Proceedings Paper:

Sharma, AK, Kumar, A and Sarhosis, V orcid.org/0000-0002-5748-7679 (2021) Evaluating the Seismic Performance of Domestic and Historical Masonry Structures in Himachal Pradesh Region of India. In: Kolathayar, S and Chian, SC, (eds.) Lecture Notes in Civil Engineering. Virtual Conference on Disaster Risk Reduction (VCDRR 2021), 15-20 Mar 2021, Online. Springer , pp. 477-490. ISBN 978-981-16-4616-4

https://doi.org/10.1007/978-981-16-4617-1_38

Forensic investigations on earthquake damaged domestic and historical masonry structures in Himachal Pradesh region of India

Ashwani Kumar Sharma[1*], Ashutosh Kumar[2], Vasilis Sarhosis[3]

[1*]M.Tech. Student, School of Engineering, IIT Mandi, Kamand, Himachal Pradesh-175005. Email: t19013@students.iitmandi.ac.in

[2]Assistant Professor, School of Engineering, IIT Mandi. Kamand, Himachal Pradesh-175005. Email: ashutosh@iitmandi.ac.in

[3]Associate Professor, School of Civil Engineering, University of Leeds, United Kingdom- LS2 9JT. Email: V.Sarhosis@leeds.ac.uk

Abstract: The state of Himachal Pradesh in India is located along the foothills of the Himalayas comprising steep terrain, mountainous region and valleys. Approximately 70% of the residential and heritage buildings in the region are made of unreinforced masonry constructed using locally available materials such as mud bricks, stones and timber composites. The region is seismically active and has already witnessed strong earthquakes causing huge loss on lives and livelihoods. Hence understanding the seismic performance of unreinforced masonry structures is important to ascertain the safety of these structures in the event of a future earthquake. With the ultimate aim to co-produce methodologies to evaluate and improve the seismic safety of lives and livelihoods in the region, this study presents the results of an extensive survey of domestic and heritage unreinforced masonry structures. One of the common structural typologies in the region is Kath-kuni architecture of Himachal Pradesh; also called Tower Temples. Stonemasonry serves as a main load-bearing stratum and the geometric form of these structures is symmetrical which make them less vulnerable to earthquakes. However, non-uniform mass distribution was observed along with the height of the structures, i.e. having higher mass lumped at a greater height, which reduces the ability of the upper portion of the structures to withstand the lateral force during an earthquake. Age-related deterioration of structural members was observed in some of the structures due to the lack of regular maintenance. This study concludes by suggesting otpions that could safeguard these structures in the event of future earthquakes.

Keywords: masonry structures; structural survey; Himachal Pradesh Region.

1. Introduction

The state of Himachal Pradesh in India is located along the foothills of the Himalayas comprising steep terrain, mountainous region and valleys. The state is divided into 12 districts in which their altitude ranges from 350 m to 7,000 m as per Jaswal et al. (2015). As per 2011 census, around 90 % of the population of the state lives in rural areas located mainly at the higher altitude and rugged terrain. Many of the villages lack the road connectivity leading to a limited supply of modern materials for construction purposes. Buildings are mainly constructed by local masons using traditional methods and locally available construction materials such as mud, stone and timber. Thus, many of the domestic and historic buildings were made of un-reinforced rubble masonry and rammed earth.

Singh et al. (1976) reported the use of earthen material and stone rubble masonry for the construction of one or two stories residential buildings. Such buildings were constructed using flat and sloping roofs supported by timber beams. Sood et al. (2012) reported the use of rammed earthen masonry construction in the Lahul and Spiti district where walls thicknesses is ranging from 300 mm to 500 mm. Thick walls were used not only to sustain the load from above but also to maintain the temperature in the building during the cold winters. Such construction type was in practice for 800 years; see the monastery in the village Kii at Figure 1a. Sood et al. (2013) reported the construction of dry-stone masonry walls with a sloping roof. The stone masonry was confined using the timber beams. This is one of the common construction typologies observed in the region, where dry stone masonry is often accompanied by the timber members. Such style of construction was named Kath-Kuni architecture and are prevalent in Shimla, Kinnaur, Kullu and Mandi districts. The literal meaning of "Kath-kuni" in Sanskrit is a "wooden corner", representing the indigenous building style of walls in which wooden beams are interlocked at corners (see Section 2). As stated by Dave et al. (2013), Kath-kuni building style is commonly found in the Himalayan region mainly in Kashmir, Himachal Pradesh, Sikkim and Uttarakhand in India while its variations could also be found in other places e.g. in Pakistan, Nuristan to Baltistan province in Afghanistan, east Himalayan region of Bhutan. This may be mainly because of the availability of stone and timber in these regions. In addition, such architectural style is very quick to construct. Das (2002) stated that the Kath-kuni building style extensively uses timber connection as a bonding element. There are several structures with the Kath-kuni architectural style. These range from traditional palaces of Maharaja of Kullu to towering temples present in district Mandi, to some simple houses in old Manali region. However, only recently the rural population is discarding the traditional method of constructions and instead building domestic houses using the new construction materials. In particular, the mud or lime mortar is now replaced by cement and such combinations of newer and traditional building materials can be in cases disastrous. In most cases, sun-dried earthen bricks and mud mortar was used for the construction of walls. So, during a seismic event, mortar can lose its strength and allow dissipation of the stress on the building. However, in case where cement mortar with higher strength than bricks was used, during a seismic event, low strength mud bricks will fail while high strength mortar not, as described by Langenbach (1986). Figure 1(b) shows the typical stones masonry structures constructed using the dressed stone masonry interlocked using cement mortar in the district Mandi.

(a) (b)

Fig 1: **a** Kii monastry in village Kii in Lahaul and Spiti district of Himachal Pradesh (Sood et al. 2012), **b** typical stone masonry house with sloping roof in Himachal Pradesh

2. Seismicity of the Himachal Pradesh region and its impact to lives and livelihoods

Another important aspect to consider is the seismicity of the Himachal region. In fact, the region has experienced many devastating earthquakes (1905 in Kangra, M_w = 7.8; 1975 in Kinnaur, M_w = 6.8; 1986 Dharamshala Earthquake, M_w= 5.7; 1991 in Uttarkashi, M_w = 6.8; 1997 Sundernagar Earthquake (M_w= 4.7), 1999 Chamoli Earthquake (M_w=6.6), and it is believed that could experience further devastating Earthquakes ($M_w \geq 6$) in future. In addition to huge harm to life and livelihoods, the 1905 Kangra earthquake had caused extensive damage to centuries-old medieval temples made of unreinforced masonry (Joshi and Thakur, 2016). Singh et al. (1976) reported the evidence of collapse of mud and stone masonry structures during 1975 Kinnaur Earthquake.

Along with these major events, moderate earthquakes like Uttarkashi (1991), Chamoli (1999), Kashmir (2005), and Sikkim (2011) have also caused significant damages to various masonry structures in the Himalayan region. The generalized tectonic features of Himachal Pradesh are shown in Figure 2. from Figure 2, it is evident that seismically active faults surround Himachal Pradesh. These faults contribute to tectonic activity in the region, primarily because of the continent-continent collision of the Indian and Eurasian plates. At present, there is no clear-cut information about the last great earthquake in this region. The recent research in the topic suggested that the currently available strain in the central seismic gap could drive one or more great earthquakes (Bilham and Gaur 2000; Bilham et al. 2001). Bilham (2019) has reported that the Central Seismic Gap (CSG) region has accumulated strain levels enough to cause an earthquake of the maximum magnitude of 8.7 in the near future. Hence, the state is facing severe seismic risk as it is located in the CSG region.

One of the most recent earthquakes that have occurred in the Himalayan region is the 2015 Nepal (Gorkha) earthquake. The earthquake has taken lives of around 8,800 people, displaced about 2.8 million people and destroyed 500,000 houses (Zhao 2016; Gautam and Chaulagain 2016). The earthquake also caused the collapse of 190 ancient heritage structures and damaged 663 monuments (Weise et al. 2017). This underlines the importance of regular maintenance and structural health monitoring of the heritage structures present in the region. Many heritage monuments, structures and temples are also situated in the regions of Himachal Pradesh, one of which is 470 years old pagoda style "Hadimba Devi temple" at Manali. Kumar et al. (2019) reported the damaged pattern of heritage structures within World heritage sites of Kathmandu during 2015 Gorkha Earthquake and stated the age-related deterioration and out-of-plane collapse of masonry wall were the main reason. Kumar et al. (2020) studied the collapse of Jaisidewal temple (historical Pagoda style architecture) in Nepal during the 2015 Gorkha earthquake. The study showed that the seismic vulnerability in a 325-years-old temple arose due to deteriorating masonry wall and presence of discontinuous columns in the temple, while there was no failure in substructure i.e. no remarkable differential settlement in the foundation. Investigations undertaken demonstrated that the exposed foundation or plinth of temples significantly affect their structural behaviour of the temples during earthquakes. In a study done by Arya (1990), it was demonstrated that the damage potential of magnitude 8.0 earthquake in the same area of Kangra as that of 1905 earthquake is still quite high and in turn increased many folds after 1905 event. It is reported that there will be high structural damage and potential deaths in case of repeatability of such event. As per estimates, it can cause the collapse of 145,000 houses and partial collapse of 268,000 houses in an area of 7,900 km^2 and loss of lives could range from 88,000 to 344,000. Gopal et al. (2017) reported that the unreinforced masonry structures are the most vulnerable in case of seismic events experiencing full or partial collapse. The Vulnerability Atlas of India (2019) shows that approximately 70 % of the houses in Himachal Pradesh are un-reinforced and made of rammed earth, low strength brick and stone constructions. This percentage includes the Kath-kuni building style from districts Chamba, Kullu, Kinnaur, Mandi, Shimla and Sirmaur. So, the coexistence of high seismicity and unreinforced vulnerable constructions in the area can increase the potential damage to life and livelihoods during a strong earthquake event.

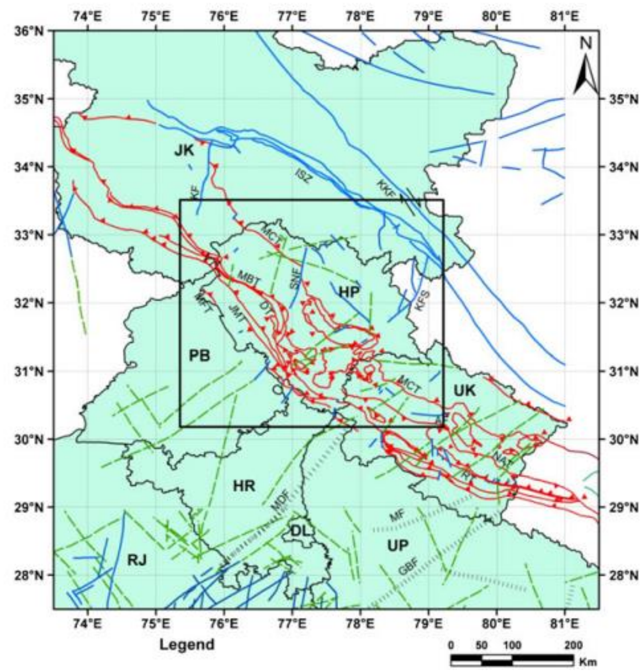

Fig 2: Tectonic features present in and around Himachal Pradesh, MCT: Main Central Thrust, MBT: Main Boundary Thrust, SNF: SunderNagar Fault, KKF: Karakoram Fault, KF: KishtwarFault, KFS: Kaurik Fault System, SS: Shyok Suture, JF: Jhelum Fault, JMT: JwalaMukhi Thrust, MDF: Mahendragarh-Dehradun Fault, MF: Moradabad Fault, DT: Drang Thrust, NAT: North Almora Thrust, RT: Ramgarh Thrust, GBF: Great Boundary Fault, AF: Alaknanda Fault. (Source: GSI 2000)

3. Aim of the study

The disastrous consequence of several earthquakes in the Himalayan region has proven that masonry structures are vulnerable to seismic events. This may be due to lack of knowledge of local masons to install seismic strengthening measures in such structures, age-related deterioration of the structural members and lack of periodic maintenance of the structure. Figure 3 shows signs of age-related deterioration of a typical unreinforced masonry structure observed in the Kullu region where bonding in the wall got weakened leading to a development of wide shear cracks and out-of-plane collapse of the walls. This study aims at understanding the construction methodology, age-related deterioration and the performance of Kath-Kuni style structure during past Earthquake events by performing reconnaissance survey. First, the study investigates the common construction typologies for the domestic and heritage structures of the Himachal Pradesh state. Then, it focusses on identifying the performance of the structure from seismic standpoint by collecting associated damage evidence present in the Kullu region. Finally, precautionary measures to be adopted to safeguard the structures from future earthquakes are suggested.

Fig 3: **a** Out of plane failure of wall, **b** development of cracks from openings

4. Field Investigation

A field reconnaissance survey was carried out in the villages of Kullu district of Himachal Pradesh during November 2020. These villages consist of a mix of historic , domestic and new buildings and temples which follow Kath-Kuni architectural style. A total of 35 structures were surveyed in villages namely Jaa, Meeteura Jari, Jari and Chenni Kothi comprising domestic and ancient heritage structures (Figure 4). Many local masons and village dwellers were interviewed to understand the engineering strategy to construct, preserve and maintain these structures.

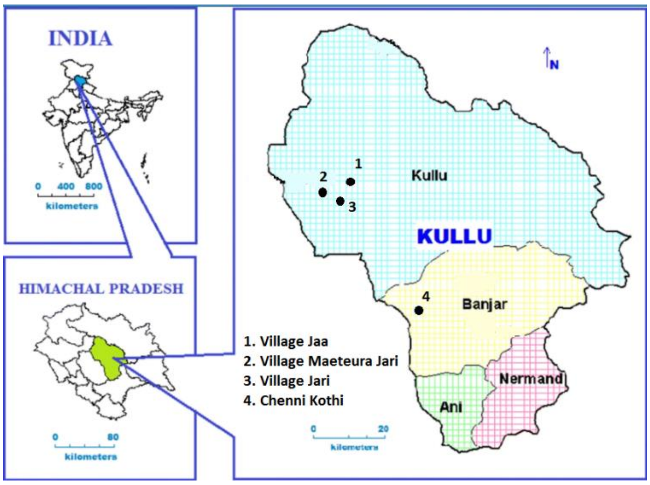

Fig 4: Places visited for site investigation.

4.1 Typical Structural Configuration and seismic adaptation

Most of the low-rise buildings (e.g. 1-3 stories) were constructed using rubble stone masonry. Figure 5(a) shows a 300 year old structure based on the Kath-Kuni architectural style and a typical arrangement of stones and timber members along the wall. Drystone-timber composite masonry walls were the main load-bearing system in the Kath-Kuni architecture. Wall openings were supported by wooden lintel beams. Buildings had alternate layers of complete dry-stone masonry and composite layers of timber as shown in Figure 5(b). These two different layers of dry-stones and timber beams also runs alternatively in the transverse wall in a way that complete stone masonry layer meets the composite layers of another wall at the corners. The composite section of load-bearing walls had two timber beams (usually of deodar) with dry stone masonry in between and masonry layer comprised of well-dressed stones. The thickness of walls varied from 460 mm to 610 mm, depending on the height of the building. The thickness of one timber beam in the wall section was around 125 mm. Such even distribution of masonry-timber composite would help distribute the stresses generated during the seismic event. Symmetrical geometrical configuration was the main feature of the structures; thus, minimizing loading eccentricities and thus reducing extra stress resultants that may arise if geometry was asymmetric. The bonding of stone within the timber members was ensured by providing the connection at the corner and mid of the two timber beams of the walls. Figure 5(c) shows the interlocking arrangement at one of the corners of the wall where the alternate composite sections of transverse walls meet. It has to be pointed out that the bonding between the structural members has a huge influence on the strength and stability of the structure during earthquake loads.

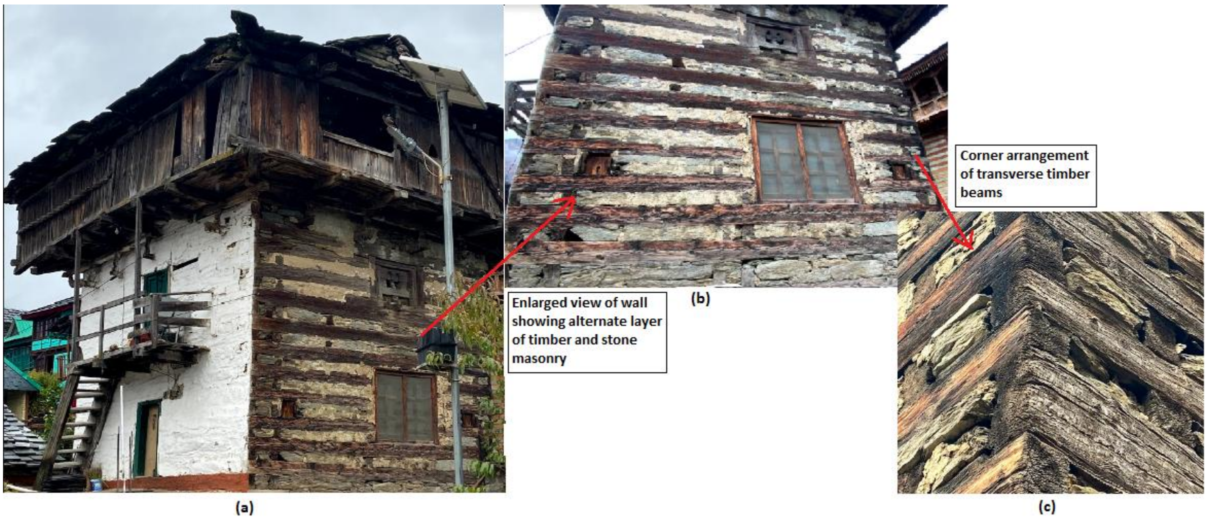

Fig 5: **a** Kath-kuni tower-like structure, **b** Enlarged view of Kath-kuni side wall **c** Corner details showing interlocking of transverse timber beams

Figure 6 shows the samples collected during the site visit and a model of a typical connection of the timber elements. Figure 6(a) shows the stones collected from a deteriorating masonry structure. It is to be noted that the walls of the building use two horizontal beams in composite action which are connected by double dovetail timber connection and their thickness is approximately 100 mm. The connections between the beams were made in the middle length of wall and at every 1.8 m after grooving to restrict horizontal movement. This wooden connection in between the composite section of wall resists local degree of freedom of the beam components. Figure 6(b) shows a model describing double dovetail timber connection in the wooden framed structure which is made by a local mason who has constructed more than 70 Kath-kuni style structures. The timber beams of cross-section 40 mm × 40 mm were used in this model and double dovetail connection has length of 100 mm and thickness of 10 mm. The scaled down model also describes the corner connection of two parallel timber beams the beams of transverse walls. Two perpendicular beams were connected by timber dowels by drilling a hole through two beams at the corner, as shown in Figure 6(c). The diameter of these dowels was generally kept as 50 mm. In case of seismic event, dowels provided lateral stiffness to resist lateral drift between two adjacent layers of the wall. Figure 6(d) shows the overall arrangement of timber beams and connection in the structure.

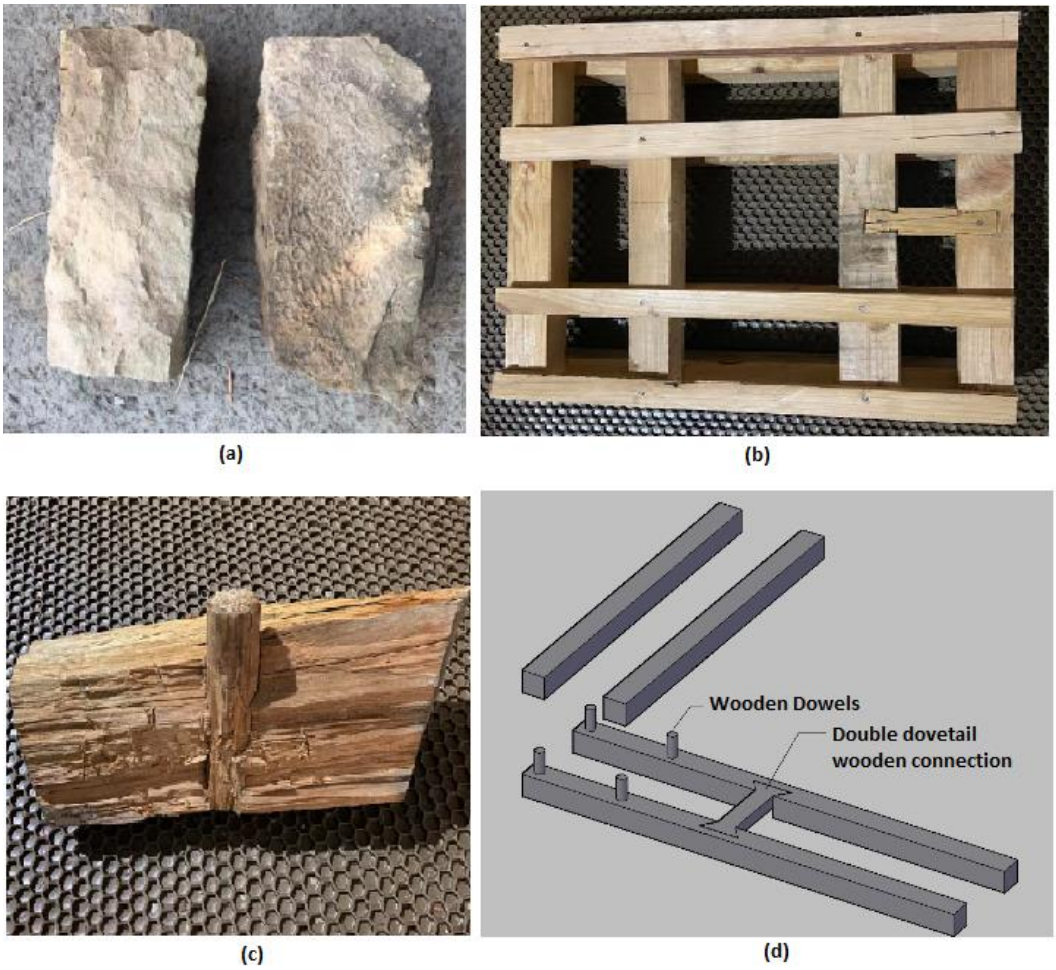

Fig 6: **a** Rubble stone collected from the site, **c** model of wooden double dovetail connection made by local mason, **c** wooden dowel in a timber beam obtained from the site **d** Modelling of connections in wooden frame present in Kath-kuni walls.

These structures were built on isolated footing made up of dry rubble masonry and depth of foundation mainly relied on the level at which hard rocky strata was encountered. Considering the rocky terrain, the depth of the footing usually varied from 0.5 m to 2 m. The plinth level of the building was approximately 150 mm above the ground and timber beam with dimension 300 mm × 300 mm was placed on it in the longitudinal direction while another beam of same dimensions was placed in transverse direction before starting the construction of a wall. These wooden beams placed at the plinth level helped in even distribution of building load to the foundation level. Besides, most of these buildings were located on the sloping ground which increases the risk of failure in case of slope subsidence during the seismic events. Although there was no proper bonding between stone masonry and timber, such construction sequence suggests a greater seismic adaptation for these buildings in terms of providing the greater stiffness by the timber members and the connection conditions at the center and corners.

However, the top floors of these buildings were cantilevered and made of timber (Figure 7a). The space available at the top floor was for lightening during the winter season. Herein, overhang beams were projected from walls to support the loads of balcony where columns made of timber were used to distribute loads of a thick sloped roof as shown in Figure 7(b). It has to be pointed out that a column discontinuity existed in the structure. This reduces the ability of the upper portion of the structure to withstand the lateral forces during a seismic event. Also, the roofing material consisted of slates that are abundantly available in the region while proper anchorage to the roof to the walls was not observed. The non-uniform mass distribution and heavyweight of slates covering the roof will attract greater inertia forces that need to be resisted in case of an earthquake event. The poor connectivity between the walls and the top portion of the building will reduce the ability of the upper portion of the structure to withstand the lateral forces during the earthquake. Furthermore, age-related deterioration of the structural members and lack of proper maintenance could further reduce the seismic resilience. The failure of the top 2 stories of 500 years old building is the evidence describing the seismic vulnerability of the structure (discussed in the Section 5).

It has to be pointed out that many of these structures survived during the 1905 Kangra Earthquake and 1975 Kinnaur Earthquakes. However, age-related deterioration of structural members, lack of periodic maintenance and loss of connection rigidity is evident in these structures and may be detrimental for future earthquake hazards. It was also noted during post-survey 2015 Gorkha earthquake that some of the masonry structures which survived the1934 Great Nepal Bihar earthquake and the 2011 Sikkim-Nepal earthquake, collapsed during the 2015 Gorkha earthquake having similar structural features, lack of proper maintenance (Kumar et al. 2019 & 2020).

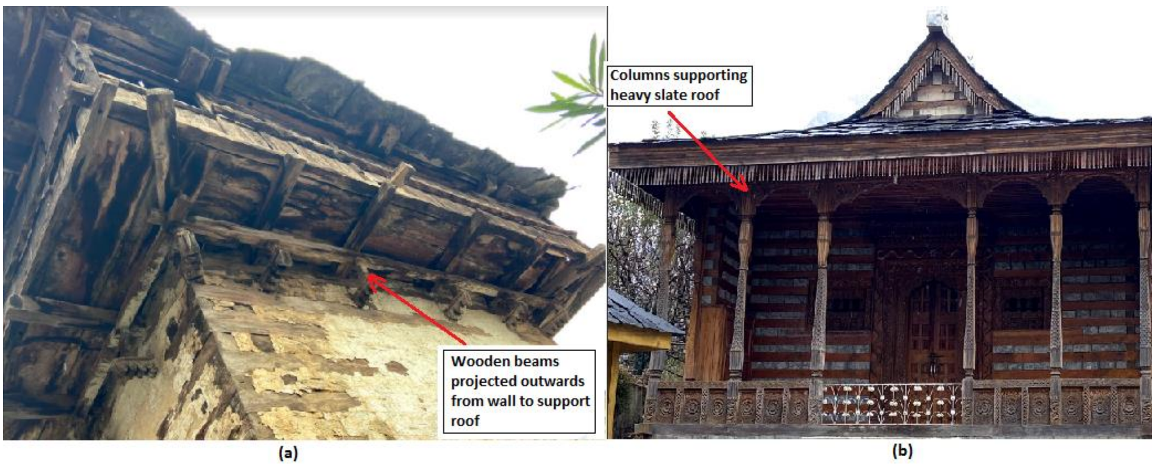

Fig 7: **a** Cantilevered balcony in old kath-kuni buildings, **b** Cantilevered balcony having columns to support slate roof.

5. Types of Kath-Kuni structures

Kath-Kuni structures were used for domestic purposes besides the existing ancient structures that were primarily used as religious places. Construction of new structures was undertaken using the locally available construction materials and the ancient structures are maintained using modern construction materials. We have divided Kath-Kuni style structures into two major types depending on its usage.

5.1 Domestic structures

Domestic Kath-kuni style structures are used by local people since several generations as shown in Figure 8. They were usually 1-3 stories where the ground storey was meant for cattle and served as storage purpose. The first storey was for living and dining and the topmost storey was often used as a place for worship and kitchen. The sloped roof was made of timber truss on which slate tiles were resting while the other structural configurations remains the same as discussed in the earlier section. The lateral dimensions of the buildings were usually dependent on the number of family members living and financial resources of the residents. Figure 8(a) shows the repair of the traditional structures with modern construction materials i.e. brick and cement mortar. Such repair practice may have negative impact on seismic resilience of the building as one portion of the structure becomes stiffer compared to the rest altering the global stiffness compatibility of the structure.

Fig 8: Residential Kath-kuni structure

5.2 Ancient Heritage Structures

Figure 9 shows a 30 m high classical tower type Kath-Kuni architecture located at Chenni Kothi village of Kullu district. The structure is believed to be more than 500 years old and survived most of the disastrous earthquakes. This ancient tower was once the palace of the Queen but now transformed into a religious place. It has a symmetrical plan and walls with a narrow opening for windows and doors. The average width of the tower was 5 m. The structure was 4 storied having cantilevered balcony in all the directions. The length of the cantilever varied from 1.2 m to 1.5 m. The tower had initially 9 stories and during the seismic event of 1905 Kangra earthquake, the top two stories collapsed. The heavy mass lumped at such height and with lack of maintenance caused the historical structure to fail under the seismic event. Irrespective of the cultural and heritage value of the structure, there was no maintenance work done and there is also no documentation of the damage happened to the structure. During 2015 Gorkha earthquake, there was the same direct economic and historical loss in case of emergency measures taken by local people after the seismic event by clearing the parts of the collapsed structure which should be recycled and reused or preserved (Coningham et al. 2019). Figure 9 also highlight a wide visible crack just below the stairs of the structure which propagates towards the corner of the building. The length of the crack was measured as 2 m. This damage pattern may be attributed to the stress concentration near of corners of the wall and their inability to bear the shear stresses. Also, the possibility of rotation of the building was not observed because of the intact rocky bearing strata. The maintenance, retrofitting and rebuilding work of such ancient marvel should be done by skilled engineers.

Some of the ancient structures are maintained using modern construction materials without assessing the primary cause of the damage. Such practise may lead to irreversible destruction of cultural heritage and potential loss of seismic adaptation being developed over the years and risk reduction strategies without highlighting the research that modern construction materials would offer enhanced resilience. This issue of discarding the usage of locally available material and disrupting the cultural heritage with modern construction material was highlighted by Davis et al. (2020).

Fig 9: Chenni Kothi heritage tower

6. Conclusions

This study presents an investigation of structural configuration and deterioration of the structural members of Kath-kuni style domestic and ancient structures of Himachal Pradesh region of India. A total of 35 buildings were surveyed in the Kullu district of Himachal Pradesh that comprises both domestic as well as ancient structures. Following conclusions are drawn from the study:

(a) The Kath-kuni structures have a great traditional value and heritage importance attached to them. The construction of the domestic and ancient structures from seismic standpoint i.e. symmetrical geometric configuration (boxed wall) to avoid loading eccentricity, location of the plinth on the rocky stratum, alternate layers of stone-timer arrangements and connections are the corner and centre of the walls were beneficial to withstand seismic forces.

(b) The lack of column continuity at the top portion of the building, greater concentration of mass at the top (driving huge inertia forces), degradation in the connection at the corners of the wall and between the composites and reducing joint strength may be a weak zone to induce collapse. The evidence of which was recorded during the 1905 Kangra earthquake that collapsed the top 2 stories of the Chenni Kothi heritage tower.

(c) It has been observed that the seismic events have affected these buildings. While interviewing the local dwellers, it was found that some of the stones from the buildings got dislodged due to out of plane collapse and they hammered back these stones in the frame.

(d) Diagonal and vertical line cracks near corners of the walls and deterioration of the timber members were the main damage pattern observed during the survey. Inspection within the buildings reveals the cracking of many wallsdue to the loss of bonding between the stones and timber members.

(e) The out-of-plane collapse noted in some of the structures was due to lack of the ability to resist the lateral forces induced by the previous earthquakes rather the failure of founding material. Age-related deterioration of timber material, loosening of connection rigidity and lack of proper maintenance may increase the seismic vulnerability of all the buildings.

A risk reduction strategy is required to be undertaken to safeguard these structures from a future Earthquake hazards and to save the loss of life and property. A periodic inspection and maintenance is suggested together with detailed structural assessment at least for heritage structures in increase their seismic resilience. Seismic strengthening measures are required to be adopted as well. The establishment of data acquisition techniques and remote sensing using (structure from motion and terrestrial laser scanners) could help to record damage on a large scale as suggested by Dhonju et al. (2018). In such a condition, community participation, consisting of heritage documentation, could potentially contribute for the preservation of this deteriorating heritage.

References

1. Arya, A. S.: Damage scenario of a hypothetical 8.0 magnitude earthquake in Kangra region of Himachal Pradesh. Bull. Ind. Soc. Earthq. Tech. Paper No. 297, 27, 121-132 (1990).
2. Bilham, R., Gaur, V. K.: Geodetic contributions to the study of seismotectonics in India. Current Science-Bangalore, 79(9), 1259-1269 (2000).
3. Bilham, R., Gaur, V. K., Molnar, P.: Himalayan seismic hazard. Science, 293(5534), 1442-1444 (2001).
4. Bilham, R.: Himalayan earthquakes: a review of historical seismicity and early 21st century slip potential. Geological Society, London, Special Publications, 483(1), 423-482 (2019).
5. Coningham, R.A.E., Acharya, K.P., Davis, C.E., Kunwar, R.B., Simpson, I.A., Schmidt, A., Tremblay, J.C.: Preliminary results of post-disaster archaeological investigations at the Kasthamandap and within Hanuman Dhoka, Kathmandu Valley UNESCO World Heritage Property (Nepal). Ancient Nepal 191–192:28–51 (2016).
6. Coningham, R. A. E., Acharya, K. P., Barclay, C., Barclay, R., Davis, C. E., Graham, C., Hughes, P. N., Joshi, A., Kelly, L., Khana,l S., Kilic, A., Kinnaird, T., Kunwar, R. B., Kumar, A., Maskey, P. N., Lafortune-Bernard, A., Lewer, N., Mccaughie, D., Mirnig, N., Roberts, A., Sarhosis, V., Schmidt, A., Simpson, I. A., Sparrow, T., Toll, D. G., Tull, B., Weise, K., Wilkinson, S., Wilson, A.: Reducing disaster risk to life and livelihoods by evaluating the seismic safety of Kathmandu's historic urban infrastructure: enabling an interdisciplinary pilot. Journal of the British Academy. 7(s2), 45–82 (2019).
7. Das, R.: Standing Firm: Traditional aseismic architecture of western-central Himalayas. Peoples' Science Institute, Dehradoon (2002).

8. Dave, B., Thakkar, J., Shah, M.: Prathaa: Kath-kuni Architecture of Himachal Pradesh. Ahmedabad: SID Research Cell, School of Interior Design, CEPT University (2013).
9. Davis, C., Coningham, R., Acharya, K. P., Kunwar, R. B.,Forlin, P., Weise, K., Maskey, P. N., Joshi, A., Simpson, I., Toll, D., Wilkinson, S., Hughes, P., Sarhosis, V.,Kumar, A., Schmidt, A.: Identifying archaeological evidence of past earthquakes in a contemporary disaster scenario: case studies of damage, resilience and risk reduction from the 2015 Gorkha Earthquake and past seismic events within the Kathmandu Valley UNESCO World Heritage Property (Nepal). J Seismol (2020) 24:729–751 (2020).
10. Dhonju, H., Xiao, W., Mills, J., Sarhosis, V.: Share Our Cultural Heritage (SOCH): Worldwide 3D Heritage Reconstruction and Visualization via Web and Mobile GIS. ISPRS International Journal of Geo-Information 7(9), 360 (2018).
11. Fitch, T.J.: Earthquake mechanism in the Himalayan, Burmese, and Andaman regions and continental tectonics in Central Asia. Jour. Geophys. Res. 75: 2699-2709 (1970).
12. Gautam, D., Chaulagain, H.: Structural performance and associated lessons to be learned from world earthquakes in Nepal after 25 April 2015 (Mw 7.8) Gorkha earthquake. Eng Fail Anal 68:222–243 (2016).
13. Gopal, N., Sankaranarayanan, K.M., Sivan, P.P.: Behaviour of masonry buildings under seismic action – A review. International Research Journal of Engineering and Technology. Volume: 6, Issue: 4.2881-2884 (2017).
14. GSI 2000. Seismotectonic Atlas of India and its Environs;Geological Survey of India.
15. Jaswal, A. K., Bhan, S.C., Karandikar, A.S.,Gujar, M.K.: Seasonal and annual rainfall trends in Himachal Pradesh during 1951-2005. Mausam, 66, 2. 247-264 (2015).
16. Joshi, M., Thakur, V.C.: Signatures of 1905 Kangra and 1555 Kashmir Earthquakes in Medieval Period Temples of Chamba Region, Northwest Himalaya, Seismological Research Letters, 87(5): 1-11 (2016).
17. Kumar, A., Hughes, P.N., Toll, D.G., Coningham, R.A.E., Davis, C.: Damage assessment within the Kathmandu valley's World Heritage Monument Zones after 2015 Gorkha Earthquake. XVII European Conference ECSMGE-2019 on Soil Mechanics and Geotechnical Engineering (2019).
18. Kumar, A., Hughes, P.N., Sarhosis, V., Toll, D., Wilkinson, S., Coningham, R., Acharya, K.P., Weise, K., Josh, A., Davis, C., Kunwar, R.B., Maskey, P.N.: Experimental, numerical and field study investigating a heritage structure collapse after the 2015 Gorkha earthquake. Natural Hazards (2020) 101:231–253 (2020).
19. Langenbach, R.: The uses of masonry in earthquake zones: A perspective on Traditional and contemporary construction practices utilizing unreinforced masonry. University of California, Berkeley (1986).
20. Singh, S., Jain, A.K., Singh, V.N. Shrivastava, L.S. The Kinnaur earthquake of January 19, 1975: A field report. Bulletin of Seismological Society of America, 66(3): 887-901 (1976).
21. Sood, A., Rahul, A., Singh, Y., Lang, D.H.: Housing Report: Mud wall construction in Spiti Valley (Himachal Pradesh. World Housing Encyclopedia*,* Report 171 (2012).
22. Sood, A., Rahul, A., Singh, Y., Lang, D.H.: Housing Report: Dry stone construction in Himachal Pradesh. World Housing Encyclopedia, Report 172 (2013).
23. Vulnerability Atlas of India (2019) http://bmtpc.org/topics.aspx?mid=56&Mid1=180, last accessed 2020/12/30.
24. Weise, K., Gautam, D., Rodrigues, H.: Response and rehabilitation of historic monuments after Gorkha earthquake. In: Gautam D, Rodrigues HFP (eds) Impacts and Insights of the Gorkh Earthquake. Elsevier, Amsterdam, pp 65–94 (2017).
25. Zhao B. April 2015 Nepal earthquake: observations and refection. Nat Hazards 80(2):1405–1410 (2016).