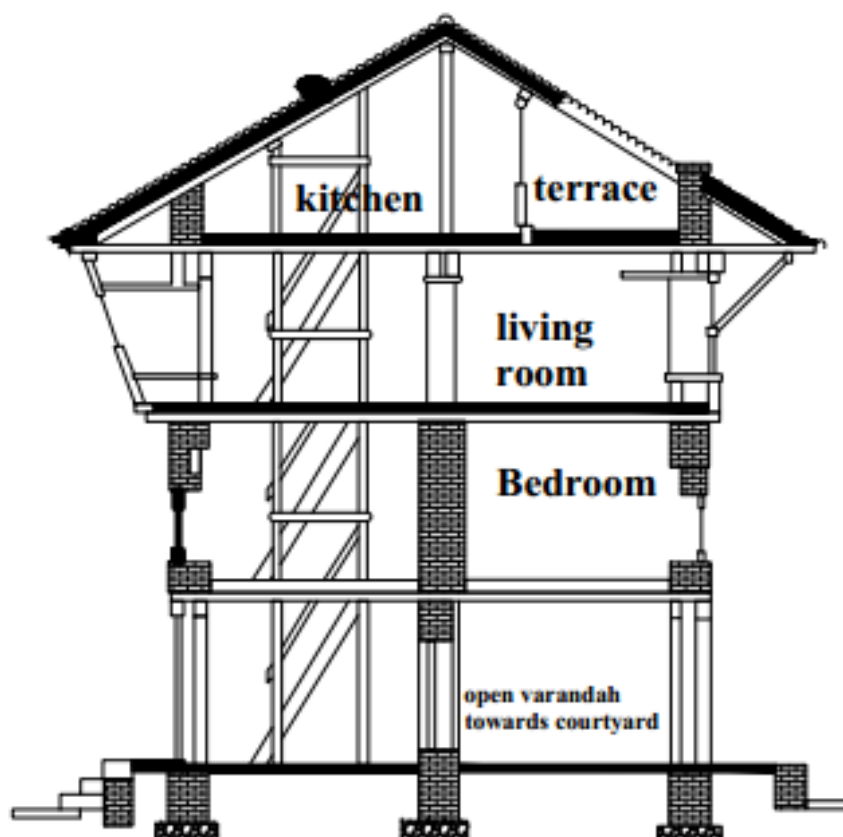
Figure 2: Vernacular brick masonry building.
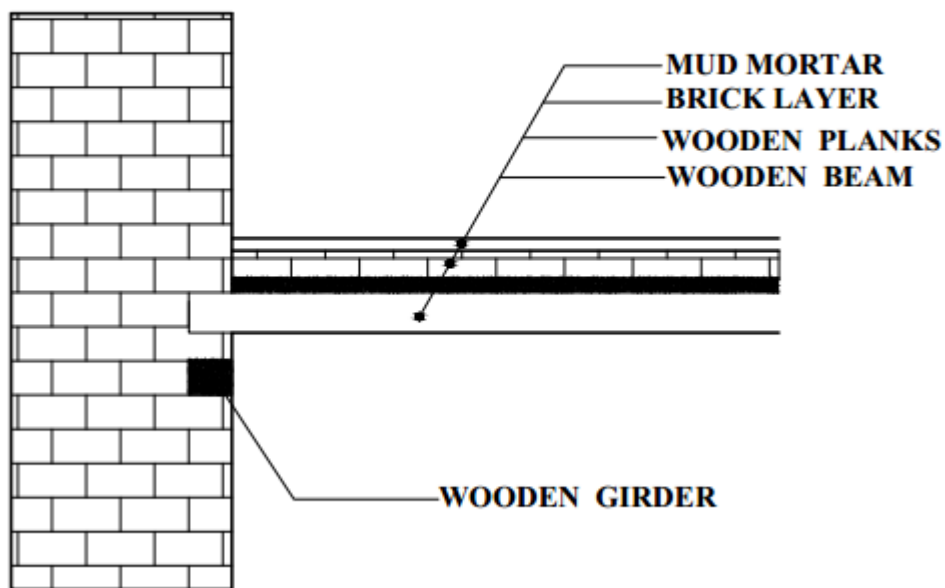
Figure 3: A section of the masonry wall.
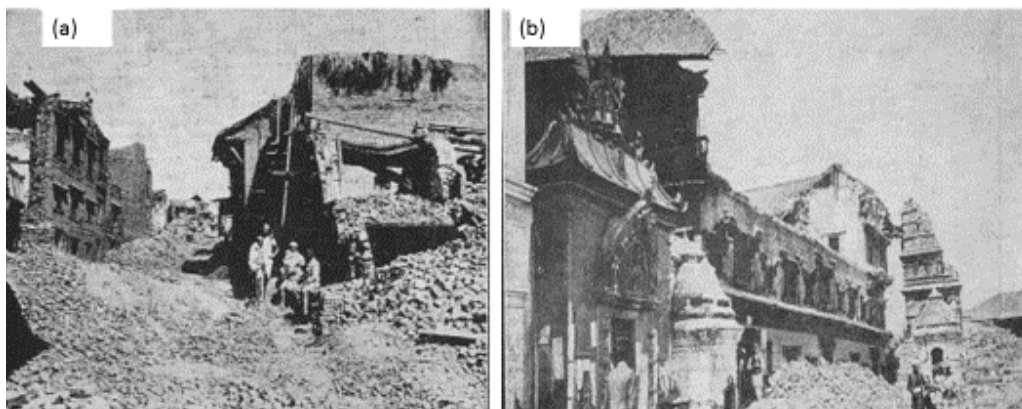
Figure 4: (a) Combined in-plane and out-of-plane failure in masonry walls (courtesy: Rana (1935)) (b) Collapse occurred in the upper story due to mass concentration (courtesy: Rana (1935)).

Figure 5: Damaged houses in sloping ground due to 1988 earthquake (courtesy: Gupta (1988)).

Figure 6: Damage due to structural pounding occurred due to 1988 earthquake (courtesy: Gupta (1988)).

Figure 7: Gable collapse reported by Fujiwara et al. (1989) during 1988 earthquake.

Figure 8: Damage due to in-plane and out-of-plane actions during 1988 earthquake (courtesy: Fujiwara et al. (1989)).
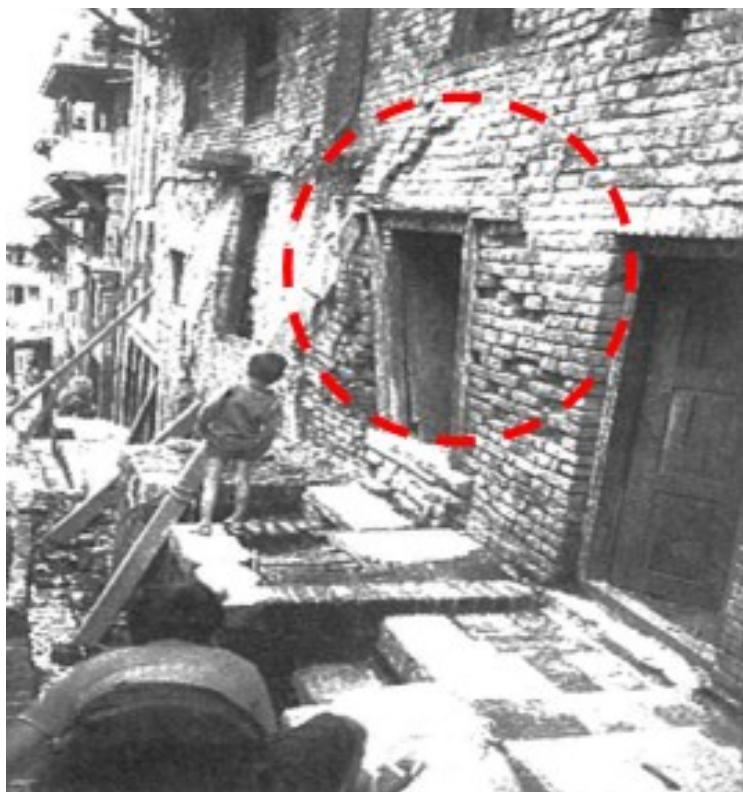
Figure 9: Bulging of wall observed above the doors due to 1988 earthquake (courtesy: Fujiwara et al. (1989)).

Figure 10: (a) Out of plane collapse of masonry wall (courtesy: Ganesh Kumar Bhattarai), and (b) structural pounding due to 2011 earthquake (courtesy: Ganesh Kumar Bhattarai).

Figure 11: (a) Gable collapse occurred in two adjoining buildings (courtesy: Ganesh Kumar Bhattarai), (b) cracks propagated towards the corners (courtesy: Ganesh Kumar Bhattarai), (c) heavy roof collapse and out of plane failure of brick masonry wall occurred due to 2011 earthquake (courtesy: Ganesh Kumar Bhattarai).
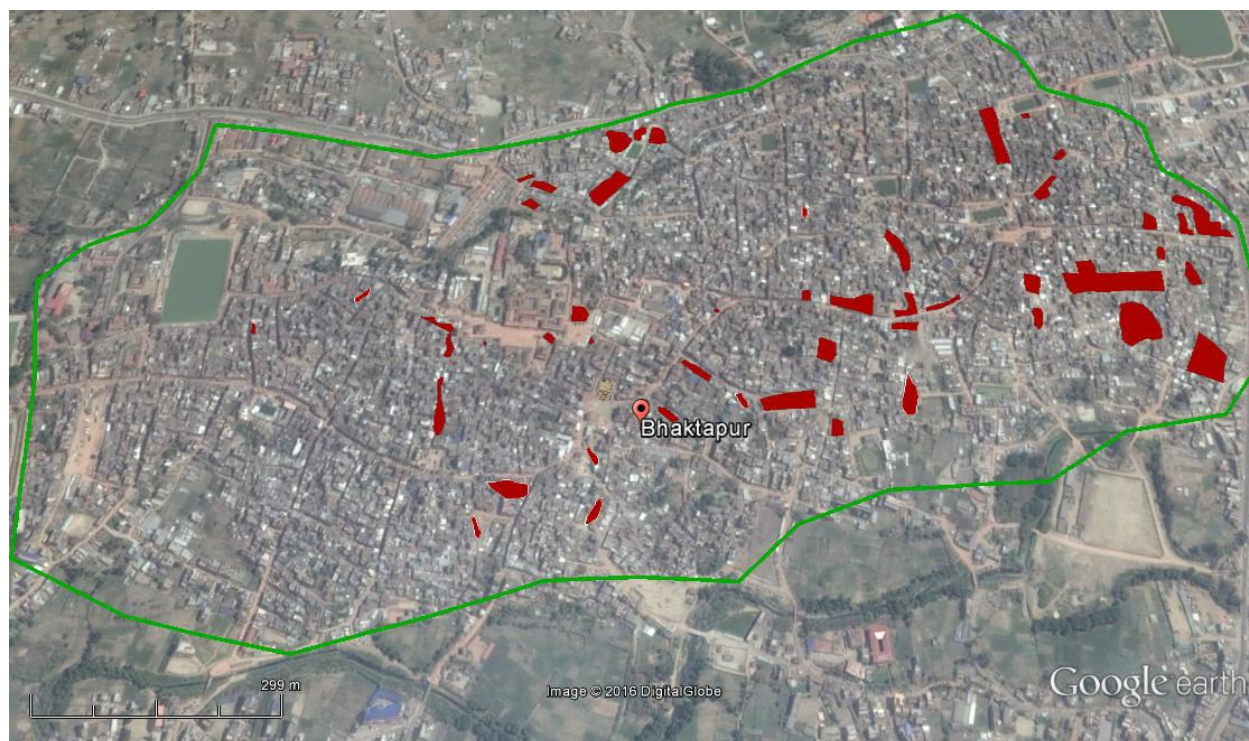
Figure 12: Major building collapse areas within the ancient settlement of Bhaktapur city (modified from: https://www.google.com/earth/).

Figure 13: (a) Minor damage on roof (b) out of plane collapse of walls (c) gable collapse occurred due to Gorkha earthquake sequence.

Figure 14: (a) Undamaged projections supported by cantilevered timber joists (b) collapsed wall on the building situated at the corner of row housing settlement due to Gorkha earthquake.

Figure 15: (a) Separation of orthogonal walls (b) delamination of wythes observed after the Gorkha earthquake.

Figure 16: (a) Reentrant corner damage along with structural pounding (b) separated masonry units and the mud-mortar (c) structural pounding led separation due to variation in dynamic characteristic of jointed buildings observed during Gorkha earthquake.
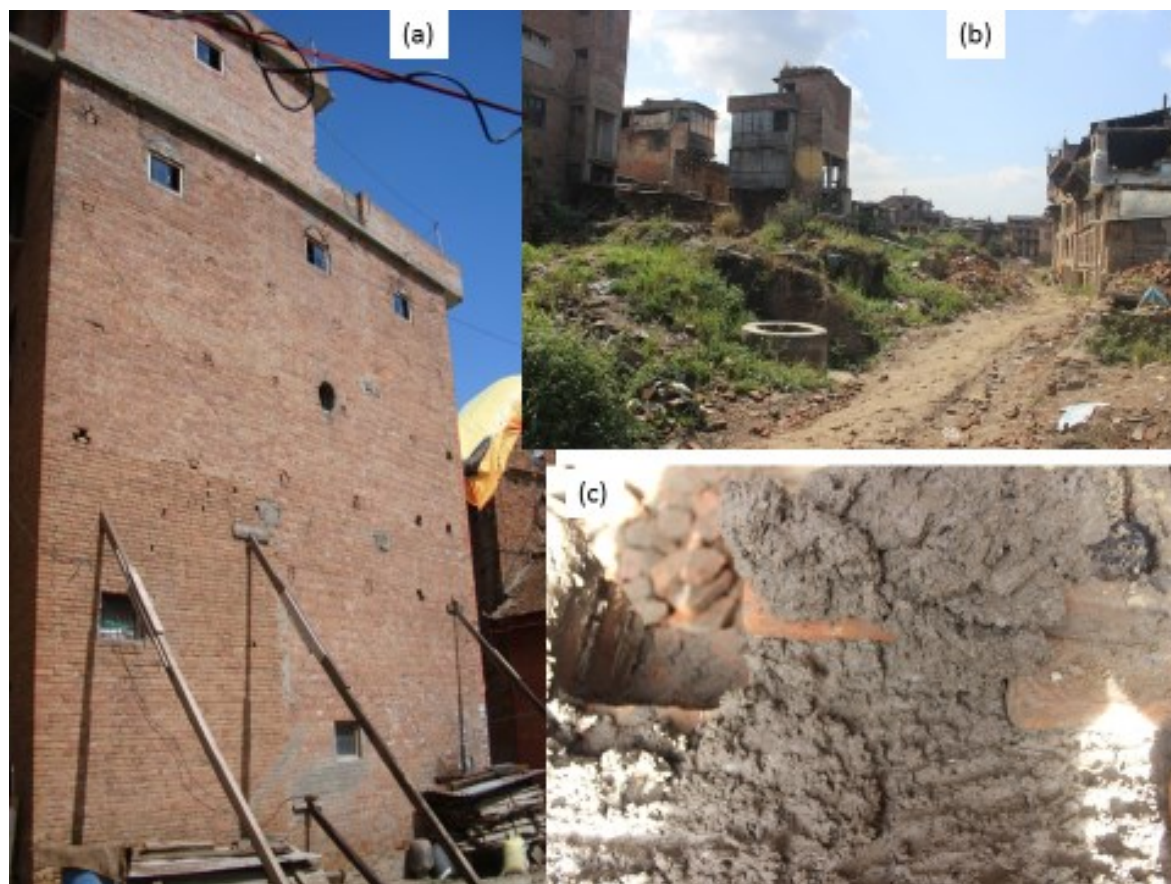
Figure 17: (a) RC slab constructed in pre-existing masonry building that underwent increment construction (b) destroyed neighborhood in Jenla ridgeline (c) mud mortar used for reconstruction after the earthquake.

Figure 18: (a) Building with one masonry and next RC incremental construction above the vernacular masonry construction (b) debris reflects decay of construction material (c) irregular size and poor quality of bricks used for structural wall.

Figure 19: Identified seismic features: (a) plinth constructed in sloping ground (b) symmetrical building practice (c) timber struts for mainstreaming cantilevered load (d) wooden ladder.

Figure 20: Identified seismic features: (a) timber bands at various levels (b) wooden pegs used to stitch connections (c) corner post.
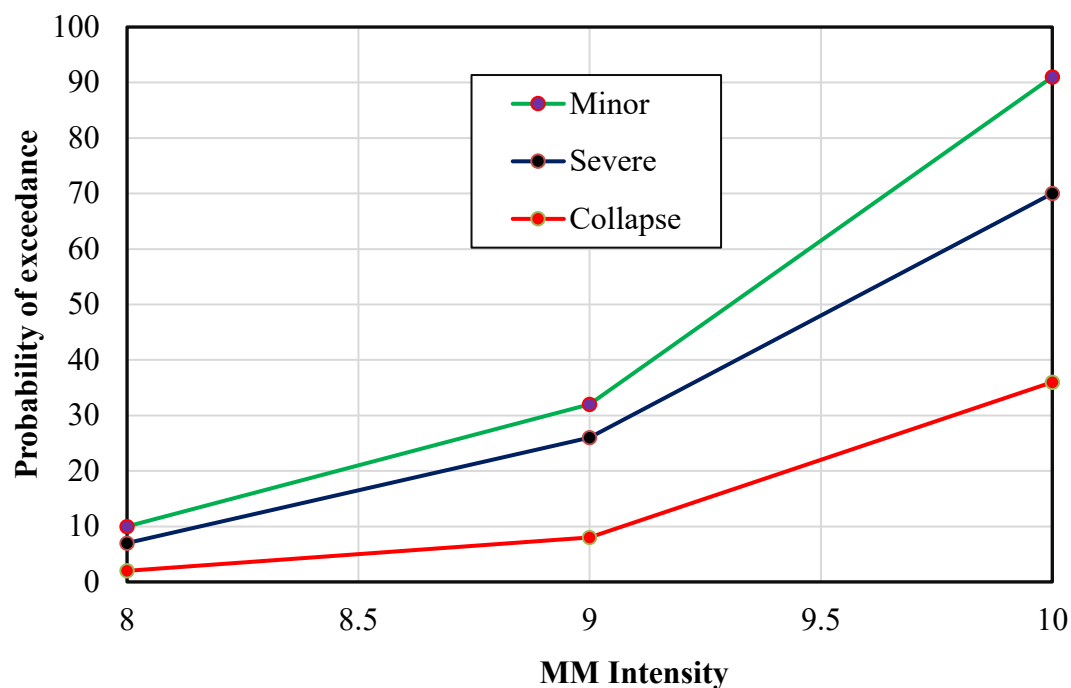
Figure 21: Fragility functions for traditional masonry buildings in Bhaktapur.
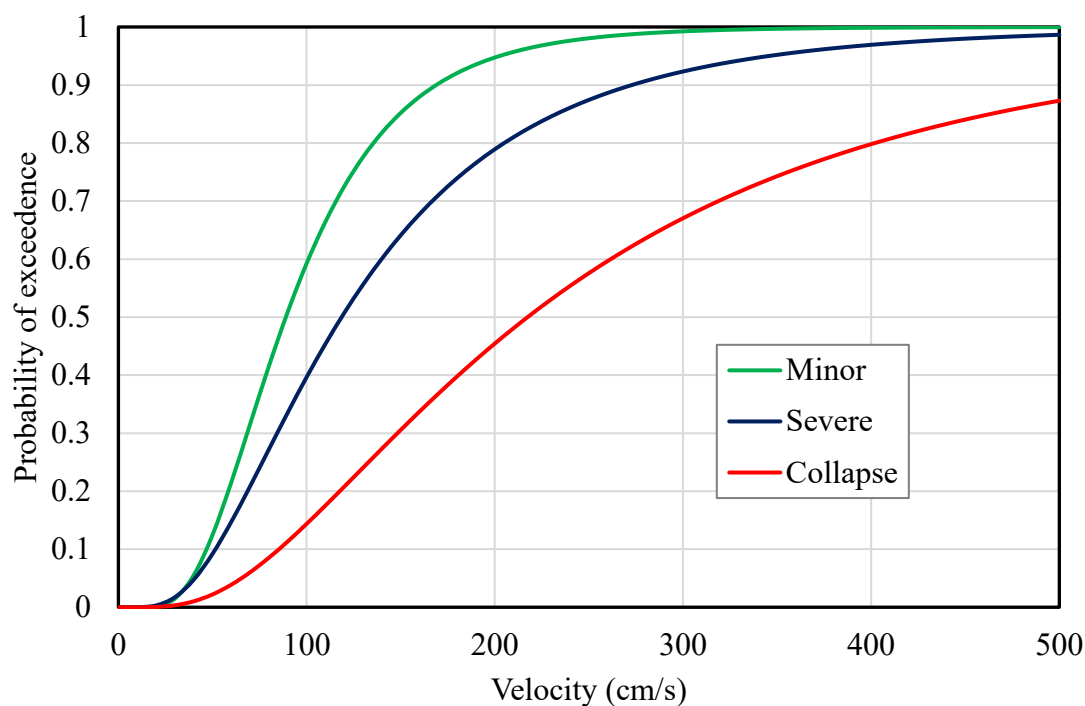
Figure 22: Fragility functions for traditional masonry buildings in Bhaktapur.

Table 1. Building element/aspect based damage scenario in Bhaktapur during Gorkha earthquake

Damage element/aspect	Damage scenario
Roof	- Heavy roofs constructed using roof tiles were suffered in terms partial roof collapse (Fig. 13a) - Galvanized iron sheets performed well
Gable wall	- Out of plane failure was commonly observed (Fig. 13b) - Majority of the buildings were lacking proper connection between gable and the masonry wall (Fig. 13c)
Projections	- Wooden projections (various forms of windows) performed well (Fig. 14a)
Wall	- Out of plane failure was observed as the most prevalent failure mechanism (Fig. 13c) - Walls on the edge of the settlement suffered progressive collapse in out-of-plane direction (Fig. 14b) - Out of plane collapse of heavy wall constructed in upper stories (Fig. 13c) - Walls were separated due to lack of proper connection and binding between orthogonal walls as well as the structural and partition walls (Fig. 15a) - Veneered partition walls performed better than the heavy brick masonry partitions - Few cases of in-plane wall failures were observed in the buildings having many openings and relatively larger in size - Delamination of wythes was observed in some cases (Fig. 15b)
Corner	- Reentrant corners were bulged out and large cracks were damaged in the interaction zone (Fig. 16a) - Corners were constructed without any special provisions - Mud mortar was found to be suffered from shrinkage and throughout the structural system, brick units were observed to be remaining in isolation marring the structural integrity (Fig. 16b)
Structural pounding	- Due to row housing system and intermediate modifications (reconstruction) and due to high variation in dynamic properties of adjoining structures, many cases of structural pounding led damaged were observed (Fig. 16c) - Sometimes single building was found to be separated exactly into two halves and partial reconstruction done, leading to damage in the remaining portion of building. Change in slenderness ratio due to division of single building was also observed in many buildings.
Ground floor	- For commercial purpose, usually ground floor was not found to be provided with structural wall rather shutters (wooden/iron) were prevalent and such buildings with more height were observed to be damaged (Fig. 16c)

RC slabs over masonry walls	-	Such erroneous practice was observed in significant number of structures and the collapse do RC slab led severe damage either in terms of brittle collapse or heavy damage in entire structure (Fig. 17a)
Construction site	-	Areas like Suryamadhi, Inacho, Golmadhi, Byasi, Jela were more affected due to inclined terrain and in some cases, due to ridgeline effect. A tow rows of more than 100 buildings were destroyed in Jenla (Fig. 17b) and beside the Suryamadhi square and Byasi all buildings except few RC were collapsed
Mortar	-	Even after the earthquake, mud mortar was being used (Fig. 17c) for reconstruction and almost 60% buildings were constructed with mud mortar that led to either collapse or heavy damage
Incremental construction	-	Many cases of incremental constructions were identified and surprisingly one or two stories of substandard reinforced concrete construction were found (Fig. 18a). Even in partly damaged buildings, after three months of the earthquake some stories of RC were found to be added
Building age and occupancy scenario	-	Many of the damaged buildings were told be used for at least three generations without any periodic strengthening even after the earthquakes during 1988 and 2011, the debris from collapsed buildings was observed to be decayed (Fig. 18b)
	-	Countable fraction of buildings of age more than 82 that sustained the 1934 Bihar-Nepal earthquake were identified during field reconnaissance
Masonry units	-	Virtually all collapsed and heavily damaged structures manifested the marginal quality of brick- improperly dried and irregular shape (Fig. 18c)

Table 2. Identified seismic features in vernacular Newari buildings

Seismic features	Observed/expected contribution	
Plinth construction	-	Some of the buildings in sloping sites were found to be provided plinths and damage occurrence was relatively insignificant (Fig. 19a)
Building shape	-	Virtually all buildings were found to be rectangular assuring L/B < 3 provision of Nepal Building Code (Fig. 19b)
Openings	-	Many buildings with smaller openings were observed and damage was found to be marginal, however the opening size was not responsible for survival of structure (Fig. 19b)
	-	Measurement in above 40 buildings showed B×H: 1.35×0.64 m size of door in average
Timber struts	-	Timber struts when provided were found to be effective in avoidance of roof heavy roof collapse (Fig. 19c)
	-	Cantilevered load was observed to be mainstreamed through timber struts in number of vernacular buildings
Vertical transportation system	-	Most impressive feature was in the form of light weight wooden ladder (often moveable) constructed from wooden planks (Fig. 19d)
Timber bands at various level	-	Timber bands (sill/lintel/roof) or *"Nas"* were found to be used in some houses (Fig. 20a) and out-of-plane action was not observed in such buildings
Wooden pegs	-	In case of vernacular buildings, several timber units were found to be tied together with wooden pegs and distortions were not observed in local scale
Corner post	-	Quite a few corner posts (brick masonry) were observed, and it was clearly observed that the damage propagation was effectively controlled by corner posts (Fig. 20b)

Table 3. DPMs for traditional masonry structures

Damage state	Damage factor range	Probability [$P (DS, I)$] of being in each damage state as a function of Modified Mercalli Intensity		
		MMI-VIII	MMI-IX	MMI-X
No to slight damage	0-5	90	68	9
Minor damage	5-30	3	6	21
Severe damage	30-70	5	18	34
Collapse (local/global)	70-100	2	8	36
Mean damage ratio (MDR)		6.98	18.55	51.50
Total buildings		10890	25322	6651

Table 4. Summary of lognormal distribution parameters

Damage state	Lognormal parameters	
	ε	β
Minor	88.98	0.50
Severe	118.62	0.65
Collapse	217.46	0.73