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ANALYSIS OF THE SEISMIC PERFORMANCE OF A STRENGTHENED PAGODA TEMPLE DURING GORKHA EARTHQUAKE

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Abstract

An earthquake of magnitude Mw 7.8 struck mid-western Nepal on April 25th 2015, followed by hundreds of aftershocks. This earthquake level is not uncommon in Nepal, where several events of magnitude 8 or even greater have occurred in the past. The earthquake destroyed approximately half a million houses and damaged another quarter million; it also damaged or destroyed part of the seven Cultural World Heritage Sites located in the Kathmandu Valley.

Following the seismic event, several field surveys were performed, which provided clear evidence to construction technologies commonly employed in the earthquake stricken areas. Specifically, interesting data have been collected about the use of wood and bricks: two kinds of bricks of different quality are traditionally employed for the masonry internal side and for the external one, respectively; masonry walls, indeed, are normally constituted by three layers, with the middle core filled with lower quality material. In relation to the use of wood as a construction material, timber elements are widely present both in vernacular and monumental architecture as well, mainly because of the large material availability; they are typically used not only for floor and roof structures, but also for the framing of openings.

All this applies to the case of temple structures as well, which are extremely significant from both the historical and architectural point of view, since they reflect high quality handcraft and the use of the best materials and workmanship available at the time of construction. In this work, attention is focused on the specific case of pagoda temples, which were destroyed in a limited number of cases, whereas most of them survived the earthquake with limited damage.

A specific building technology has been observed in these structures, which deserves special attention. Pagoda temples, indeed, exhibit specific characteristics, related to the response to earthquake motion: lack of continuity of the masonry walls in the vertical direction, conical configuration of the internal masonry structure, open spaces at the ground level, poor connections between structural elements.

In order to interpret the dynamic behavior of a pagoda in a Buddist monastery in Lalitpur, Kathmandu Valley, information on recent renovation interventions have been collected. On the basis of available information on the structure geometry, construction details and material properties, a numerical model has been developed. Dynamic analyses performed in the linear range indicated the interest for more sophisticated computations, based on the recognition and the analysis of specific local collapse mechanisms.

Keywords: Nepal earthquake; masonry; collapse mechanisms; pagoda temple; numerical model

1. Introduction

An earthquake of magnitude Mw 7.8 struck mid-western Nepal on 25 April 2015. The earthquake was followed by hundreds of aftershocks, with the most significant (Mw 7.3 with the epicenter located north-east of Kathmandu) occurred on 12 May 2015. The rupture propagated from west to east, thereby leading to more severe destruction in the eastern part of Nepal compared to western Nepal [1]. This earthquake level is not uncommon in Nepal, where several events of magnitude 8 or even greater have occurred in the past, as a result of the collision between the Indian Plate and the Eurasian Plate.

The only available recording for the 2015 main shock provides a peak ground acceleration value of 0.16 g for the city of Katmandu. The peculiarity of this motion is in the frequency content, which shows a remarkable amplification in the range of periods between 3 and 6 s, as shown in Fig. 1. This particular behavior is related to the geological structure of the Katmandu valley basin, characterized by the presence of deep soft clay deposits.

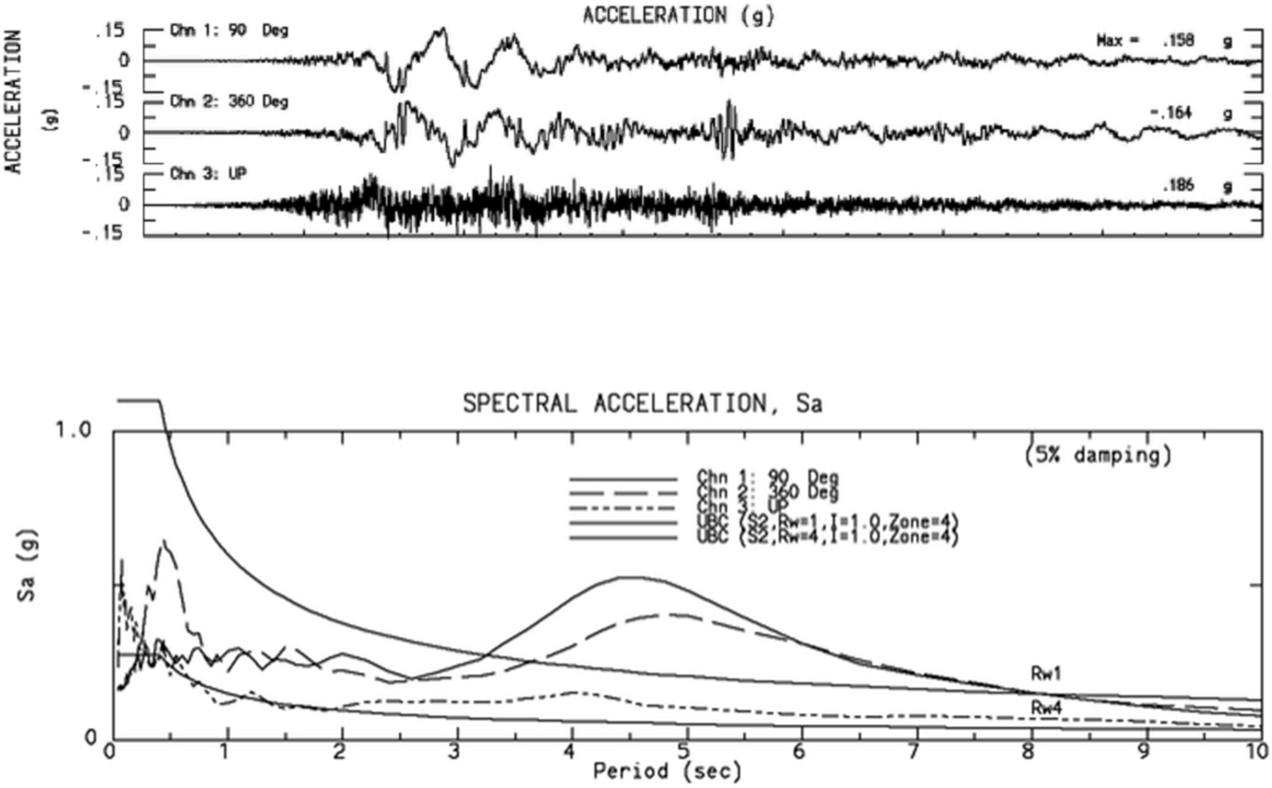


Fig. 1 – 2015 Nepal earthquake recordings and response spectra (US Geological Survey).

As reported by the Government of Nepal, the earthquake affected an area of approximately 30,000 square kilometers across fourteen districts, resulting in approximately 9,000 death and another 23,000 injured. The earthquake destroyed approximately half a million houses and damaged another quarter million; it also damaged or destroyed part of the seven Cultural World Heritage Sites located in the Kathmandu Valley [2].

Typical images of the earthquake effects show extensive damage and destruction of both monuments and residential houses, and provide clear evidence to construction materials and technologies commonly in use in the area. From these, also considering systematically recurring collapse modalities, interesting considerations can be made about the use of timber elements in conjunction with stone and brick masonry.

In this work, attention is focused on the specific case of pagoda temples, most of which survived the earthquake with limited damage, while total collapse took place in a limited number of cases. For the pagoda temples, brick masonry and wood are typically used as construction materials, in relation to a specific building technology. On the basis of available information on the structure geometry, construction details and material properties, a numerical model has been developed to interpret the seismic behavior of these pagoda temples.

Before discussing analytical modeling and analysis of the pagoda temples, a review of local construction materials and technologies is presented, based also on the results of post-earthquake field inspections.

2. Nepalese Pagoda temples: materials and structural characteristics

Environment, materials and architectural traditions, all had a key role in the development and characterization of the 'Nepali' architecture, also known as 'Newari style'. This peculiar architectural style is different from those found in the neighboring Asian countries, even if both cultural traditions and religions are similar [3,4].

In Nepal, the building tradition is mainly based on the use of wood and bricks, also accompanied by a limited recourse to stone masonry, mainly employed for sculptural works and monumental architecture. This aspect, i.e., modalities adopted for the selection and use of different materials, represents the most distinguishing factor within the Nepali architectural tradition.

Looking at the specific case of the sacred building heritage in the Kathmandu Valley, a combination of structural timber frames and brick masonry walls can be mainly found. In multi-tiered temples, the mixed use of wood and bricks for structural purposes is also found in the frame system of the peristyle and in the walls of the central cell. These structures are usually square in plan and made of thick walls which rise upwards improving the stiffness of the building structure [3]. A similar combination of these construction materials can be found in the typical Newari houses where, however, it is applied in a simpler way.

In relation to masonry, different clay types are present in Nepal, each of them being used for different purposes. Grey and black clays are mainly employed for common bricks and, in particular, the grey variety is also used for mortar or plaster; external joints, instead, are made with yellow clay. The brick size used in these temples is not standard; however, it does not differ significantly from the European standard. Bricks are manufactured by specialized workmanship; manufacturing consists of two main steps, namely, they are first sun-dried and then fired into kilns.

There are two main kinds of bricks, used on the masonry internal side and on the external one, respectively [3]. The first one, named by the natives *ma apa*, is a low cost brick and has a rectangular shape. Dimensions depend on both the location and the age of manufacturing (the average size for this element can be considered 4x10x22 cm). The latter, *daci appa*, is different for various aspects but, mainly, for its trapezoidal shape in cross section and brilliant color. The colour is produced by an additional working step in the manufacturing procedure: after drying, the fair face is immersed into semi liquid red clay in order to obtain a vitrified surface [5].

Timber as a construction material is extensively used in Newari buildings (both vernacular and monumental as well) mainly because of its large availability in Nepal. Several tree species are found all around the Kathmandu Valley: *Gwaisasi* (Schima Wallichi), *Salla* (Pinus Roxburghii), *Utis* (Alnus Nepalensis). Among these, the *Gwaisasi* is suitable for construction purposes. However, the variety which is most widely used for structural elements, due to its long life and aesthetic properties, is *Sal* (Shorea robusta), which can be commonly found in the Terai region, in the southern part of Nepal. Both *Sal* and *Gwaisasi* are good hardwood species, suitable for use in construction because of strength and termite resistance properties. They do not require any particular treatment for protection from insects and water; they are therefore used for beams, columns, bands and for the framing of openings [3]. *Sal*, as well as the other hardwood species employed for construction, comes from the southern Terai region, which is characterized by sub-tropical climate, favorable to this kind of trees.

The Newari temples (see Fig. 2) are built using brick masonry and timber elements and are covered by tiles or a metal roof (golden, copper). The larger part of them are located in Kathmandu, Patan and Bhaktapur, and date back to the 14th century. Since the Malla Dynasty, i.e., from the middle of the 14th century, Nepalese Pagoda temples (properly named *dega*) started to be conceived for religious or spiritual activities [6].

Such Nepalese holy heritage is extremely significant from both the historical and architectural point of view, since it reflects high quality handcraft and the use of the best materials and workmanship available at the time of their construction [7]. The structural characteristics of Pagoda temples are: large wall thickness, the multi-tiered roof, the box type configuration, the considerable plinth section and the slenderness ratio [8].

According to Nienhuys [9], special attention is deserved by some relevant structural solutions; specifically: the symmetrical structural arrangement, the conical mass distribution with a wide base, a huge massive plinth. All these design criteria had been developed in order to enhance earthquake resilience; they demonstrate an empirical approach to design by which, learning from experience, a progressive refinement of building techniques is achieved.

Some other characteristics are reported by Pradhan [10] and outlined by Theophile and Ranjitkar [11]; apparently, they might not be in favor of a positive response to the earthquake motion:

1. often a clear lack of continuity of the masonry walls is present in the vertical direction: at each new floor, walls are eccentric with respect to the lower ones and rest on timber beams;
2. despite the conical configuration of the internal masonry structure, the roof systems are of considerable size and heaviness;
3. open spaces at the ground level produce a soft-story type condition, thus compromising the global building resistance;
4. in general, poor connections between structural elements are present, both in masonry and timber; again, this is not in favor of seismic resistance.

For a better understanding of these structures, the above details require accurate modeling in numerical analyses and critical interpretation of the results as well. In this work, a contribution in this sense is offered.

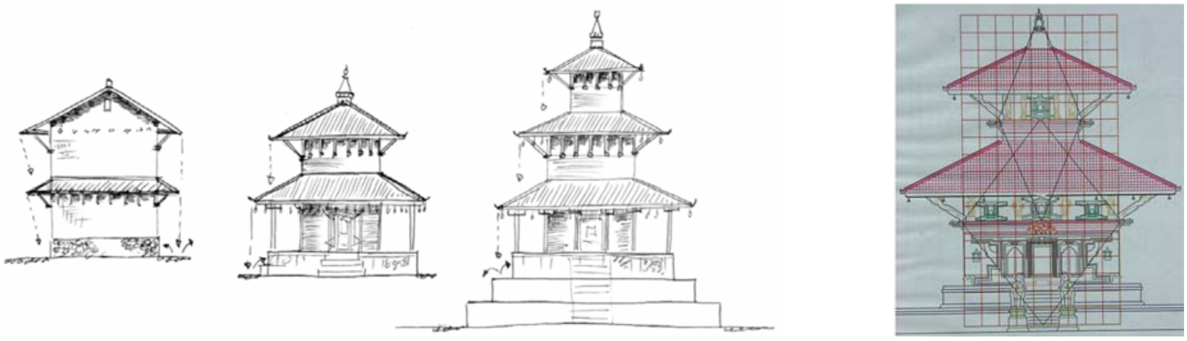


Fig. 2 – Typical elevation of a house and a tiered-pagoda roof (left); geometric proportion of a pagoda temple in Lalitpur Durbar Square (Dangol, 2007) (right)

The wall thickness of these temples is not uniform along the height; reductions are present at each storey level (Fig. 2). The average thickness ranges between 500 to 750 mm, however thickness values in the range of 900 mm have also been observed. Walls are usually constituted of fired bricks and mud mortar with three layers: the outer face of the wall is made of fired bricks; usually, these are trapezoidal in section to minimize visible thickness of mortar; the inner face is made of sundried bricks or fired bricks of lower quality. In between the outer and inner faces, the middle core is filled with rubble stones, brick bats, inferior quality bricks and mud [12]. The inner and outer faces of the walls are not tied with the middle core. Walls are laced by timber bands at different levels, starting from the plinth level. Usually these bands are provided also at the springing level of roofs, at floor levels, at the top of walls, etc.

Floors and roofs, in these pagoda structures, are made of timber elements. Roofs are constructed with steep pitch and large over hangs, covered by clay tiles (*jhingati*) laid over mud or metal sheets supported by a wood structure. From the structural point of view, these are loose fit structures with a unique joinery system. Pagoda temples have symmetrical pitches springing from the central point of the inner masonry cell. Pitches are constituted of small rafters that spring from the corner in a radial arrangement. At the different levels they are supported on walls. On the other hand, there are large overhangs supported by eaves beams, which in turn are supported by carved wooden struts. At the inner side, rafters are anchored to a tie beam fixed to the walls. All elements are joined by wooden wedges [3].

3. Observed Performance of Pagoda Temples

The available records show that pagoda temple structures in the Kathmandu Valley suffered from major damage to destruction in the past earthquakes. Photographic evidence and written documents of earthquake damage are available from the 1934 M8.3 earthquake (Fig. 3). During this event, in the Kathmandu Valley 492 temples and inns suffered destruction, though neither specific data are available on the number of damaged or destroyed pagoda temple structures, nor specific analysis on the performance of these structures and subsequent rebuilding [13].

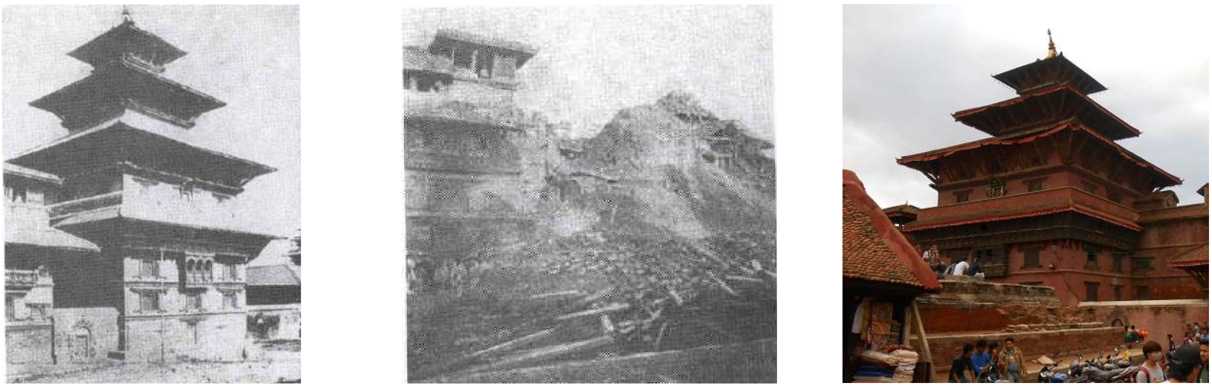


Fig. 3 – Degutale temple before (left) and after (centre) the 1934 earthquake [13] and, on the right, after the 2015 Gorkha earthquake.

Although most of pagoda temples performed well during both the 1934 and 2015 earthquakes (Fig. 3), many other pagoda temples suffered destruction during the 2015 earthquake, despite low level of shaking in the Kathmandu Valley (Fig. 4). The performance of pagoda structures varied extensively from case to case, even in the presence of similar construction materials, technologies, and architectural features. Damage levels range from local mechanism activation to global failure [14].

The performance variation could be attributed to topographical effects, geological conditions [15], maintenance, structural features, size of the structure, etc. One of the main reasons behind the poor performance of pagoda structures could be attributed to the lack of proper maintenance and to dilapidated conditions due to aging, harsh climatic conditions, deterioration of walling material and timber, etc. Other attributes that led to poor performance of these temples are: weak and brittle construction materials, inferior construction quality, weak or absent connections between structural elements, structural heaviness (e.g., thick walls, clay tiles on thick layer of mud for roof).

Although out of plane toppling of walls was not observed, possibly due to the large wall thickness and tying of the walls by timber members, other local failures were observed.

Fig. 4 – Delamination of multi-leaf wall veneer (left); diagonal sliding shear failure (right).

4. Hirnya Varna Mahavihar (KWA Mahavihar)

4.1 The structure

Hirnya Varna Mahavihar is a Buddist monastery in Lalitpur, Kathmandu Valley, Nepal. It is believed that this temple complex (see Fig. 5) was constructed in the twelfth century by a local King, Bhaskara Dev Varma. Inside the pagoda, at the upper storey, the golden image and a large prayer wheel can be observed [16].

This temple is located in a courtyard and is a three-tiered rectangular pagoda structure which rises above surrounding structures. Its roofs and screened windows, including cornices and struts, are all gilded with gold. The pagoda building, also known as KWA Mahavihar or Golden Temple, is a 6 story monastery built with brick masonry in mud mortar, which is typical of the Kathmandu type historical construction (Malla era). Structures surround the temple on three sides, up to the second story. Walls of neighboring structures appear seamless with the building.

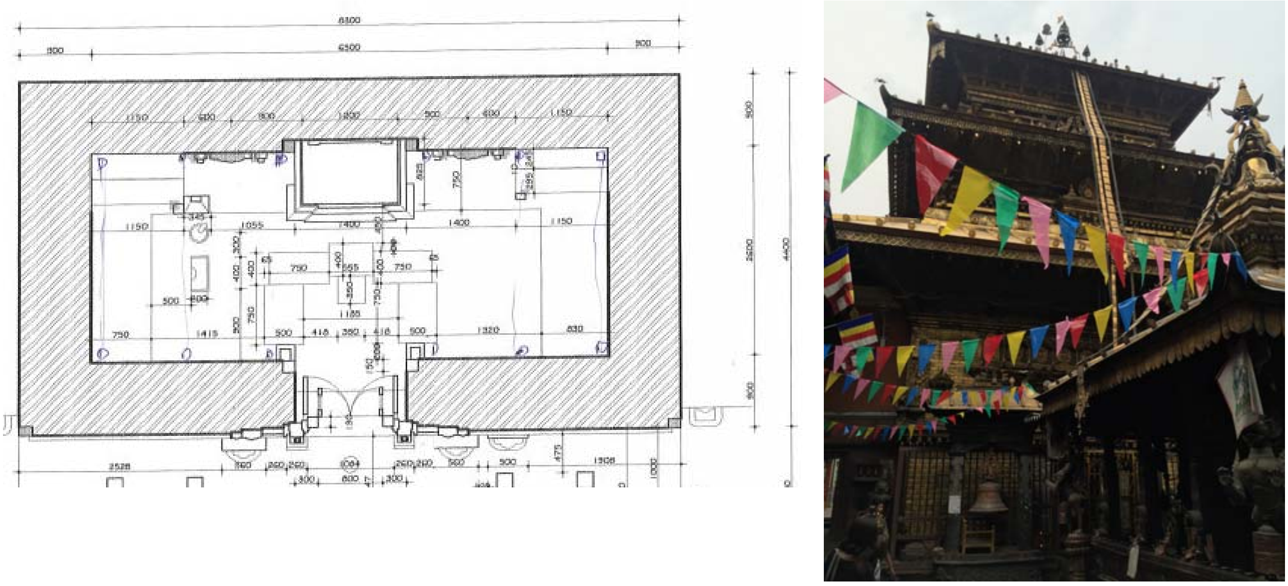


Fig. 5 – Plan and external view of the temple.

Renovation works for this temple began in 2008 and were completed in 2012 with the assistance of SCAEF, the Society of Consulting Architectural and Engineering Firms in Nepal. The building survived the 2015 earthquake with only minor damage. The temple was in a fairly rough condition before it was renovated. Many wooden members were rotting, and areas of masonry were significantly deteriorated.

Fig. 6 – Deteriorated timber elements (before interventions) [16].

The building is a three-tiered six story masonry structure. The building structure is rectangular in plan, symmetrical in both directions, and has reducing plan areas at the upper two levels. The structure is founded on the ground without steps, like other pagoda temples. The foundation of the building is not known, but due to the thick walls, soil pressure is not considered a problem.

The monastery masonry walls in the longitudinal and transversal directions constitute the main load bearing system. The wall thickness of this structure is not the same over the height, as it reduces at each story. The thickness at the ground floor is 900 mm which reduces to 600 mm at third floor level. The walls move inwards twice and the upper levels are supported by the timber floor structure. The top tier of the structure is framed entirely in wood.

Considering the previously mentioned typical practice of construction for tiered pagoda temple walls, it is assumed that the wall is constituted by three layers, the outer face of the wall being made of fired bricks, the inner face of sundried bricks, and the middle core filled with rubble stones, brick bats and mud [12]. The inner and outer faces of the walls are not tied with the middle core.

The temple floors originally consisted of a timber structure overlain by mud. During renovation, mud was replaced by a thin layer of reinforced concrete. Floor beams rest on masonry walls and extend to the outer face of the wall. The floor structure could be considered a flexible diaphragm, though it is now a thin concrete layer. The temple has roofs at three levels with reducing size, constituted by timber elements overlaid by a light metal roof. The roof has symmetrical pitches on all sides which spring from the inner masonry core.

Strengthening interventions were designed in 2004-05 and actual onsite works started in 2008, see Fig. 7. As part of the building strengthening, wooden frames were constructed within the temple from the ground to the roof. Large wooden beams are supported by the full width of walls at each story. In some cases, these beams extend beyond the outer face of the wall in order for vertical wooden pegs to connect the beams to the wall. Timber trusses were attached to these beams, creating a continuous truss up to the fifth floor. In addition to beam wall connections, the truss engages the walls with steel rods attached to steel bearing plates on the external face of the building. Horizontal wooden beams were used internally and externally (at higher stories) as an out of plane support at the floor midpoints. A concrete ring beam was placed at the building mid height, at the third floor level.

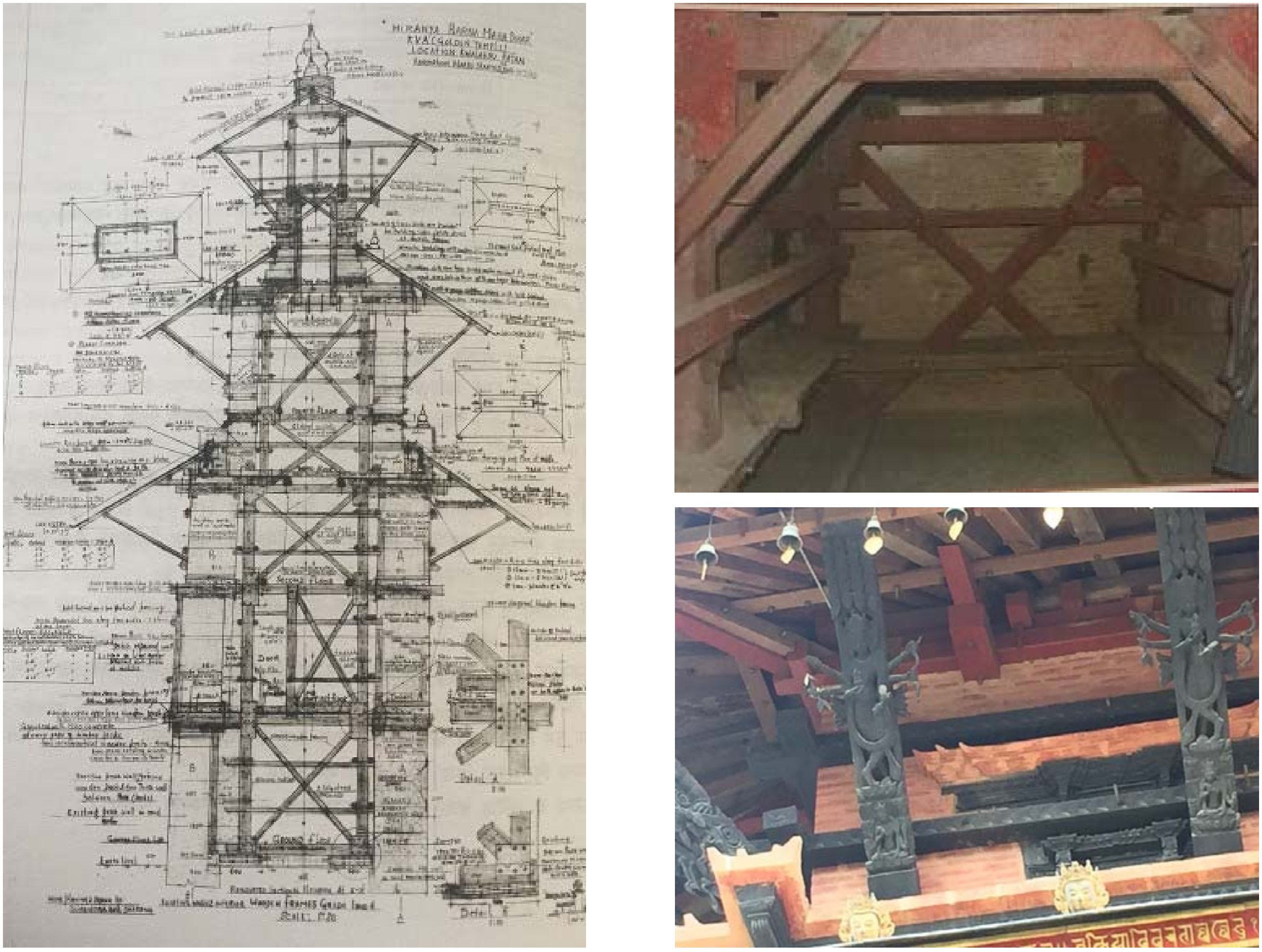


Fig. 7 – Strengthening interventions design and execution [16].

4.2 Numerical analysis

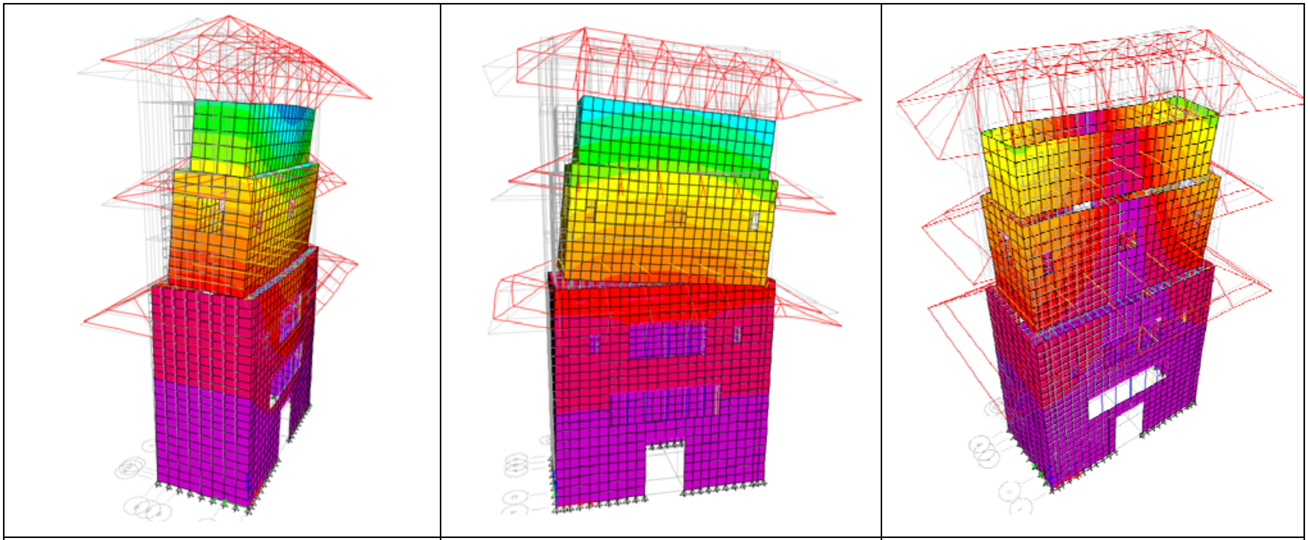
In order to interpret the dynamic behavior of the building, a numerical model has been developed, assuming linear elastic properties for the materials. Values for the elastic parameters have been assumed according to Shakya [17] and are presented in Table 1. To exclud local modes, the specific weight of timber has been neglected in the modal analysis, although the element cross sections have been correctly described.

Table 1 – Material parameter values for the numerical analysis.

Material	**Specific weight (kN/m^3)**	**Young's modulus (MPa)**	**Poisson's ratio**
Timber	-	1250	0.12
Mud-mortar brick masonry	20	800	0.10

In this study, the model corresponding to the structure with strengthening interventions did not include the foundation system and no soil-structure interaction has been considered.

Initially, a modal analysis has been performed (see Fig. 8) in order to characterize the seismic response with reference to the acceleration response spectra obtained from the recorded ground motion.



First mode: T = 0.38 sec
Effective mass ratio = 0.49 (Y dir)

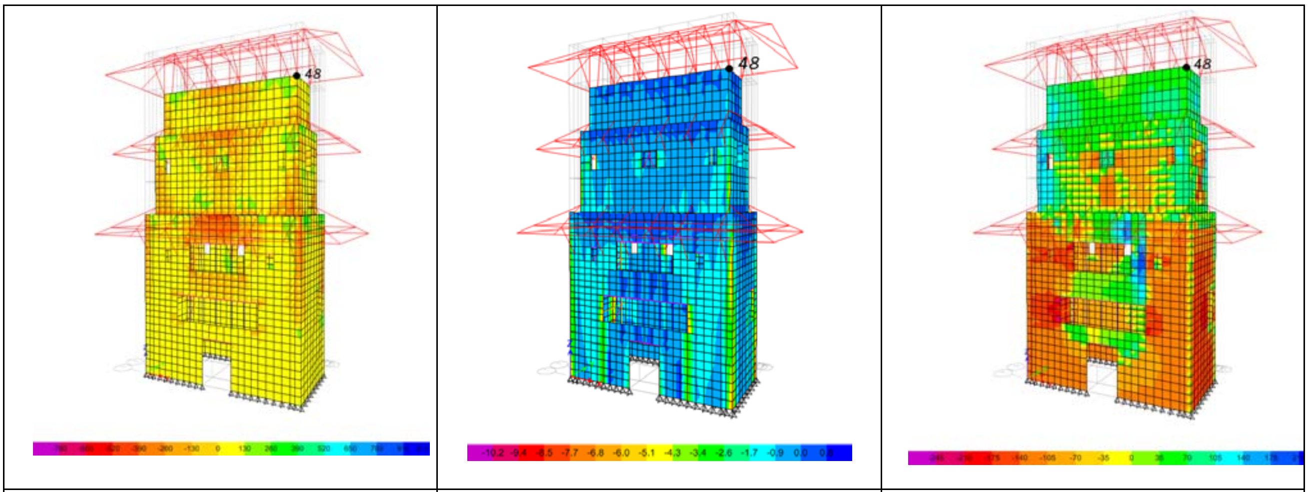
Second mode: T = 0.27 sec
Effective mass ratio = 0.48 (X dir)

Third mode: T = 0.22 sec
Effective mass ratio = 0.45 (Tors.)

Fig. 8 – Modal analysis: mode shapes and frequencies.

The comparison between models with and without strengthening interventions shows that the variations in the natural frequencies are negligible. Wood bracing, indeed, does not modify the dynamic behavior of the temple, as mode shapes and frequencies are substantially determined by the wall mass and stiffness properties.

In order to estimate the stress state generated by the April 25th, 2015 earthquake shaking, data recorded in Kathmandu (USGS Station KATNP), located about 4.2 km from the temple have been used. A time history analysis has been performed using both the North-South (90°) and East-West (360°) acceleration components, applied to the building main directions X and Y, respectively.



S11 direct horizontal stress acting on the shell elements
(max 0.80 MPa).

S22 direct vertical stress acting on the shell elements
(max 8.0 Mpa).

S12 shear stress acting on the shell elements
(max 0.25 MPa)

Fig. 9 – Time history analysis: stress distributions.

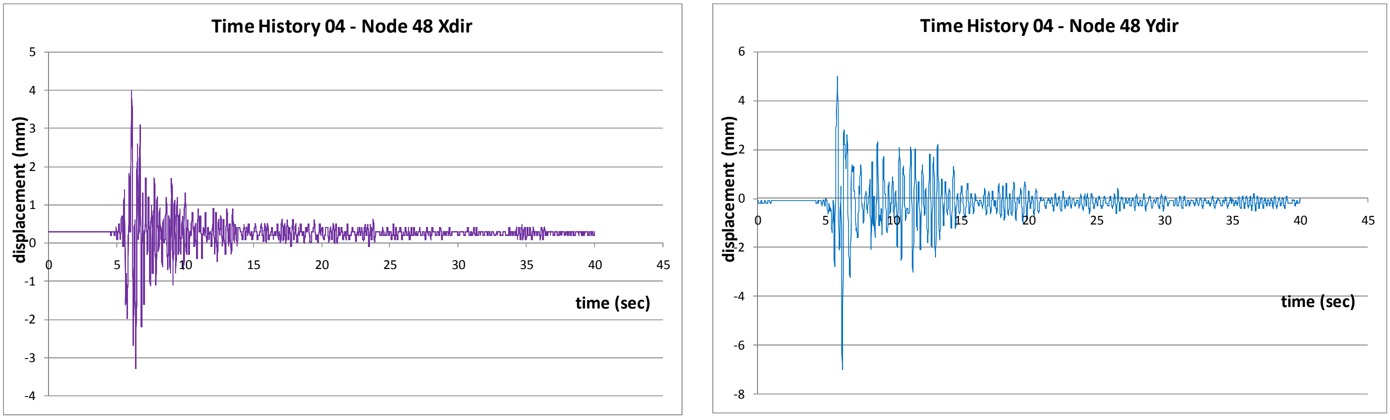


Fig. 10 – Displacements at the top of the building in the horizontal directions.

Stress distributions generated by the 2015 earthquake (see Fig. 9) can be compared to the working stress values proposed by Shakya for brick masonry [15]. Maximum compression stresses (S22) are much higher than the limit values, but are located at corners of walls and openings, while at other locations maximum values are less than 1.0 MPa. Maximum horizontal displacements are 4.0 mm in the X direction and 6.9 mm in the Y direction at the top of upper walls.

The above results have been obtained from a linear elastic model, not suitable for a correct evaluation of the building seismic capacity. It allows, however, a good interpretation of the building geometric configuration; in this sense, in the specific case of the temple here analyzed, an interesting aspect has to do with the misalignment of the vertical walls, according to the scheme shown in Fig. 12. This clearly has important implications on the structural stiffness; it should be considered that, if plate elements are used to model walls, as in the present analysis, the phenomenon is correctly interpreted only for walls which are completely misaligned.

For a global evaluation of the building seismic safety, linear analysis results should be integrated by the study of local collapse mechanisms, interpreting limit equilibrium conditions for well defined portions of the structural complex. In the Italian Guide Lines for the seismic analysis of monumental buildings [18], typical local mechanisms are defined and the verification procedure is specified. Fig. 11 refers to the typical case of churches, where a number of meaningful structural components can be recognized.

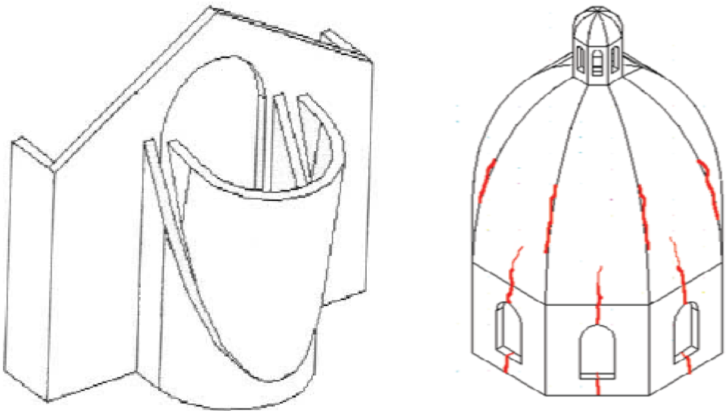


Fig. 11 – Examples of out of plane mechanisms typical of churches

After identifying typical structural details, the analysis of limit equilibrium conditions for specific structural components could be meaningfully applied also to Nepalese pagoda temples. In this case, a major problem is clearly related to misaligned walls, supported by elements with different vertical rigidity (Fig. 12), i.e., the bottom wall and the timber beams. Different rigidities in the wall support system would lead to the development of a local failure mechanism specific of this structural typology, not previously analyzed.

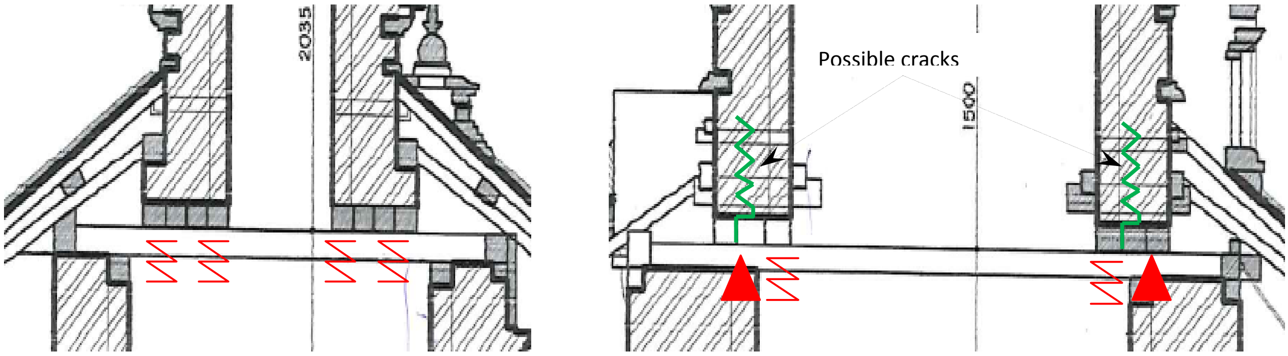


Fig. 12 – Different support conditions for masonry walls, at different levels, and the corresponding schematic interpretation (in red).

In terms of local collapse mechanisms, a simple, but fundamental case to be considered is the out-of-plane behavior corresponding to the wall overturning around the base. This would require, however, a monolithic behavior of walls. In the pagoda temples, the overturning mechanism usually is not observed because of the large wall thickness; the brick resistance in compression, indeed, seems to be the critical parameter, actually affecting the behavior of the temple.

5. Conclusions

Pagoda temples are characterized by a peculiar structural configuration, which affects the dynamic behavior and, consequently, seismic resistance. Such configuration, besides depending on geometry and mass distribution, is also influenced by the mechanical properties of masonry; in particular, by resistance in compression, which is very low. Hence, material local collapse often takes place before more extended collapse mechanisms can be activated.

In order to characterize the seismic performance of this type of structures, computational tools for the global dynamic analysis should be used, associated with specific procedures for the evaluation of both in-plane and out-of-plane resistance of masonry walls at ultimate conditions. For such local safety verifications, meaningful results could be acquired by the local collapse mechanism approach based on equilibrium limit analysis. In this sense, a methodology is presented by the Italian Guidelines [18] for the safety verification of monumental structures under seismic actions. In the Italian code, reference is made to a variety of collapse modalities, typical of local building typologies. In analogy to this, specific collapse modalities could be developed for pagoda temples, interpreting peculiarities due to geometry, dimensions, and material properties.

Through the present work, a first contribution is given to the evaluation of seismic safety margins available for this structural typology, in view of developing more specific analysis procedures.

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