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Seismic Vulnerability of Urban Vernacular Buildings in Nepal: Case of Newari Construction

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ABSTRACT

This paper analyzes the seismic vulnerability of vernacular Newari buildings in Nepal. Based on the damage statistics and failure modes recorded during 1934, 1988, 2011, and 2015 earthquakes, damage probability matrices and seismic fragility functions are derived in this paper. Notable seismic features of the Newari buildings are identified and reported using forensic approach. The result of this study highlights that the vernacular Newari buildings are highly vulnerable in the case of minor to major earthquakes; however, the seismic features have contributed to downscale the damage extent.

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Vernacular Construction; Masonry Building; Seismic Vulnerability; Damage Probability Matrix; Fragility Function

1. Introduction

Vernacular masonry buildings in urban centers comprise the significant fraction of total housing stock in Nepal. Due to lack of adequate seismic capacity against the seismic forces, historical earthquakes have depicted massive damage concentration in urban vernacular building stocks worldwide (e.g., [Ortega *et al*., 2017; Gautam and Dong, 2018; Ortega *et al*., 2018]). Seismic vulnerability of vernacular buildings has gotten considerable attention worldwide. Barros *et al*. [2018] presented seismic analysis of Portuguese vernacular buildings and suggested retrofitting techniques for rammed earth vernacular constructions. Similarly, Stellacci *et al*. [2016] presented the case study of seismic performance of Gaiola and Borbone vernacular construction system and concluded that both construction systems consist significant earthquake-resistant features. Many vernacular building types such as Pombalino [Stellacci *et al*., 2017], Casa baraccata [Dipasquale *et al*., 2014], Himis (Aktas and Turer, 2016], Dhajji dewari [Ahmad *et al*., 2012], Ghumaune dhi [Gautam *et al*., 2016a], among others have been studied in the past. Seismic performance of urban vernacular building stocks is crucial to identify as their performance may alter the damage and death statistics, especially in traditional settlements.

Nepal lies in one of the most active seismic zones; meanwhile, a large number of vernacular buildings exist in both urban and rural neighborhoods. Loose records of 1255 earthquake denote that one-third of the population of Kathmandu valley was killed due to this event including the then King [Gautam and Chaulagain, 2016]. Since then, Kathmandu valley has become the hotspot of damage during almost every earthquake

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that struck Nepal Himalaya. As systematic records of earthquake damage are available since the 20th century only, little is known about the devastating earthquakes until the 19th century. To this end, the available record of 1833 earthquake (M_L 7.7) can be considered as the more detailed one though unexhaustive. Bilham [1995] reported that 410 deaths and more than 4000 building damage were recorded in Kathmandu valley 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 [Chaulagain *et al.*, 2018]. Among them, most of the earthquakes were far-field events thus accounts of building damage are available for 1934, 1988, 2011, and 2015 earthquakes only. Since the recorded history of earthquakes in Nepal that affected Kathmandu valley, Bhaktapur city is identified as the city to be damaged in the greater extent than other neighborhoods in Kathmandu valley. Recently, magnitude 7.8 earthquake struck central, eastern, and part of western Nepal on April 25, 2015. The Gorkha earthquake sequence destroyed l498852 buildings and 256697 buildings were partly damaged (NPC, 2015]. Consistently, Bhaktapur was one of the most affected towns in Kathmandu valley during 2015 Gorkha earthquake. Owing to the evidence of damage concentration, Bhaktapur city was selected to analyze the seismic vulnerability of urban vernacular buildings. The present paper aims to discuss the failure modes that are common in urban vernacular buildings. Furthermore, this study also aims to identify the most likely causes of damage using forensic approach. The most important aim of this work is to derive damage probability matrix (DPM) and fragility functions for the urban vernacular masonry buildings in Nepal using empirical data.

2. Case Study of Urban Vernacular Construction: Newari Buildings of Bhaktapur

Bhaktapur is one of the oldest (13th century) towns in Kathmandu valley with unique row housing settlements and cultural constructions in the form of vernacular Newari buildings [locally called as '*Chhen*']. Bhaktapur is a densely populated medieval town located 12 km east of the capital city of Nepal, Kathmandu (see Fig. 1]. The historic town is located within the area of 6.88 km^2 where about 18600 buildings were constructed until 2014. Per the 2011 census, more than 80% of the buildings were vernacular masonry buildings (*Newari chhen*). Vernacular buildings are generally rectangular and constructed in gently sloping terrain as traditional Newari settlements were basically established in gently sloping terrains to avoid flooding. Vernacular Newari buildings comprise three to four stories and the construction system is unreinforced brick masonry. The first story comprises relatively large openings, the upper stories comprise lesser opening areas. In the third and fourth stories, wooden posts are also provided and wooden staircase for vertical access is present in Newari buildings. The first story of Newari building is used for commercial activities; the second floor is used for bedrooms; the third floor is used for living rooms; and the fourth floor is used as the kitchen. Upper stories are usually provided with depressed and projected windows whereas the lower stories comprise dormer or lattice windows. In general, gable box roofs made up of tiles are present in vernacular masonry buildings. Fig. 2a illustrates a common vernacular Newari building and Fig. 2b highlights a wall section. The thickness of brick masonry wall varies between

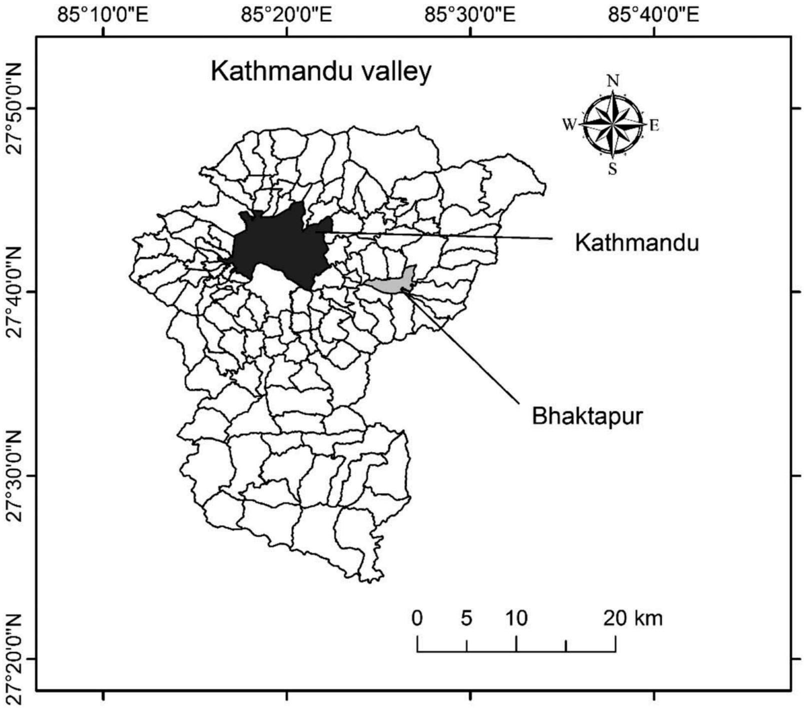


Figure 1. Location of Bhaktapur city in Kathmandu valley.

250 and 600 mm. The wall section comprises mud mortar, brick layer, wooden plank, and timber beam as shown in Fig. 2b. Two types of wall partitioning can be observed in vernacular buildings; the first is throughout wall construction with reduced dimension and the second is partitioning with veneers or wooden planks. Primarily, brick masonry-based shallow foundation is provided in vernacular Newari buildings.

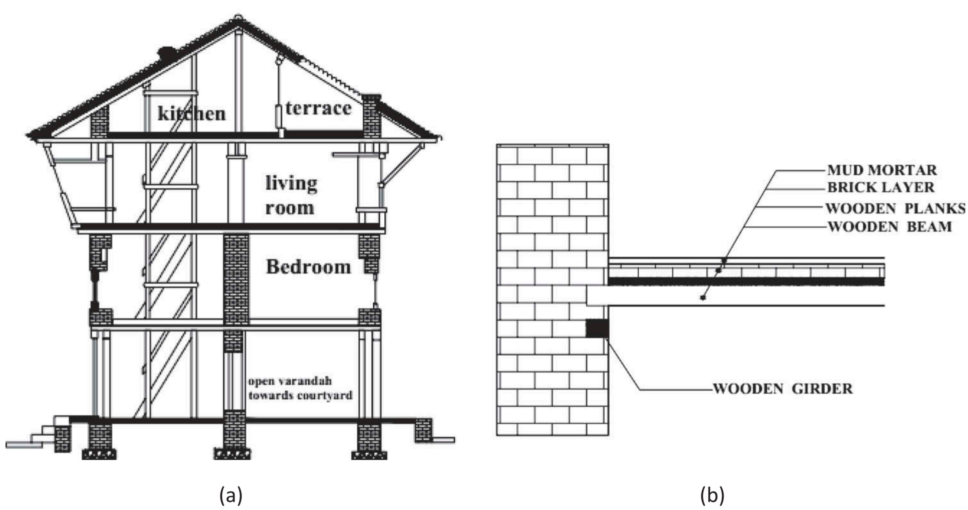


Figure 2. (a) Vernacular Newari building (b) a section of a wall.

3. Seismic Performance of Vernacular Newari Buildings during Major Earthquakes

3.1. *Bihar-Nepal Earthquake (1934)*

The strongest earthquake in the modern history of Nepal occurred in 1934 January,15. The earthquake magnitude is believed to be moment magnitude 8.4. The epicenter of the earthquake was in eastern Nepal and the effect of earthquake was observed throughout Nepal and northern India. Rana [1935] reported the focal depth of the earthquake as ~24–40 miles. Rana [1935] also reported that the effective shaking duration was around 2 min. Loose records of the earthquake contend that the overall shaking duration was around 8 min but it is not possible to verify independently. The shaking was initially dominant along the horizontal axes; however, the horizontal shaking was readily dominated by circular shaking [Rana, 1935]. Significant vertical shaking was reported by Rana [1935]; however, owing to the lack of accelerometric records, it cannot be confirmed. 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, undoubtedly, strong shaking should have occurred in Kathmandu valley. Although, the epicenter of the earthquake was nearly 150 km east of Bhaktapur city, severe damage was occurred therein. Higher damage in Bhaktapur when compared to adjacent neighborhoods should have been attributed to the site characteristics of Bhaktapur (alluvial deposit), construction technology, building population, and vulnerable of building stocks. Report of building damage due to the Bihar-Nepal earthquake is presented in the following section. Further details regarding the earthquake can be found elsewhere (e.g. [Rana, 1935; Chaulagain *et al*., 2018]).

3.1.1. *Reported Building Damage in Bhaktapur*

In total, 6047 residential buildings were damaged in Bhaktapur city due to the Bihar-Nepal earthquake [Rana, 1935]. Apart from the residential building damage, more than 177 monuments and heritage structures were also damaged. The most common failure mode was reported to be the combination of in-plane and out-of-plane mechanisms as shown in Fig. 3a. Moreover, poor binding among the masonry units and wythes can be observed in the damaged wall section. Fig. 3b illustrates the collapse of heavy gable wall as heavy gables were commonly practiced at that time.

Rana [1935] reported that the damage percentage in Kathmandu valley was between 40 and 100%. As noted by Rana [1935], the damage causes can be reinterpreted as: (a) multistoried unreinforced masonry (URM) buildings; (b) buildings with higher opening percentage; (c) structural pounding in dense settlements; (d) buildings constructed with low quality bricks (unbaked); (e) improper bonding between the brick units; (f) load concentration in the upper stories and gable; (g) poor site selection and foundation problems (unleveled); (h) buildings undergone with incremental construction; (i) projections; and (j) lack of integrity in the orthogonal walls.

Images taken by Rana [1935] after the earthquake confirm that the buildings at the corner of row housing settlements were damaged more than the standalone buildings. This may be due to combination of vulnerability as well as additional lateral load imposed by adjoining buildings.

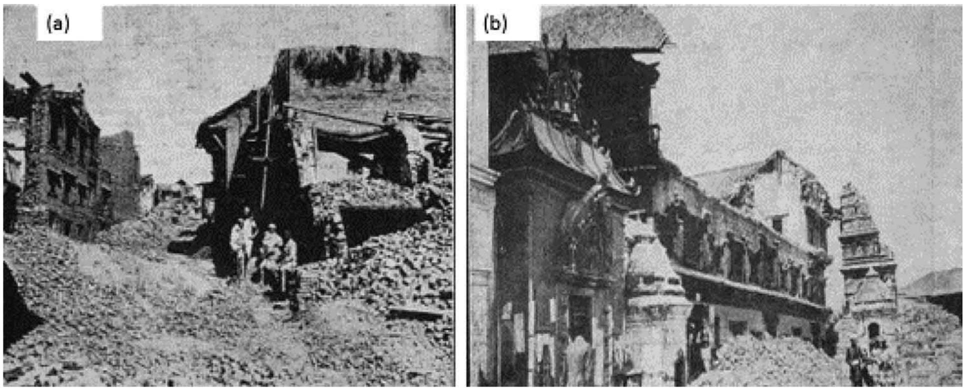


Figure 3. (a) Combined in-plane and out-of-plane failure in masonry walls (courtesy: [Rana, 1935]) (b) collapse occurred in the upper story due to mass concentration (courtesy: [Rana, 1935]).

The description presented by Rana [1935] also considered some of the improvement measures for post-earthquake reconstruction as: (a) use well-dried bricks with smooth finish; (b) Oil mixed and dried bricks "*Chiga: appa*" are 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 and land plots beside the ponds for construction; (i) provide timber band "*Nas*" in masonry walls; (j) reduce weight of gable portion; (k) provide sufficient masonry wall in between the openings; (l) lime mortar is superior to mud mortar or mud with cow dung; and (m) determine building height and foundation depth per the quality of construction materials.

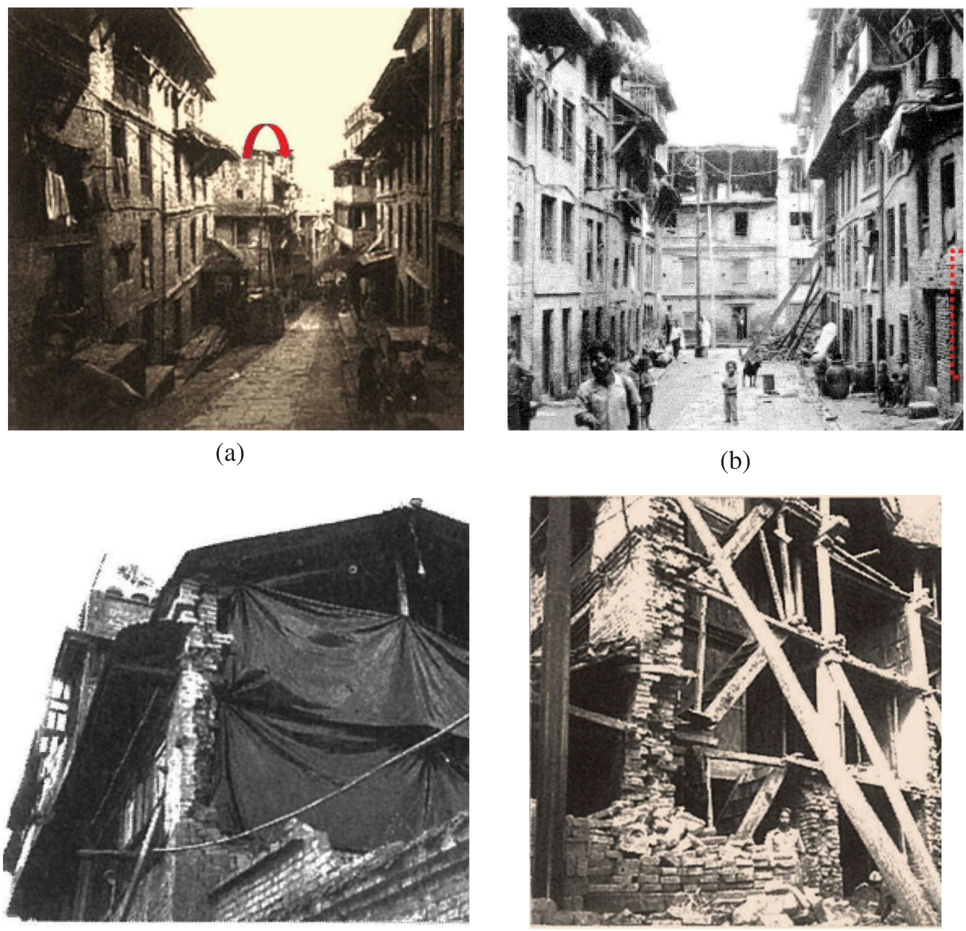
3.2. *Udaypur Earthquake (1988)*

After the Bihar-Nepal 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 nearly150 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 as MMI-V and the 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 the same for Kathmandu and Patan were assigned to 6.67 and 6.57 maximum intensity respectively by Fujiwara *et al.* [1989]. Gupta [1988] and Fujiwara *et al.* [1989] reported that most of the buildings damaged due to the Udaypur earthquake were the survivors of the 1934 Bihar-Nepal earthquake.

3.2.1. *Reported Building Damage in Bhaktapur*

During the Udaypur earthquake 274 buildings were collapsed and 1477 buildings were partially damaged in Bhaktapur district. Due to lack of statistical records in localized scale, exact scenario of damage distribution is not possible to disseminate; however, the descriptions provided by Gupta [1988], Fujiwara *et al.* [1989], and Dixit [1991] suggest that the town of Bhaktapur was the most affected in Kathmandu valley. Fujiwara *et al.* [1989]

reported that the buildings partly damaged during 1934 earthquake were used without any repair thus, 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 by Rana [1935] after the Bihar-Nepal earthquake. Causes of the damage identified by Gupta [1988] and Fujiwara *et al.* [1989] can be summarized as: (a) buildings situated in sloping ground (Fig. 4a; b) building constructed using mud-mortar; (c) buildings constructed up to 4–5 stories in brick masonry without any earthquake-resistant provisions (Fig. 4a; d) structural pounding (Fig. 4b; e) poor quality of construction material for foundation; (f) poor mortar quality; (g) separation of masonry units due to shrinkage; (h) marginal quality of construction at the corner joints and joints in between different walls within the diaphragm; (i) unbaked clay bricks used in walls; (j) lack of diaphragm action due to improper timber



(a) (b) (c) (d)

Figure 4. (a) Damaged buildings in the sloping ground due to Udaypur earthquake (courtesy: [Gupta, 1988]) (b) structural pounding in row houses (courtesy: [Gupta, 1988]) (c) gable collapse (courtesy: [Fujiwara *et al.*, 1989]) (d) damage due to in-plane and out-of-plane mechanisms (courtesy: [Fujiwara *et al.*, 1989]).

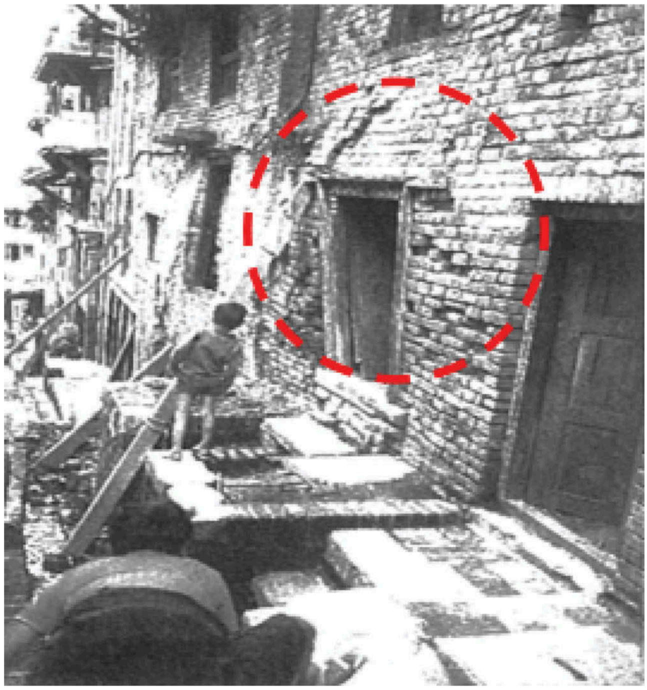


Figure 5. Bulged wall observed above the door after the Udaypur earthquake (courtesy: [Fujiwara *et al.*, 1989]).

joists; (k) heavy gable construction and roofing (Fig. 4c; l) heavy masonry wall (thickness ≥500 mm); (m) in-plane and out-of-plane mechanisms (Fig. 4d; n) improper opening placement [Fig. 5]; and (o) cantilevered projections.

Following their field investigation, Fujiwara *et al.* [1989] recommended some measures of earthquake-resistant constructions as: (a) lower the overall building weight avoiding the brick topping on floor level and replace 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 construction will be developed which assures better structural integrity; (c) place horizontal bracing in roof and floor slabs and also provide diagonal bracing at the corners; and (d) improve mortar quality.

3.3. *Sikkim-Nepal Border Earthquake (2011)*

The Sikkim-Nepal border earthquake (M_W 6.9) affected primarily eastern Nepal. After the earthquake, field reconnaissance was performed in Kathmandu valley that concluded the most affected region in the valley was Bhaktapur. Although the earthquake occurred ~272 km east of the capital city with a focal depth of 19.7 km (USGS [2011]), notable damage was observed in Bhaktapur.

During the field reconnaissance, it was known that the damaged buildings were the buildings in which damage evolution was already noticed after the Udaypur earthquake. Although the accelerometric records in Kathmandu valley show low peak ground acceleration (~0.05 g) [Gautam, 2017a], some of the buildings in Bhaktapur sustained partial collapse and many others sustained minor to moderate damage. Interestingly, some of the

Figure 6. (a) Out-of-plane collapse of masonry wall (courtesy: Ganesh Kumar Bhattarai), and (b) structural pounding due to the Sikkim-Nepal border earthquake (courtesy: Ganesh Kumar Bhattarai).

already bulged buildings due to the 1988 Udaypur earthquake remained unaffected in some locations of Bhaktapur. The reason behind the survival may be correlated to the weak shaking. During the field reconnaissance, two cases of out of plane wall collapse were observed [Fig. 6a] in Bhaktapur. A case of structural pounding was also noted which was due to the contrast in dynamic properties between the adjacent buildings [Fig. 6b]. Damages in heavy gable wall [Fig. 7a], cracks on masonry walls especially at the corner regions [Fig. 7b], and damage in heavy roof [Fig. 7c] were identified as other damage modes during the field reconnaissance. Since 1934, the construction technology was not found to be much varied thus similar failure modes were expectedly observed during the field reconnaissance.

3.4. *Gorkha Earthquake (2015)*

The 2015 Gorkha earthquake (M_W 7.8) affected the ancient Bhaktapur town heavily and the damage can be roughly compared to the damage that occurred during the 1934 earthquake. The epicenter of Gorkha earthquake was located ~78 km N-NE of Kathmandu valley at 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.* [2016b] and Gautam and Chaulagain [2016]. In Bhaktapur, above 80% building stocks were the vernacular Newari buildings and most of the remaining buildings were 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 resulted low damage statistics and hence previous

Figure 7. (a) Gable collapse occurred in two adjoining buildings (courtesy: Ganesh Kumar Bhattarai), (b) cracks propagated toward the corners (courtesy: Ganesh Kumar Bhattarai), (c) heavy roof collapse and out-of-plane failure of brick masonry wall occurred due to the Sikkim-Nepal border earthquake (courtesy: Ganesh Kumar Bhattarai).

loss estimation models depicted by Chaulgain *et al.* [2016] were not able to represent the actual damage scenario.

3.4.1. *Report of Building Damage in Bhaktapur*

Although the intensity of earthquake in Kathmandu valley was generally VIII, some areas of Bhaktapur like; Golmadhi, Suryamadhi, Jela, Byasi were destroyed. Thus, it is better to assign IX intensity to Bhaktapur. Fig. 8 depicts the areas which were heavily damaged or destroyed locations within Bhaktapur city. Apart from this, slight, minor and heavy damages were observed in all neighborhoods of the city. The major damage locations were toward the eastern fringe of the city 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 reconnaissance, apart from the widespread damage and failure examples, many survival cases were also identified. It was observed that the buildings comprising some specific features were either damaged in less extent or undamaged when compared to the buildings without such features. It was observed that the features highlighted in Table 2 effectively contributed in collapse prevention and in many cases, life safety should have assured by such components too. Table 2 outlines the identified seismic features in vernacular Newari buildings of Bhaktapur.

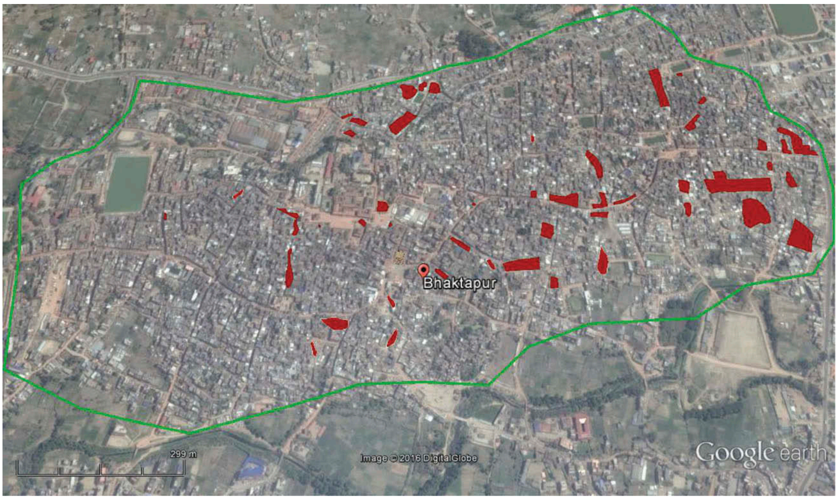


Figure 8. Major building collapse areas within the ancient settlement of Bhaktapur city (modified from: https://www.google.com/earth/).

4. Construction of DPM and Fragility Functions

Seismic vulnerability of buildings is usually presented either in terms of damage probability matrices (DPM) or fragility functions [Elnashai and Di Saeno, 2015]. Fragility functions depict the probability of reaching or exceeding the damage state when the structure or component is acted upon by the intensity measure e.g., peak ground acceleration, story drift, etc. Many researchers have formulated fragility functions for buildings 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, 2017b; Gautam, 2018]), hybrid (e.g. [Kappos *et al*., 2006; Kappos and Panagopoulos, 2010]), and expert opinion (e.g. [ATC, 1985; ATC, 1996]) approaches. To the best of authors' knowledge, fragility functions for vernacular Newari buildings do not exist; however, their vulnerability is important due to their large population in major urban centers of Kathmandu valley. To facilitate the understanding of seismic vulnerability of vernacular Newari buildings, we have derived 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, i.e. VIII, IX, and X. The mean damage ratio (MDR) at given intensity level (I) can be calculated as:

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

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:

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

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 sustained partial roof collapse [Fig. 9a] • Galvanized iron sheets performed well
Gable wall	• Out of plane failure was commonly observed [Fig. 9b] • Majority of the buildings were lacking proper connection between gable and the masonry wall [Fig. 9c]
Projections	• Wooden projections [various forms of windows) performed well [Fig. 10a]
Wall	• Out-of-plane failure was observed as the most common failure mechanism [Fig. 9c] • Walls at the edge of the settlement suffered progressive collapse in out-of-plane direction [Fig. 10b] • Out-of-plane collapse of heavy wall constructed in upper stories was also common [Fig. 9c] • Walls were separated due to lack of proper connection and binding between orthogonal walls as well as the structural and partition walls [Fig. 11a] • Veneered partition walls performed better than the brick masonry partitions • Few cases of in-plane wall failures were observed in the buildings having many openings and relatively large size • Delamination of wythes was observed in some cases [Fig. 11b]
Corner	• Reentrant corners were bulged out and large cracks were developed at the interaction region [Fig. 12a] • Corners were constructed without any special provisions thus damage was commonly observed at the corner region • Mud mortar was found to be shrunk throughout the structural system; brick units were observed to be remaining in isolation so that structural integrity and homogeneity was compromised [Fig. 12b]
Structural pounding	• Due to row housing system and intermediate modifications [reconstruction) and due to the variation in dynamic properties of adjoining structures, many cases of structural pounding were observed [Fig. 12c] • Sometimes single building was found to be separated exactly into two halves and partial reconstruction done which led to the damage in the remaining older portion of the building. Change in slenderness ratio due to division of single building into two was also observed in many buildings.
Ground floor	• For commercial purpose, the ground story was provided with shutters instead of structural masonry wall and damage was also recorded in such buildings [Fig. 12c]
RC slabs over masonry walls	• RC slabs over the masonry walls was observed in many buildings and many of such buildings observed damage either in terms of brittle collapse or heavy damage in the entire building [Fig. 13a]
Construction site	• Areas like Suryamadhi, Inacho, Golmadhi, Byasi, Jela were more affected due to inclined terrain and in some cases, due to ridgeline effect. Two rows of more than 100 buildings were destroyed in Jenla [Fig. 13b]. Similarly, beside the Suryamadhi square and Byasi neighborhood, all buildings except few RC were collapsed
Mortar	• Even after the earthquake, mud mortar was being used [Fig. 13c] for reconstruction; however, almost 60% of the collapsed buildings were constructed using mud mortar
Incremental construction	• Many cases of incremental constructions were identified and surprisingly one or two stories of substandard reinforced concrete construction were found in some locations [Fig. 14a]. 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 repair and strengthening, even after the earthquakes during 1988 and 2011. The debris from the collapsed buildings was observed to be decayed heavily [Fig. 14b] • Countable fraction of buildings of age more than 82 that sustained the 1934 Bihar-Nepal earthquake were also identified during field reconnaissance
Masonry units	• Virtually all collapsed and heavily damaged structures manifested the marginal quality of brick; improperly dried and irregular shaped [Fig. 14c]

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. The DPMs for traditional masonry buildings are presented in Table 3.

The database was taken from Rana [1935]; Gupta [1988]; Fujiwara *et al.* [1989], NPC [2015] and some news outlets. The damage data from the reports were not

Figure 9. (a) Minor damage on roof (b) out-of-plane collapse of walls (c) gable collapse occurred due to the Gorkha earthquake.

classified as per newly proposed system thus, we re-interpreted the damage cases reported by various authors and agencies and segregated the damage data into four damage states. The damage data in this study come from reports of damaged buildings. Meanwhile, the total number of available buildings was also available and the same information was used to create DPM and fragility functions. To create fragility functions, we considered peak ground velocity (PGV) as intensity measure (IM) which was estimated from the Modified Mercalli Intensity (I_{MM}) using the correlation proposed by Wald *et al.* [1999] as:

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

Similarly, for the comparison purpose, the peak ground acceleration (PGA) was considered as an IM. To estimated PGA from the intensity, we used the correlation proposed by Gama-Garcia and Gomez-Bernal [2008] as:

$$I_{MM} = 3.0262 \times \log(PGA_H) + 1.0195;\ \sigma = 0.523;\ bias = 0.0\ [For\ the\ interval\ of\ III \leq I_{MM} \leq IX] \tag{4}$$

Initially, the data were segregated into three damage states as minor, severe, and collapse. Four damage states were considered in this study as no damage, minor, severe, and collapse. All four damage states were defined per the overall damage ratio of building. The no damage state was considered when the damage ratio was less than 5%. Minor damage was defined in the damage ratio range of 5–35%, severe damage state was defined in the range of 35–70% damage ratio and greater than 70%

Figure 10. (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.

damage ratio was considered collapse state. Once the damage data were classified the IM values were assigned to each damage state and bins were created so as to obtain the lognormal distribution parameters. Many previous studies affirm the lognormal distribution as the representative statistical distribution for post-earthquake damage database (e.g. [Porter and Kiremidjian, 2001; Beck *et al.*, 2002; Pagni and Lowes, 2006]), we also used the lognormal distribution in this study. The two-parameter lognormal cumulative distribution function which is used to define the fragility functions can be written as:

$$F(C|IM = x) = \Phi\left(\frac{\ln(x/\varepsilon)}{\beta}\right) \tag{5}$$

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 presented in Table 4. As shown in Table 4 lognormal distribution parameters were estimated considering PGV

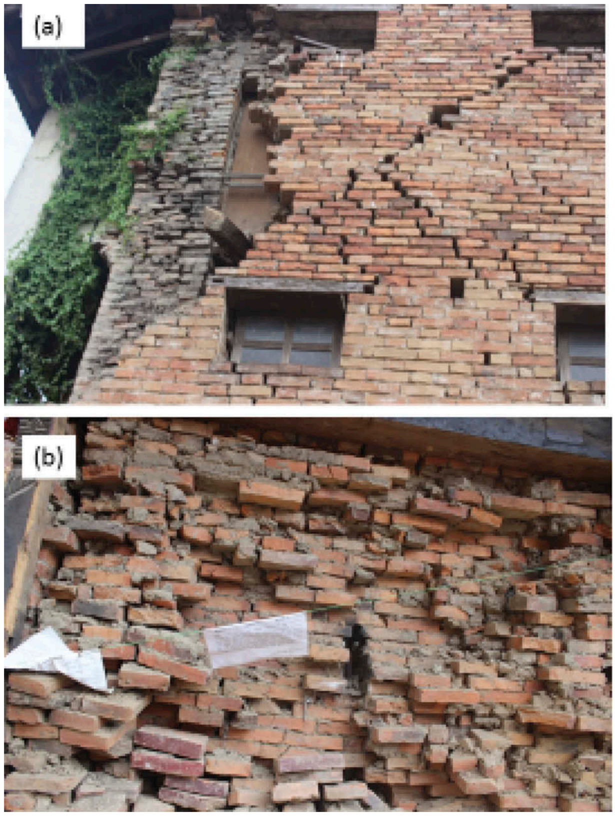


Figure 11. (a) Separation of orthogonal walls (b) delamination of wythes observed after the Gorkha earthquake.

and PGA as IMs. The former is used to depict the fragility functions per the reported or estimated velocities, whereas, the latter is used to compare the newly derived fragility functions with the fragility functions derived for close building class. The lognormal distribution parameters can be easily estimated using available statistical packages or Microsoft Excel calculations. Further details on MS-Excel based calculation can be found in the paper by Porter *et al.* [2007]. Fragility functions for the vernacular Newari buildings considering PGV as IM are presented in Fig. 17. Meanwhile, Fig. 18 depicts the comparative plots of existing fragility functions for brick masonry buildings along with the newly derived fragility functions. As we did not find any fragility functions for close building class derived considering PGV as IM, we chose a different correlation to estimate PGA as shown in Eq. 4. As shown in Fig. 17, 50% probability of exceedance for minor damage state occurs at the PGV lower than 100 cm/s. This highlights that vernacular Newari buildings are likely to be damaged even in minor to moderate shaking. In the case of severe damage, 50% probability of exceedance is occurred at the PGV ~125 cm/s. The collapse state shows there is 50% probability of occurrence or exceedance of collapse state only at the PGV of >225 cm/s. As shown in the Fig. 17, the damage initiation could be seen at the PGV

Figure 12. (a) Reentrant corner damage along with structural pounding (b) separated masonry units and the mud-mortar (c) structural pounding observed due to the Gorkha earthquake.

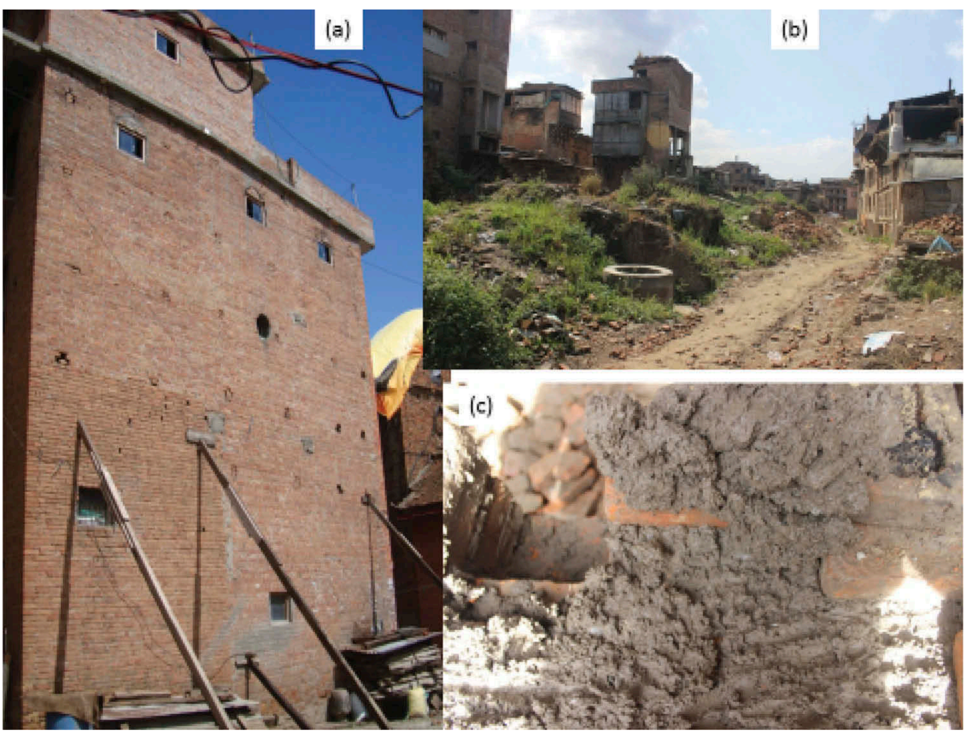


Figure 13. (a) RC slab constructed in the existing brick masonry building which underwent incremental construction after the Gorkha earthquake (b) destroyed neighborhood in Jela ridgeline (c) mud mortar used for reconstruction after the earthquake.

Figure 14. (a) Building with masonry and RC incremental constructions above the vernacular masonry construction (b) debris reflects decayed construction materials (c) irregular size and poor quality of bricks used in structural walls.

Figure 15. Identified seismic features: a) plinth constructed in sloping ground b) symmetrical building c) timber struts for mainstreaming cantilevered load d) wooden ladder.

Figure 16. Identified seismic features: (a) timber bands at various levels (b) wooden pegs used to stitch connections c) corner post.

as low as 25 cm/s, thus vernacular Newari buildings are highly vulnerable even in the case of minor to moderate earthquakes.

The comparative plot as shown in Fig. 18 highlights that the existing fragility curves generally overestimate the vulnerability. For instance, at 0.4 g PGA, existing curve depicts 60% probability of collapse whereas newly derived curve highlights 30% collapse probability only. It should be carefully noted that the comparison is made between broadly comparable building classes; however, brick masonry class used by Chaulgain *et al.* [2016] does not exhaustively represent vernacular Newari buildings. Hence, the discrepancies are obviously expected in fragility functions. It is interesting to note that the fragility curve for the minor damage state is even below the fragility curve for extensive damage state proposed by Chaulgain *et al.* [2016] until PGA 0.4g.

5. Conclusions

The present study provides the first systematic account of the damage mechanisms and seismic features of urban vernacular buildings in Nepal. The damage reports of 1934 and 1988 earthquakes were forensically interpreted first and the field evidences from 2011 and 2015 earthquakes were integrated to depict the common damage modes. This study has further examined the seismic features of vernacular Newari buildings which

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 raised plinths and damage occurrence was relatively insignificant in such buildings [Fig. 15a]
Building shape	• Virtually all buildings were found to be rectangular assuring L/B <3 provision of Nepal Building Code [Fig. 15b]
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 solely [Fig. 15b] • Measurements in above 40 buildings showed B × H: 1.35 × 0.64 m size of door in average
Timber struts	• Timber struts wherever provided were found to be effective in avoidance of heavy roof collapse [Fig. 15c] • Cantilevered load was observed to be mainstreamed by timber struts in number of vernacular buildings
Vertical transportation system	• A significant feature was the light weight wooden ladder [often moveable) constructed from wooden planks [Fig. 15d]
Timber bands at various level	• Timber bands [sill/lintel/roof) or *"Nas"* were found to be used in some buildings [Fig. 16a] and out-of-plane mechanism was not observed in such buildings
Wooden pegs	• In the 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. 16b]

Table 3. DPMs for vernacular Newari buildings.

		Probability [*P (DS, I)*] of being in each damage state as a function of Modified Mercalli Intensity		
Damage state	Damage factor range	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 the lognormal distribution parameters.

	Lognormal distribution parameters			
	PGV (cm/s)		PGA (g)	
Damage states	ε	β	ε	β
Minor	88.98	0.50	0.23	0.56
Severe	118.62	0.65	0.31	0.73
Collapse	217.46	0.73	0.63	0.83

contributed in downscaling the damage during every earthquake. Based on the damage data from notable earthquakes, damage probability matrices and fragility functions were derived for the urban vernacular building stocks in Nepal. The fragility functions depict that the damage in the case of urban vernacular buildings could start even at the PGV as low as 25 cm/s. The sum of observations highlights that the urban vernacular building stocks in Nepal are highly vulnerable even in minor to moderate shaking; however, some seismic features exist in such buildings which downsize the damage extent. As this study focuses on empirical fragility functions only, future studies should investigate the possibility of calibrating the empirical fragility functions with the analytical or hybrid fragility functions.

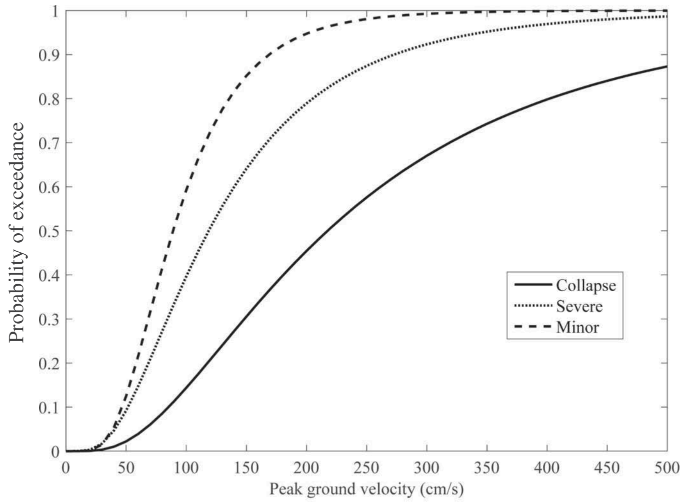


Figure 17. Fragility functions for vernacular masonry buildings.

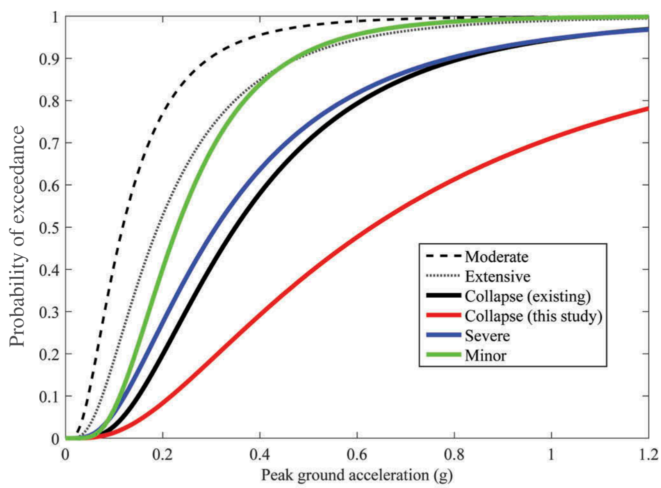


Figure 18. Comparison between the newly derived fragility functions for vernacular Newari buildings and the existing fragility functions for brick masonry buildings proposed by Chaulgain *et al*. [2016].

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