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FIELD OBSERVATIONS ON THE PERFORMANCE OF HERITAGE STRUCTURES IN THE NEPAL 2015 EARTHQUAKE

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Abstract

On April 25 2015, Nepal was struck by a Mw 7.8 earthquake. The epicenter was located in Barpak, about 76 km northwest of Kathmandu. Over the next two months, more than sixty aftershocks with a moment magnitude 4.0 or higher were recorded, including, the most important aftershock, seventeen days later, on May 12th, with Mw 7.3. The epicenter of the second event was located 19 km southeast of Kodari, approximately 80 km east-northeast of Kathmandu.

At the end of the two months, and over 8832 casualties and 22309 injuries, thirty-one of the country's seventy five districts were reported to be affected, out of which fourteen were declared 'crisis-hit' for the purpose of prioritizing rescue and relief operations; another seventeen neighboring districts were partially affected. With respect to the built environment, the total number of government and private houses fully damaged was 530502 and an additional 281598 were partially damaged. As for cultural heritage, 741 buildings and sites were severely affected, including 133 fully collapsed, 95 suffered partial collapse and 513 partially damaged, according to the Department of Archaeology, Government of Nepal. The Post-Disaster Needs Assessment (PDNA) report indicated that the total economic impact was close to US$ 7000 million. In particular, the economic impact to the cultural heritage sector was expected to be US$ 192 million.

The current paper provides an overview of the performance of cultural heritage properties in Nepal, particularly in an around Kathmandu. Typological differences in the structure and architecture, recurrent damage and collapse mechanisms are reported for a selected set. Performance of Pagoda-style and Shikara-style temples, and Rana-style buildings are assessed. The paper is an outcome of missions conducted in May-June 2015, involving researchers from IIT Madras, India and University of Porto, Portugal, as part of a joint initiative by ICCROM, ICOMOS, ICOM and Smithsonian Institute.

Keywords: Nepal Earthquake 2015; Heritage Structures; Seismic Response

1. Introduction

Nepal is located in a highly active tectonic region of the Himalayan belt, between the Indian and the Eurasian plates. The seismic history of Nepal shows the occurrence of a large devastating earthquake every 60–70 years. The prominent earthquakes in the last hundred years in Nepal include the Great Bihar–Nepal earthquake in 1934 (M 8.4), Udayapur earthquake in 1988 (M 6.5) and the Barpak (M 7.8) and Kodari (M 7.3) earthquakes in 2015. The April 25, 2015 earthquake caused severe effects in the densely populated Kathmandu valley in terms of fatalities, structural damage and loss of heritage.

Nepal is the seat of one of the ancient civilizations of the world. The earliest inscription found in Kathmandu Valley within the World Heritage Site of Changunarayan area dates back to 425 AD. The town of Bhaktapur, one of the three main settlements of the valley, is stated to have been established in the 9th century AD with several buildings that are believed to have been constructed more than 100-200 years ago. A survey of vernacular building types in various parts of Nepal revealed several earthquake-resistant features incorporated in local building constructions [1]. These include symmetric plan configurations, small length-to-breadth ratio, symmetrically located small openings, a low floor-height, and a limited number of stories. Use of wooden studs that are found to render resistance to lateral loads, and the energy-dissipating property of some of the typical construction details are example of earthquake-resistant elements used in indigenous constructions.

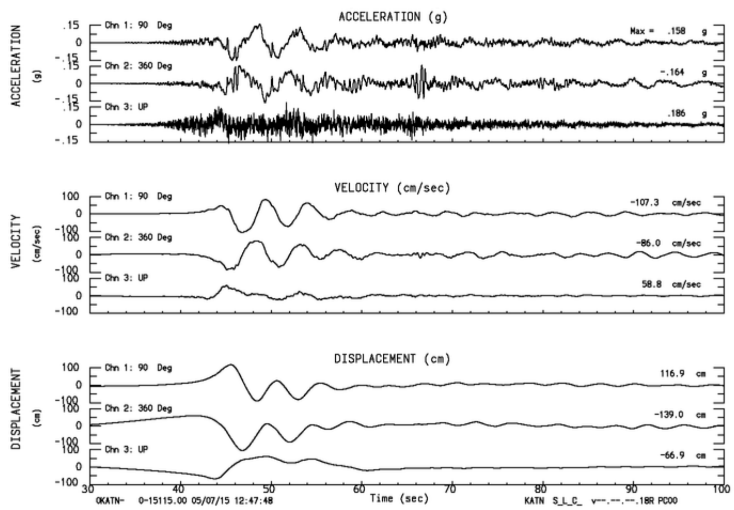

Fig. 1 – Record of the 25th April, 2015 earthquake at Kanti Path, Kathmandu (Stn: KATNP): Source: CESMD

In several ways, mainly with regard to heritage structure, the 2015 earthquake saw history repeating itself, with a number of scenes of collapse or severe damage in the monuments of Kathmandu Valley reminiscent of the Great Indo-Nepal earthquake of 1934. The report in the Bulletin of Earthquake Research Institute, Vol. XIII on the The Great Indian Earthquake of January 15, 1934 [2]: "*All the three important towns of Kathmandu, Bhatgaon and Patan were severely shaken and almost all the houses either demolished or damaged. The intensity of the shocks at Kathmandu was estimated to be X on the Mercalli scale. Large cracks appeared on the maidan and several of the roads in Kathmandu. Amid the havoc caused at Kathmandu however, the temple of Pasupatinath, the Guardian Deity of Nepal, still stands intact, entirely undamaged.*"

Few historical monuments showed disastrous performance (e.g. Darahara tower and few buildings of Hanuman Doka), while some others survived unscathed, and many more were moderately to severely damaged. This article attempts to provide an overview of the performance of such historical monuments, with an aim of understanding what caused poor performance in some typologies and what ensured survival or good performance of some others. The work is not exhaustive, but delivers a different reading of the earthquake effect on historical monuments by examining a select list of affected structures and documenting the observed damage. The typologies examined here are limited to the *Pagoda*-style and *Shikara*-style temples, and the later *Rana*-style buildings of the Valley.

2. Shikara-Style Temples

2.1 Pratappur Temple: Swayambhunath

2.1.1 Structural System and Materials

A *shikara* is the tall masonry spire located above the sanctum sanctorum, a feature common to Hindu temples. Two *shikhara*-style temples of Pratappur and Anantpur were built by King Patap Mallain 1654 AD to appease the angry spirits at the site of Swayambhu Mahachaitya, one of the UNESCO world heritage sites of the Kathmandu valley, which is the most revered Buddhist stupa in Nepal.

The temple is styled as *navarathasikharagranthakuta* and has a square sanctum sanctorum of a size equal to half its outer containing square (see Fig. 2). The outer surfaces of the sanctum wall are offset into nine surfaces reflecting its *navarathasikhara* roof on the plan form. The sanctum has a narrow two-pillared entrance portico and is accessed through a single doorway. The portico goes up to form a *kuta* attachment to the base of *shikhara*. The outer corner-to-corner plan dimension measures 4.4m, the total height of the temple is 4w or 19.19 meters, and height of the plinth, *prasada* and *shikhara* up to the base of *ghantakalas*, stated in terms in terms of w, the design side of the square, appears to be 1/3 w, w and 2w, respectively.

The original structure was built in brick masonry with mud mortar and except for the stone pillars at the entrance the entire surface of the temple is plastered in lime and whitewashed with lime. In August 2003, the temple was gutted by a fire, and subsequently destroyed by heavy monsoonal rains. The Department of Archaeology (DOA) dismantled the superstructure and reconstructed it in brick and lime mortar above the original foundation in mud mortar. The restoration work started in 2003 and was completed in 2004-05.

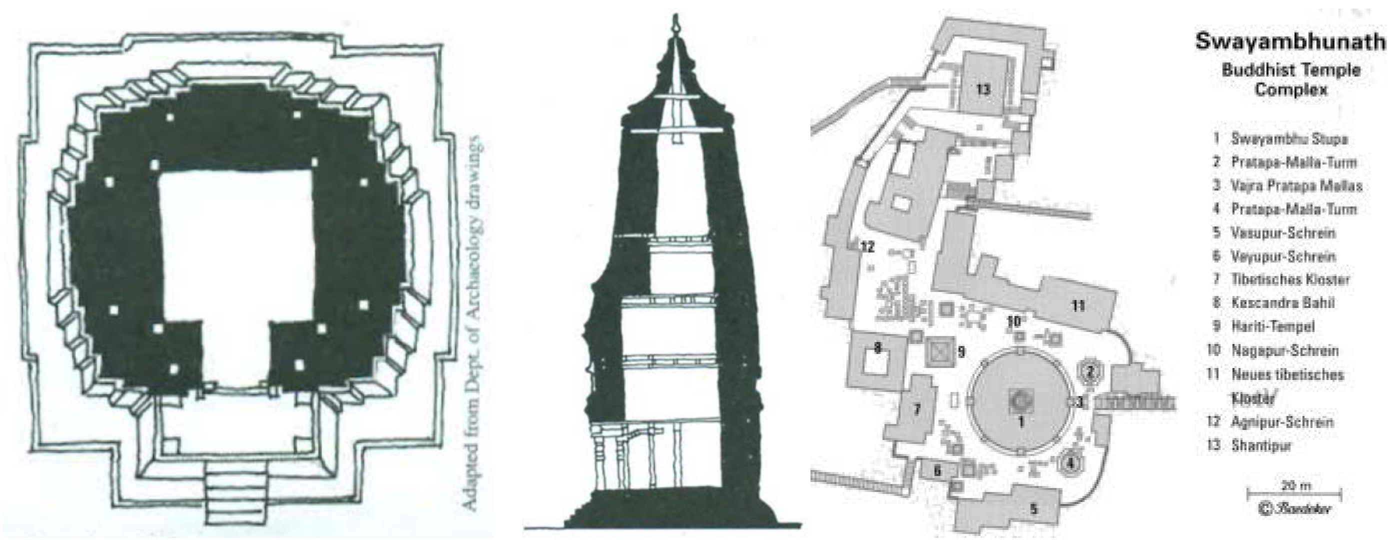

Fig. 2 – Plan, section and location map of Pratappur temple (Source: Department of Archaeology, Nepal)

2.1.2 Observed Damage

At first instance, the Pratappur Temple almost looks intact except for the collapsed portico (see Fig. 3A, 3D). On closer examination, one notices damage localized at the interface between the superstructure and the plinth all around the main structure on the northern, eastern and western sides (see Fig. 3B). About eight courses of masonry appear to be affected in the region. A series of vertical and sub-vertical cracks can also be noticed confirming crushing mode of failure of the masonry (see Fig. 3C). These courses of masonry show evidence of mud mortar as the bed and head joint mortar. As reported earlier, rest of the superstructure was reconstructed in brickwork with lime mortar, thereby introducing a weaker and a softer layer in the load path, and more so at a critical section. The large displacement response, seen in Fig. 1, induced by the earthquake has resulted in the entire, relatively stiffer superstructure rocking as one unit, hinged at the plinth, thereby causing significantly high flexural compressive stresses at the compressed toe for the brick masonry in mud mortar.

It is clear that in the case of this structure, it was the earlier intervention, which was responsible for the triggering of such a critical damage mechanism, i.e. flexural compression failure of the masonry in the critical section. The situation could have been different if care was taken in the earlier reconstruction efforts in creating better connection between the plinth and the superstructure. Interestingly, in the next example that is studied, a similar structural configuration has shown a different mechanism. At the entrance, the collapse stone pillars of the portico demonstrates the insufficient connection, both at the base and the top of the pillar (see Fig. 3D, 3E). This is a recurring feature of the temples in the Valley, which should be addressed in reconstruction efforts.

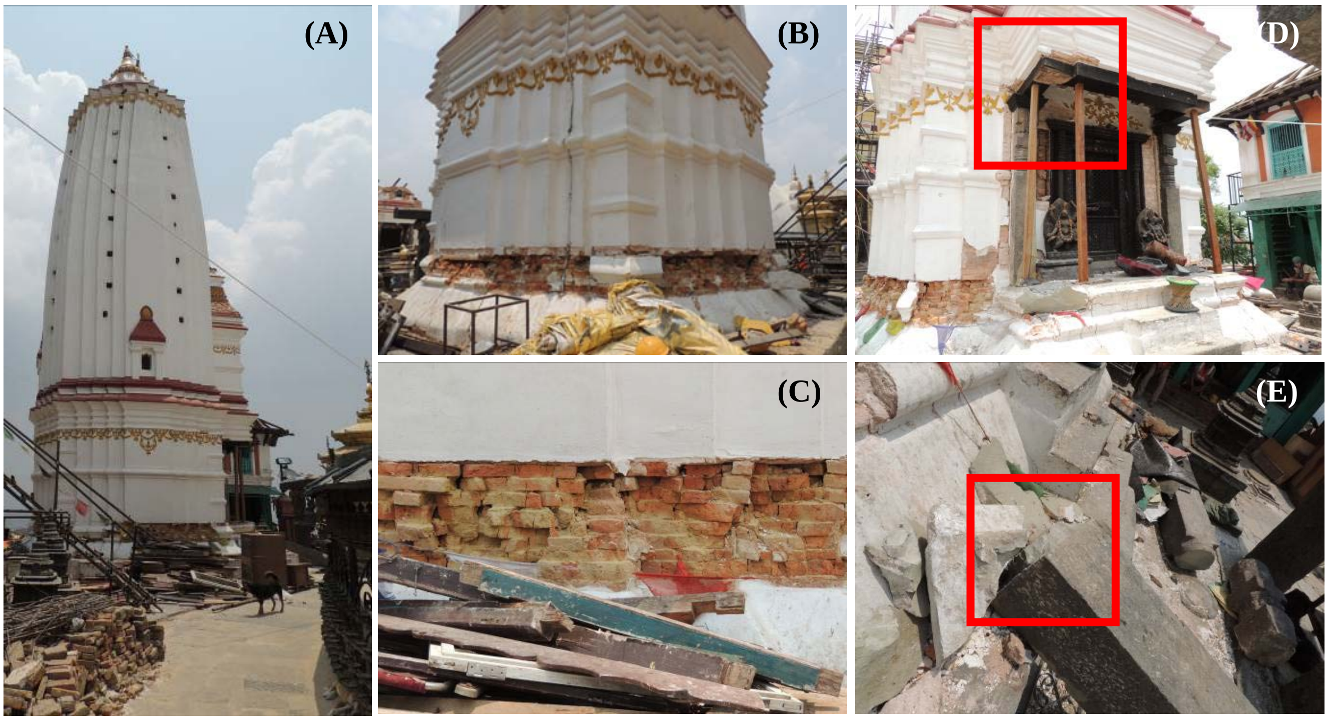

Fig. 3: (A) Pratappur Temple; (B) Damage to masonry plinth; (C) Crushing of brick masonry layers in mud mortar; (D) Collapsed portico of the temple; and (E) Lack of good connectivity at stone pillar base

2.2 Anantpur Temple: Swayambhunath

2.2.1 Structural System and Materials

The temple's plan configuration is similar to the Pratappur temple located within the same complex. The superstructure is made of brick masonry in lime mortar with vertical timber posts and horizontal timber connecting members, embedded in the masonry, providing greater lateral deformation capacity. These vertical posts at corners play a role in tying the walls of the structure together. This latter feature is a characteristic of the *Shikara*-style temples, including the Pratappur Temple (see Fig. 2).

After a landslide in 1978 on the southeastern slope of the Swayambhu hill, the brick foundation had been made more robust by installation of reinforced concrete beams. Vertical cracks on the foundation walls were also apparently repaired using new bricks and cement mortar. As the drainage of the slope was improved to prevent water from infiltrating from the pavement level and to relieve water pressure in the slope, the foundation can be considered to be stronger compared to traditional brick foundations (see Fig. 4D).

2.2.2 Observed Damage

Due to the ground shaking, the *shikhara* had completely collapsed and the walls had also undergone significant damage, as observed from the photographs in Fig. 4. Despite the presence of the embedded timber frames, the four walls of the structure could not be held together, and significant dilation of the superstructure is noticed from the formation of large vertical separation cracks (see Fig. 4A and 4C). Homogeneity across the masonry cross section of the walls is apparently lost, despite the presence of the embedded timber framing. This points either to a deteriorated state of the timber framing elements of inadequate timber framing for the level of displacement demand that the structure was subjected to in the earthquake. On the rear wall, diagonal shear cracks are observed, indicating the predominant direction of the ground shaking, i.e. east-west at the site. This also indicates that largely, out-of-plane mechanisms have been overcome (towards which the embedded timber framing and superimposed load of the shikhara have contributed) and the in-plane resistance of the shear walls has been garnered. This is in contrast to the Pratappur Temple where damage is localized at the base.

It is noticed that the front portico of the main temple has almost detached itself from the main structure, again, owing to lack of adequate interlocking of the structural elements of the portico to the masonry walls. The portion itself stands risk of collapse due to further ground motions (i.e. aftershocks) and temporary interventions must address this aspect prior to salvage of the contents of the structure.

Fig. 4: (A) Anantpur Temple with collapsed shikhara; (B) Rear view of the structure showing repaired plinth; (C) Vertical cracks showing dilation of the structure; and (D) Shear cracks on the rear wall.

2.3 Narayan Temple: Bhatkapur Durbar Square

In a similar but smaller structure of the *shikhara*-style, the Narayan Temple located in Bhaktapur Durbar square, showed interesting damage patterns. The structure is symmetric in plan, constructed in brick masonry, but without the projecting entrance portico. The embedded timber framing for the superstructure is also present.

The details of the timber framing can be observed in another structure in Kathmandu that partially collapsed in the earthquake. The nature of interconnection, entirely by timber dowels, and the levels at which the framing is provided are visible in the photograph in Fig. 5A. More importantly, it must be observed that the interconnections do not traverse the entire masonry cross-section or wall thickness, but are limited to the inner masonry leaf, raising doubts on their effectiveness in tying. The collapse mechanism triggered in this structure itself, points to lack of effective tying between orthogonal walls provided by the embedded timber framing.

In the Narayan Temple in Bhaktapur, the earthquake ground shaking caused considerable damage to all the four walls of the and the shikhara. The main axis of the structure is oriented along the NNE-SSW direction and typical diagonal shear cracks are noticed on the south-eastern and north-western facades, implying dominant in-plane response (see Fig. 5C and 5D). On the front facade, the cracking is more pronounced due to the presence of the arched opening. Vertical splitting of the masonry is observed on the front facade, primarily due to insufficient interlocking of the masonry units at corners. Since the timber frame is present inside the masonry façade, the horizontal tie beams fail to provide any confinement or effective tying to the masonry. On the side walls, horizontal cracks have been observed occurring both in the walls and in the shikhara as shown in Figure 14. These cracks can be attributed flexural tension along the out-of-plane direction. The horizontal crack on the shikhara (see Fig. 5B) is again indicative of the poor interconnectivity of the embedded timber frame with the outer masonry leaf, which responds almost independently. This horizontal crack in the shikhara could also be aligned with the level at which the horizontal timber element is provided. This could not be verified as the structure was unsafe for access to the interior.

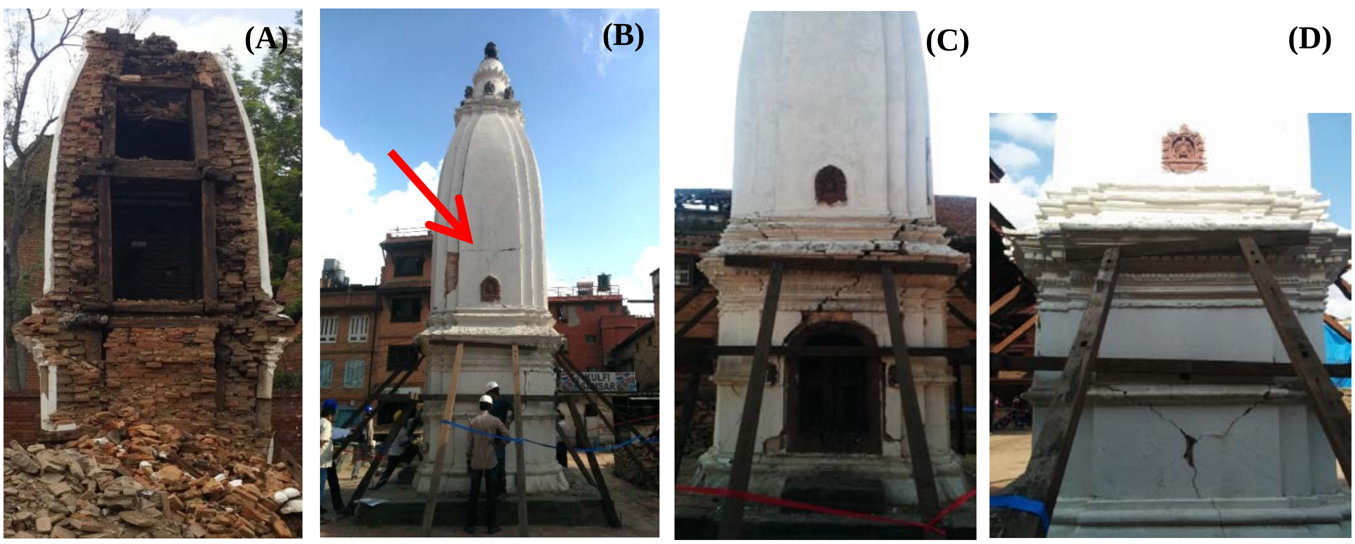

Fig. 5 – (A) Embedded timber frames seen in another damaged shikhara-style structure; (B) Temporarily shored Narayana Temple showing horizontal cracks on the shikhara; (C) Damaged south-eastern facade showing shear cracks (D) Damaged north-western facade showing shear cracks

2.4 Summary of Damage in Shikhara-Style Temples

The shikara-style temples are characterised by load-bearing brick masonry towers, with interior timber framing embedded in the masonry wall thickness, meant to as a seismic-resistant feature. However, with the timber framing positioned in the inner leaf of the two-leaf masonry, its effectiveness in tying up the orthogonal walls is suspect, as demonstrated by the damage and partial collapse mechanisms in the structures addressed here. The timber framing elements possibly work as an internal space frame preventing inward collapse of the walls and the shikhara, thereby protecting the contents of the temple. But since the timber is always in contact with the masonry, deterioration due to moisture is a present hazard. Effectiveness of the embedded timber framing is further reduced in such circumstances.

The shikhara structure is rather slender, with aspect ratios (base dimension to height) in the order of 1:4 - 1:5. Higher modes could play a role in the dynamic response. But with the embedded timber framing limited to the inner leaf, a decoupling of the natural modes of vibration of the masonry with embedded timber frame and the outer masonry leaf is probable, with the latter afflicted by local modes or out-of-plane damage modes.

Previous interventions can play a significant role in the global earthquake performance in future earthquakes as demonstrated by the Pratappur temple.

3. Pagoda-Style Temples

3.1 Kileshwar Mahadev Temple: Changunarayan

3.1.1 Structural System and Materials

The Pagoda-style temples are characterised by multi-tiered timber framed structures with overhanging timber roofs. The current paper makes specific reference to Sri Kileshwar Mahadev Temple in Changunarayan UNESCO World Heritage site. The three-tier Kileshwar Mahadev Temple with its symmetric square plan sits on a square plinth. The characteristics of the Pagoda temples are their significant wall thickness, multi-tiered structure, box-type configuration, and considerable plinth section and height. The foundation is often just as wide as the plinth platform itself and appears as a masonry mat. Brick masonry walls form the main load-bearing system, but are lain with timber framing embedded in them (see Fig. 6C). In case of multi-tiered temples, wall thickness reduces from the ground storey to the top. The thickness of the masonry walls range from 50 to 75 cm and constructed with two leafs in a single cross-section. The outer leaf is made up of fired clay bricks *Dhinchiapa* with smooth finish and the inner leaf is made up of sun-dried bricks *Maapain* and mud mortar. On the exterior, the mortar joint thickness is minimised so that the mud mortar is not washed away by rain, and this is achieved by the use of wedge shaped brick units (see Fig. 6A and 6B).

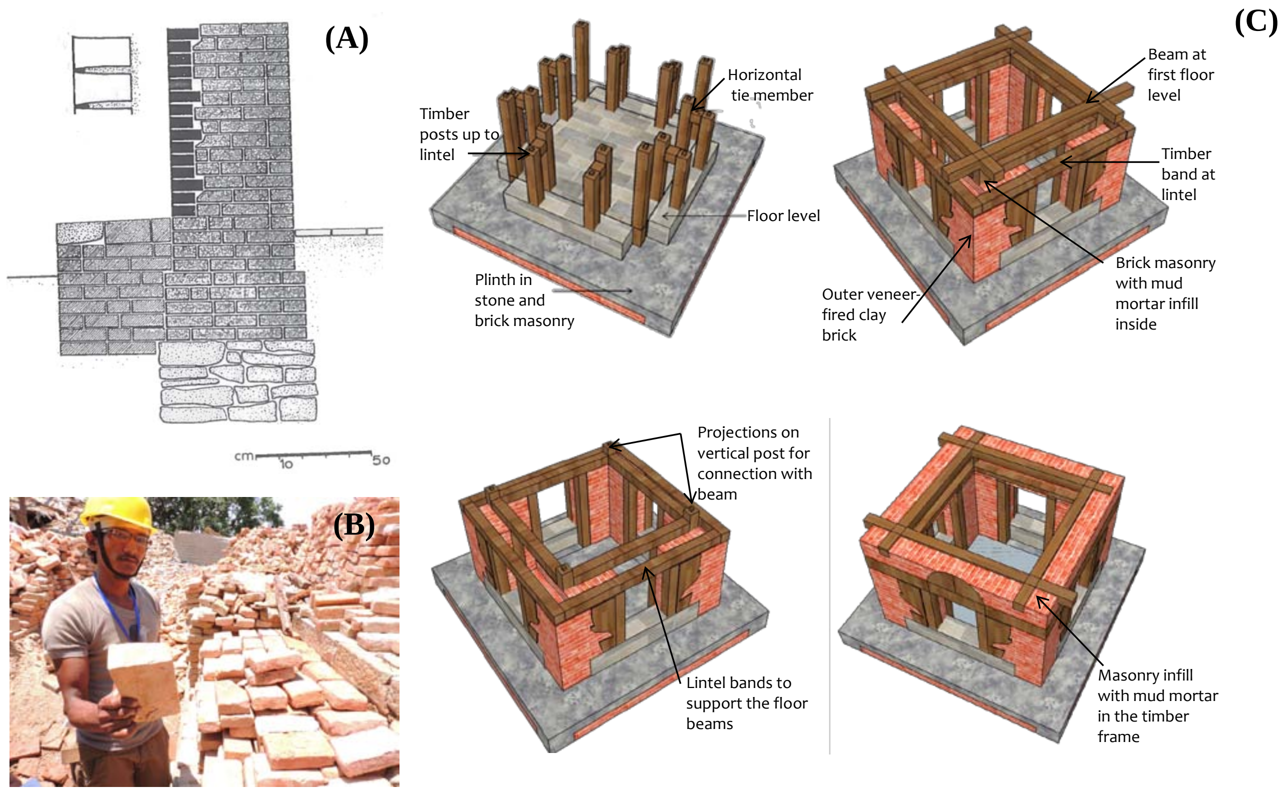

Fig. 6 – (A) Typical wall section [3]; (B) Wedge-shaped fired clay unit
(C) Assembly of timber posts, lintels and beams, and masonry walls in the Kileshwar Mahadev Temple

Usually a dressed natural stone or a wooden threshold supports the wooden post and wooden bracket, which transport the load from the lintels and beams on to the posts. A long peg, extending from the post, passes through the bracket into the beam and holds the three elements in position. The windows are decorative since the tower containing these windows can never be accessed and often there are no openings in the brickwork behind the windows [3]. The ground floor consists of a Sal wood (*Shorea robusta*) timber framing system. These frames support the wall of 2.5–3.5 m height above it, which supports the first roofing system. The sections in Fig. 7 reveal the traditional construction of the top tower, which rest on timber joists and timber columns along with timber beams, supporting the walls above.

A large roof overhang protects the walls from the heavy monsoon rain and blocks direct sunrays on the facade during summer. The rafters of the topmost roof of the temple meet at a point on a central post. The ridge piece rests on a row of simple vertical posts. The wall plates rest on low sleeper walls that are an extension of the lower wall structure now enclosed in the roof space, and the roof plate rests wither on an eaves structure or on slanting struts. Wooden nails keep the various components in place. The cornice supporting the lower end of the inclined roof struts is formed by different projecting carved timbers and two or three layers of projecting moulded bricks, which overlap at the corners of the building to become a decorative element.

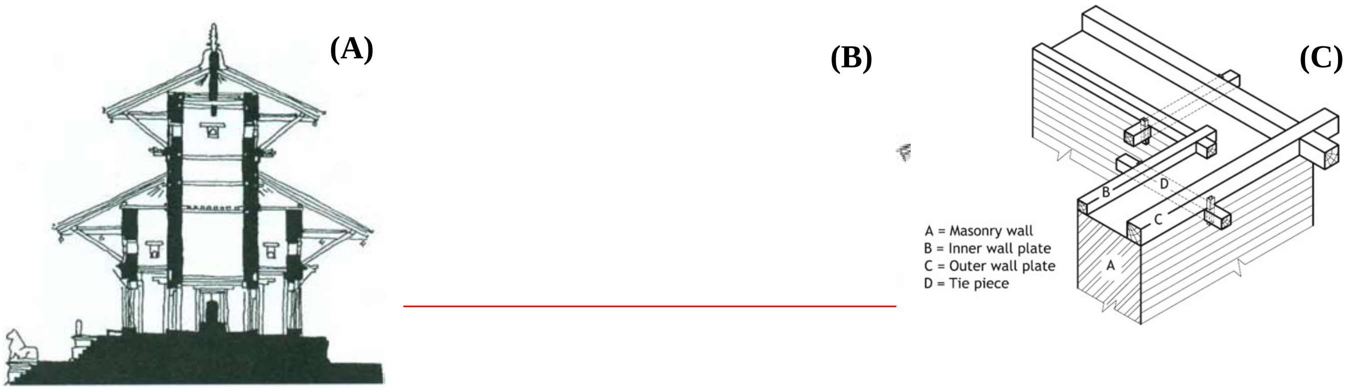

Fig. 7 – (A) Section through a tiered temple [3]; (B) Typical roof detail in section [4];
(C) Typical joinery detail at timber frame [4]

3.1.2 Observed Damage

The brick masonry walls of the temple have been severely affected with the earthquake. Both inner and outer leaf masonry have collapsed at the corners leaving the inner timber post and upper floor timber band exposed, and this is attributable to the fact that there was no tying member between the masonry leaves along the height (see Fig. 8A-C). In the upper floors, there is no collapse but cracks and out of plane deformation are visible (see Fig. 8D and 8E). Despite the extremely high standard attained in the brick firing, the quality of the brickwork and, as a result, the structure of the building is surprisingly weak, which can only be attributed to the following reasons: the use of mud mortar; poor bonding between the facing and the backing brickwork, difference in size between the face brick and the standard brick and the fact the orthogonal walls have no ties at the corners.

The double framed doors and windows act as reinforced openings. Posts are erected at strategic points along the walls to support the flooring system, which is supported by different framing systems independent of each other. The masonry is only partially used to support the flooring and acts as a curtain wall. Thus, the timber frame inside does not restrain the masonry facade from falling in the out-of-plane direction.

Structural characteristics in the design and configuration of the Pagoda-style temples, which affect the earthquake performance [5] are identified as: Lack of vertical structural continuity created by supporting the upper temple level on timber beams rather than directly on the masonry wall structure below. The heavy roof structure, covered by mud and tiles, are supported by a ground storey that is highly perforated by openings, thereby creating a soft ground storey, which undergoes significant deformation (accompanied by collapse of the masonry leaves). Lack of rigid connections are found in a poor through-wall bonding of the multi-layer masonry wall, structurally deficient timber joinery and traditional timber pegged joints, rigid in only one direction.

Another possible contributory factor for the out-of-plane collapse of the masonry leaves is wedge-shaped configuration of the units of the outer leaf (recall photograph in Fig. 6B). In the absence of through-stones or interconnecting elements with the inner leaf of sun-dried bricks, the outer-leaf by itself has almost no out-of-plane resistance and individual units will rotate about the thicker end due to the gaps created by deteriorated mud mortar joints above and below along the width of the unit, thereby making the wall very susceptible to out-of-plane shaking.

Fig. 8 - Kileshwar Mahadev temple: (A) Collapsed masonry at corners; (B)-(C) Dislodged outer leaf; (D) Shear cracks and dislodged masonry in north wall at first floor level and (E) Split in the timber strut of the west wall.

3.2 Shantipur Temple: Swayambhunath

3.2.1 Structural System and Materials

The Shantipur Temple is a sacred temple located on the Swayambhunath hill, and apart from its importance as a cultural heritage building, its powerful symbolism for the local community highlights the intangible natural of its cultural importance. Owing to its sacredness, this structure presented difficulties for the post-earthquake damage survey, as the interior of the structure could not be accessed by persons other than priests. The Shantipur Temple has a simple rectangular plan as shown in Fig. 9, with massive masonry walls about 1m thick in solid brickwork with mud mortar, embedded with horizontal timber ties at regular intervals along the height. The interior of the structure is provided with a series of closely spaced timber posts that support the timber truss roof (NB: not shown in the plan as the interior was not accessible), and reduces the load from the roof on to the peripheral masonry walls. The inner chamber exhibits valuable mural paintings in its peripheral walls.

3.2.2 Observed Damage

A simple damage map showing the observed distress in the eastern, northern and southern elevations is shown in Fig. 9. The longitudinal axis of the temple is aligned North Northeast-South Southwest.

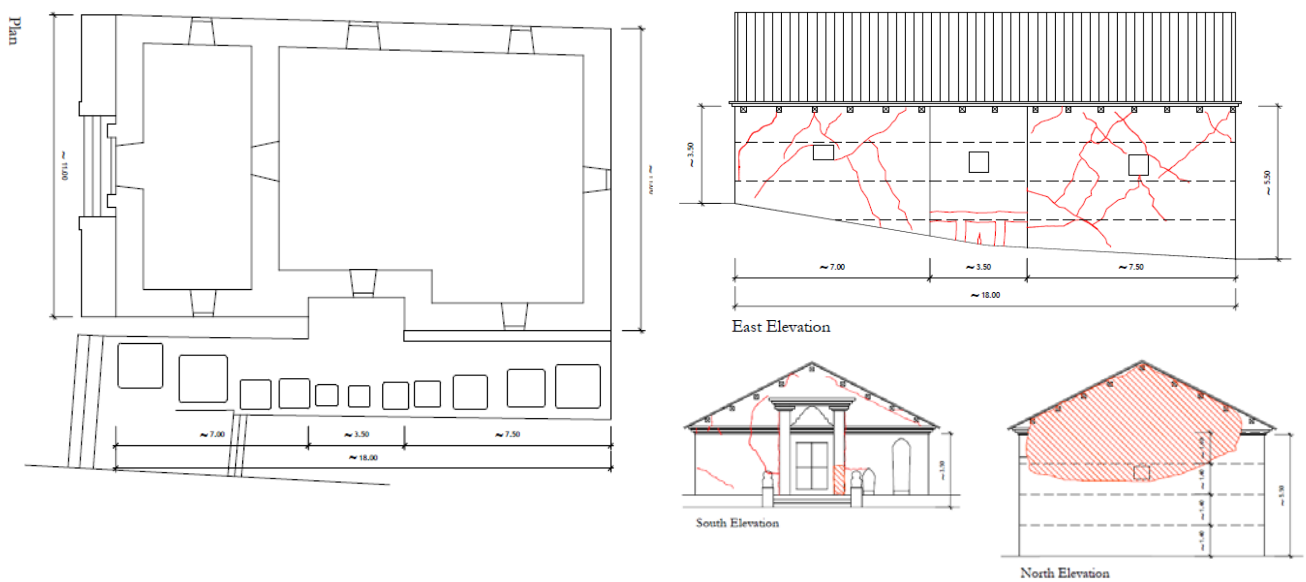

Fig. 9 - Plan and elevations of the Shantipur Temple, Swayambhunath

Fig. 10 - Shantipur temple: (A) Front facade (south); (B) Eastern facade showing out-of-plumb; (C) Eastern facade showing in-plane shear cracks and timber bands and (D) Rear facade with out-of-plane gable failure.

As can be seen from Fig. 10B-C, the left and right side walls of the temple, parallel to NNE-SSW direction, exhibit diagonal shear cracks with different levels of severity, typical of dominant in-plane earthquake loading. Clearly, there is distributed cracking owing to the presence of timber bands along the height. Some of the small horizontal cracks found across the left, right and rear walls of the temple are the locations of the embedded horizontal timber ties. Slight out-of-plane bulging is also observed on the eastern wall.

Partial out-of-plane of the gable wall was observed on the northern wall or rear facade as shown in Fig. 10D. This points to two important aspects of these constructions: Firstly, there is very little to no load transferred from the roof to the masonry walls. The load is mostly carried by the interior timber posts. Such a situation reduces the overturning resistance of the walls due to superimposed loads. The gable wall here acted almost as a free cantilever with no superimposed load. Secondly (and possibly, more important), the timber horizontal ties, which extend to a height of 5.5m do not continue into the gable wall, which could have prevented the out-of-plane collapse. This must be noted for future reconstruction as a possible deficiency in the original configuration. Finally, it is noted that based on the brief access that was granted to the interior of the temple, the interior wall suffered a partial out-of-plane collapse and that 2 timber beams also collapsed.

3.3 Summary of Damage in Pagoda-Style Temples

The pagoda-style temples are characterised by the interior timber framing, which is the primary lateral load resisting system. These structures are typically multi-tiered. The structure discussed in section 3.2, though different in terms of structural configuration, presents a similarity in terms of an internal timber frame and peripheral load-bearing walls. The holistic timber frame, which supports the heavy roof system, is clearly the reason for no collapse of such structures, despite extensive damage, particularly the portions in masonry. The lack of interconnectivity between the two masonry leaves, the sun-dried bricks and the fired-clay bricks, is a cause for concern, particularly at the corners, where the articulation with the timber elements does not guarantee out-of-plane resistance. The presence of horizontal timber ties in the peripheral masonry walls ensures sub-panelling with distributed shear cracks. But the timber ties are absent in critical locations such as the gable wall, which is therefore, highly susceptible to out-of-plane collapse.

4. Rana-Style Temples

The Rana-style buildings, Neoclassical or Baroque, dating back to mid-1800s, constitute the most vulnerable constructions that have demonstrated their weakness in every earthquake. These massive, multi-stored brickwork with lime/mud mortar structures with no seismic-resistant features, e.g. timber bands seen in vernacular styles, that unfortunately make up most of the strategically important administrative and public buildings today, are in the high seismic risk category. They also feature seismically vulnerable structural elements such as arches.

Fig. 11: (A) Extensively damaged Hanuman Dhoka; (B) Out-of-plane collapse in Nepal Academy of Fine Arts

These massive masonry constructions have seen disastrous performance (see Fig. 11) due to their excessive inertial mass and lack of earthquake-resistant features, particularly, lack of tying elements critical for monolithic behaviour. The classical out-of-plane failure seen in Fig. 11B points to the vulnerability of such multi-storied constructions.

The contemporary Dharahara tower would also belong to this category of unreinforced masonry towers, which was affected in all previous earthquake, reconstructed after the 1934 event in brickwork with lime, and collapsed in 2015 killing at least 60 persons. A review of medieval towers in high seismic region such as Italy, revealed that all of the surviving masonry towers are located in moderate to low seismic zones, not the highly active ones [6].

5. Concluding Remarks

In conclusion, with regard to the performance of historical monuments and heritage structures in Nepal, the following aspects are enumerated:

(1) The presence of embedded timber framing in the load-bearing masonry did not preclude total or partial collapse in the *shikara*-style temples. The timber framing was not successful in tying the different leaves of the masonry, and at times showed independent dynamic response. The interactions between the timber frame and the load-bearing masonry should be investigated, particularly on their adequacy.

(2) Previous structural interventions play a crucial role in the seismic performance, particularly if the interventions have inadvertently altered the load path or stiffness and strength of critical sections with respect to the rest of the structure. The response of the Pratappur Temple is a case in point.

(3) Deterioration of structural materials due to weathering and aging of materials and lack of maintenance or periodic replacement play a significant role in the satisfactory seismic performance. Specifically with the embedded timber framing elements, constant contact with moisture is a challenge. Restrictions on the use of timber due to current legislations do pose hurdles, and need to be reviewed [7].

(4) In the pagoda-style temples, the massive interior timber framing supporting the roof is responsible for the no-collapse condition. But extensive damage and partial collapse seems to be recurrent in the masonry portions, which almost act as infill panels, but with better tying detailing could be less vulnerable as a falling hazard.

(5) The Rana-style buildings require intervention as they are the most vulnerable stock, and pose very high seismic risk as they house important public and strategic administrative functions.

(6) Seismic strengthening must be seriously considered in the reconstruction of collapsed or partially collapsed historical monuments, incorporating new detailing, improving upon vernacular or historical designs, which at times have proven inadequate. The good performance of the strengthened Cyasilin Mandap in Bhaktapur [9], reconstructed after the 1934 earthquake is a case in point (see Fig. 12).

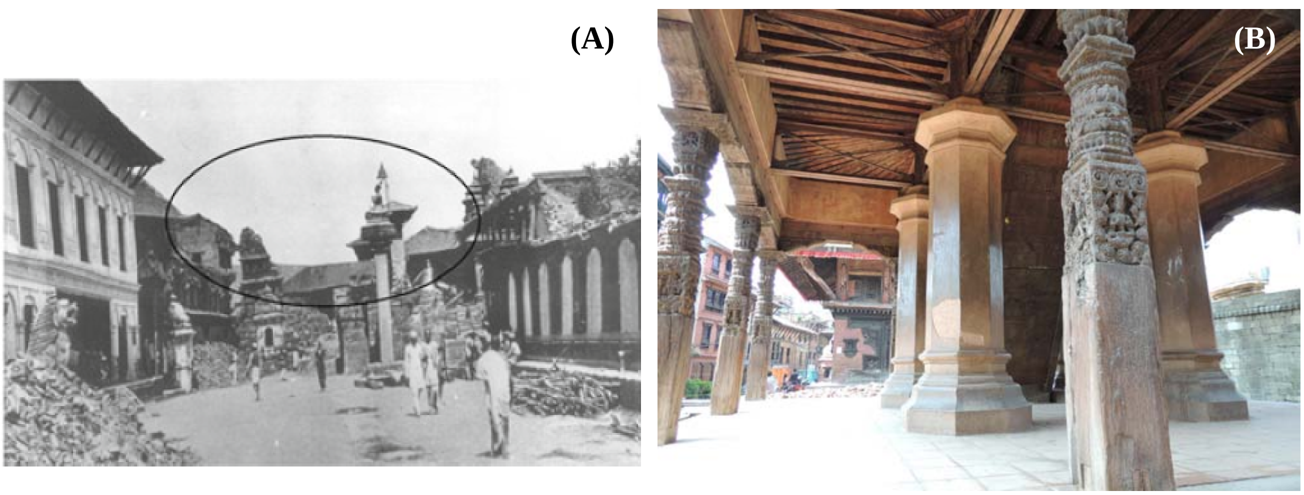

Fig. 12 - (A) Collapsed Cyasilin Mandap in the 1934 earthquake [8]; (B) Reconstructed and seismically strengthened Cyasilin Mandap that survived the 2015 earthquake [9]

5. Acknowledgements

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