Structural Vulnerability of Nepalese Pagoda Temples

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SUMMARY:
Nepal is located in one of the most severe earthquake prone areas of the world, lying between collisions of Indian to the Eurasian plate, moving continuously, resulting in frequent devastating earthquakes within this region. Moreover, different authors refer mention that the accumulated slip deficit (central seismic gap) is likely to produce large earthquakes in the future. Also, the analysis of the available information of previous earthquakes indicates the potential damage that can occurs in unreinforced traditional masonry structures in future earthquakes.

Most of the Nepalese pagoda temples were erected following very simple rules and construction details to accomplish with seismic resistance requirement, or even without any consideration for seismic resistance, during the period of *Malla* dynasty (1200-1768). Presently, conservation and restoration of ancient monuments are one of the major concerns in order to preserve our built heritage, transferring it to the future generations. The present paper is devoted to outline particular structural fragility characteristics in the historic Nepalese pagoda temples which affect their seismic performance. Moreover, based on the parametric analysis identified structural weaknesses/fragilities of pagoda topology, the associated traditional building technology and constructional details.

Keywords: Temples; structural component; FE modeling; parametric analysis; structural fragility

1. INTRODUCTION

Nepal is a Himalayan country located in one of the most severe earthquake prone areas of the world. UNDP/BPCR (2004) has ranked Nepal as the eleventh place in terms of earthquakes risk. The Himalaya evolved as a result of the collision between the Indian and Eurasian plates around 45-50 million years ago, because of its tectonics, the Himalaya is one of the active seismic belts on the globe. Geodetic measurements indicate that if an earthquake happened today in the central seismic gap (western Nepal), tectonic plates may slip by more than 4m resulting earthquake roughly M=7.8, M=8.0 or M=8.3, if the slip area measures 100km (N/S) by 300km (E/W). It is hard to estimate how much casualty and damage will be caused if such earthquake strikes Nepal in present time.

Record of past earthquakes show that Nepal felt two major earthquakes in last 100 years i.e. 1934, Bihar-Nepal earthquake (magnitude 8.4), which caused over 200,000 buildings and temples to heavy and severe damage, nearly 81,000 of which were in Eastern Nepal completely destroyed. In Kathmandu alone 55,000 buildings were affected, 12,397 of which were completely destroyed. Similarly in 1988, Udayapur (magnitude 6.5), epicentre in the Southeast of Nepal, caused 66,382 buildings to collapse [MoHA/DPNet, 2009].The 1934 earthquake pre and post earthquake photographic information as shown in Fig.1 is reveal that not only public buildings were damaged, but also a vast number of monuments, which represents the valuable cultural heritage of a nation, were destroyed by the quake. As no photographic evidence of the earlier earthquakes exists, we cannot imagine how much was lost and in what ways the cityscape changed.

Figure 1. Bhaktapur darbar world heritage site before and after 1934 earthquake [Ranjitkar, 2000]

Presently, preservation of the built heritage with cultural value is considered a fundamental issue in the cultural live of modern societies. Nepalese pagoda (multi-tiered roofed) temples, built as a structure reserved for religious or spiritual activities, began to appear around the middle of 14th century during the *Malla* Dynasty (1200-1768), who ruled Kathmandu valley prior to its amalgamation into a United Kingdom of Nepal [Parajuli, 1986]. Almost all the monuments irrespective of types such as different tiered roof temples, *pati*, *sattal*, *monastris*, *dhungedhara*, *chaityas*, *viharas*, *stupas* etc. and traditional private houses belong to the *Malla* period which is also known as the medieval period. Each different type of structure has its own distinctive character and utility but is linked with one another by common ties of construction technique and materials. These monuments were constructed when there were no mechanical and technical facilities and were handcrafted to a high quality and in a vast quantity, with the best available materials and skills at the time of their construction [Ranjitkar, 2006].

The main aim of this paper is to outline particular structural fragilities and characteristics of the historic Nepalese pagoda temples which affect their seismic performance. Parametric analysis is carried out, on three Nepalese pagoda temples to understand the fragility of structural components and propensity to damage that effect on fundamental frequency or which ultimately means the global stiffness of the structure. Results reveal masonry as the most crucial structural component to be protected from degradation and damage. More precisely, base storey masonry wall is predominant in the reduction of the global stiffness of the structure. Outcomes of this research help to understand the structural fragilities of pagoda temple topology and the associated traditional building technology and constructional details. It also helps to identify the structural parameters for seismic vulnerability assessment. The study scope is directed towards conservation and restoration of ancient monuments such as temples which is one of the major concerns in order to preserve our built heritage for future generation.

2. STRUCTURAL CHARACTERIZATION OF NEPALESE PAGODA TEMPLES

2.1. Foundation

Conservation works are usually done plinth upwards, therefore, the foundation of existing temples have rarely been studied in depth hence the condition of foundation is unknown. After the 1934 earthquake some temples were rebuilt on the old foundation as those were still in good condition. The foundation of the tiered temple is often just as wide as the plinth platform itself and appears as a masonry mat, this has led many observers (apparently expecting a foundation in the pattern of stepped footings for the main walls) to suggest that tired temples had no foundation at all [Tiwari, 2009]. Observations of existing temples with high plinth show that it is usual for the plinth mat to be built directly off the ground level or on a thin brick soling. However, the temples with shallow plinths rise from some depth below ground. As for the foundation and massive plinth (1 to 5m height) in pyramid shape, these yield even more complexity. These huge plinth base massive foundations will be benefited to eliminate the earthquake risks associated with soft soils [Nienhuys, 2003].

2.2. Masonry walls

Brick masonry walls constructed at longitudinal and transverse directions are the main load bearing system in these temples. The main peculiarities of pagoda temples with other traditional structures are their considerable wall thickness, multi-tiered roof, box type configuration, and considerable plinth width. In case of multi-tiered temples, wall thickness is not same for every storey reducing from base storey to top tower. The thickness of the walls range from 50cm to 75cm and are constructed with three layers in a single. Wall structure was always built with three layers, the outer face of wall is made of fired clay brick with smooth finishing and inner face is made of sun dried bricks [Thapa, 2011]. Outer and inner face layers were not well connected with the middle core wall. Normally the middle core is filled with rubble stone, brick bats and mud, which made the wall very poor to withstand the heavy load from the main structure. The bonding mortar inside the massive walls is not visible from the outside but has a very large influence on the structural strength and resistance of the temple. In many temples yellow color clay mortar, mud mortar and more rarely lime-surkhi mortar is used [Ranjitkar, 2000].

2.3. Roof system

In respect to roofing system the temples can be distinguished as one roof, two roof, three roof or five roof temple. Similarly, according to roof style, temples can be divided as either pagoda style or sikhara style. Temple roofs have symmetrical pitches springing from the central point of the inner masonry cell. The pitches are constituted small rafters that spring from the corners in a radial arrangement [Bonapace *et al.*, 2003]. In Fig.2 is shown the roof construction system of pagoda temples.

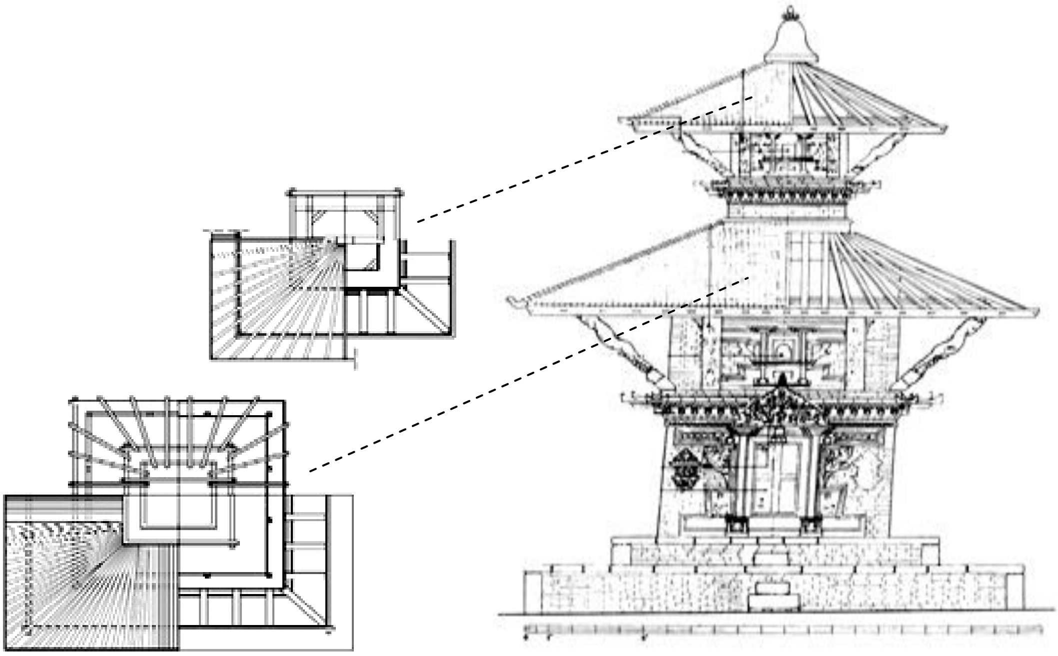


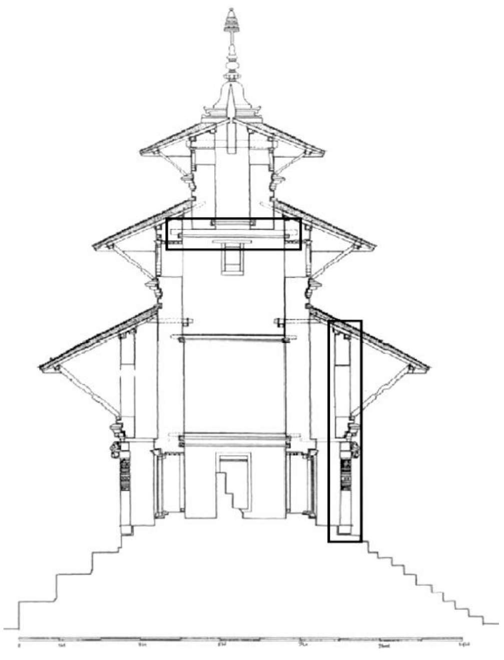
Figure 2. Roof construction system in Temples ([Theophile *et al.*, 1992]; [Bonapace *et al.*, 2003])

Inner end of diagonal rafters connected to the wall plate or on timber post (in case of top roof), at the intermediate length they are supported by wall plates laid on the wall, and the outer part sits on the purlins. The whole roof dead load (tile or metal) is supported by rafters, which transferred to wall plates and purlins. Simple timber pegs are inserted through roof rafters to brace them against the wall plates and purlins in which they rest, which is the most common traditional timber joinery detail. Moreover, the inclined timber struts are the members that hold the roof by transferring loads from purlins to the wall section, but there is no rigid connection in between strut with purlin and main masonry wall of the temple.

2.4. Timber members

The temples are one to five diminishing tier symmetric structures with brick masonry and timber elements. The ground floor consists of a Sal wood (*Shorea Robusta*) timber framing system. The frames arrange support the wall of 2.5-3.5m above it, which supports the first roof and also has decorative features. The sections marked in Fig. 3 reveals the traditional construction of top tower which rest on timber joists and timber columns along with timber beam supporting wall above it. The timber columns on the base level stand on the base stone with a small pin inserted on the stone base and the top of the timber column’s pin goes through the beam as shown in Fig. 4.

Most of the temples have timber first floors, built using simple battens or joists upon which planks are laid. These in turn support the final floor finish. Given that Nepal is located in an earthquake zone, carpenters have developed their construction techniques accordingly to provide additional bracing by linking the vertical and horizontal structural components [Bonapace *et al.*, 2003]. This practice is very effective in preventing relative sliding of the floor structure on the walls in the presence of lateral forces and hence creates a box behavior response. This connection is made using wedges (timber peg) that fix the wall plate along the perimeter through the joists that run inside and outside the building. The wall plate, which runs throughout the perimeter of the wall constituting a type of ring-beam, allows a better distribution of the dead and live loads along the wall length, also allowing a better in plane stiffness and stress distribution [Neves *et al.*, 2011]. The floor is then joined to the horizontal frame (wall plate) using battens, some of which also run through the wall and are fixed in position using wooden wedges. But in many of temples floor, simply joist are laid in one direction and the anchoring of the joist into the walls is by support only.



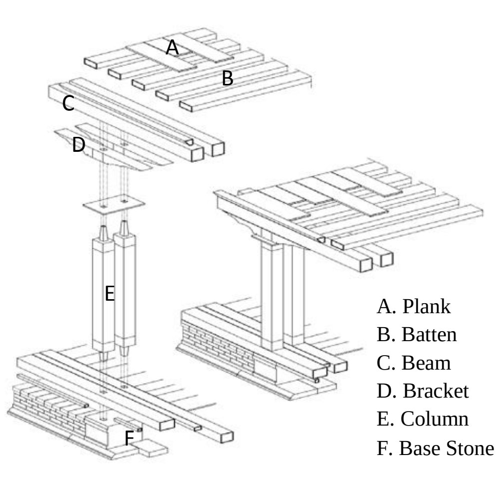


Figure 3. Section view of Narayan temple (KVPT, 2000) **Figure 4.** Beam-column joint [Bonapace *et al.*, 2003]

3. NUMERICAL MODELING OF NEPALESE PAGODA TEMPLES

Every structural problem is primarily aimed to be solved by numerical studies and calibrated by testing. However, because of various difficulties in numerical modeling, some problems may require complicated experimental investigation to calibrate the results. Therefore, numerical analysis an initial task is necessary to understand global behaviour and response of structures. The main difficulties in numeric modeling of historic buildings and particularly for temple structures are:

- Lack of data on geometric dimensions;
- Material properties of the inner construction components those not visible exteriorly of the structural members that are huge in al dimensions;
- Difficulties in identifying the characteristics of construction material;
- Excessive cost of detailed laboratory testing;
- Variability of the data due to construction techniques and natural material use;
- Altering material properties even along the same structural member due to long-lasting construction process;
- Uncertainties in construction process and phasing.

Even though many uncertainties, three temples namely a) Shiva temple, b) Lashmi Narayan temple and c) Radha Krishna temple as shown in Fig. 5, are selected in this paper to model them for parametric analysis.

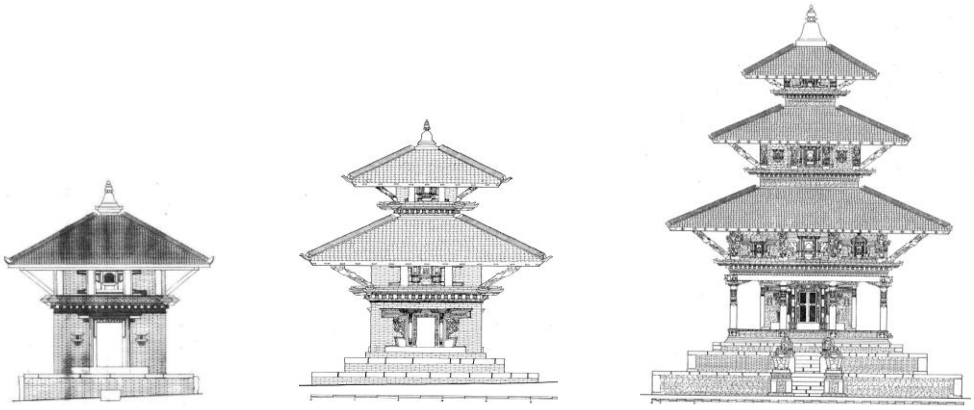


Figure 5. Front elevation, a) Shiva temple (Bhaktapur municipality, 1977), b) Lashmi Narayan temple (KVPT, 2004), c) Radha Krishna temple (KVPT, 1992)

The detailed characteristics of these three temples are listed in Table 1. These three temples are selected as representative of the most common types of pagoda temples in Nepal. It is a fact that every temple can't be categorized or generalized as they are different with each other in many aspects. The first temple selected is Shiva temple, which is the representation of one roof plan symmetrical temples with uniform wall thickness throughout the height and with low plinth level. Secondly selected temple is Lashmi Narayan temple, which represents the most widely found temples in Nepal. It is the temple with two roofs, having symmetric plan but having vertical load path discontinuity (i.e. top tower resting on timber joist instead of wall below). Finally selected temple is Radha Krishna temples, which represents few temples masonry but are very precious due to their marvelous architecture and also are listed in UNESCO world heritage. This temple is of plan symmetrical with extend gallery at base level and standing on a high plinth. The wall thickness is not uniform throughout the height and also has a double wall at the second storey with a walkway floor between walls. As the second temple it also has a vertical load path discontinuity.

Table 1. Dimensions of three selected temples

Temple	Height (m)	Base cross-section (m^2)	Top cross-section (m^2)	Wall thickness at base (m)	Wall thickness at top (m)
Shiva	4.73	2.82 × 2.82	2.82 × 2.82	0.46	0.46
Lakshmi Narayan	5.92	2.52 × 2.52	1.27× 1.27	0.48	0.40
Radha Krishna	12.1	3.48 × 3.48	1.69 × 1.69	0.64	0.45

Temple structure is a very complex structure to model due to numerous uncertainties and lack of initial testing. In this paper, eight node solid elements is used to model masonry structure, frame element is used to model timber structure and shell element is used to model roof and floor structure. The models take into account the presence of openings and the variation of wall thickness at different levels. Moreover the materials of structural components are assumed homogeneous, isotropic and linearly elastic and its properties is adopted as summarized in Table 2, which are presented by Jaishi *et al.* (2003) and Nienhuys (2003). The base at the level of plinth was considered rigid with the fact that there is no reliable knowledge on the foundation. Floors were considered rigid in their plane only on those places where there are heavy concentrations of timber elements on both directions attached rigidly. The pinnacle, door and windows are not considered in modeling.

The 3D finite element model of Shiva temple consists of 992 solid elements, 512 shell elements and 513 frame elements with total 2323 nodes, resulting in 6717 active degrees of freedom. Lashmi Narayan temple consists of 832 solid elements, 524 shell elements and 713 frame elements with total 2043 nodes, resulting in 5877 active degrees of freedom. Similarly, Radha krishna temple consists of 9572 solid elements, 1960 shell elements and 3136 frame elements with total 16171 nodes, resulting in 47817 active degrees of freedom.

Table 2. Material properties used in numerical modeling of temple structure

Material	Density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio
Timber	800	1250	0.12
Roof (tile + clay layer)	1400	400	0.10
Mud-mortar brick masonry	2000	800	0.10

It is difficult to ensure the optimized model without verifying the analytical results with some experimental values obtained from sensitivity testing procedure. Thus, the results of previous related works in experimental testing and analytical modal analysis by Jaishi *et al.* (2003), show the fundamental time period of Nepalese temples are less than 0.6sec. The manual and analytical vertical stress and axial stress at base level and timber strut respectively is nearly the same, which indicates a reliable model.

4. PARAMETRIC ANALYSIS AND RESULTS

In order to study the effect on fundamental frequency of temple structures due to changes in global stiffness caused by damages or degradation of fragile members, a parametric analysis is carried out. Damages in fragile members cause fundamental frequency to decrease due to reductions on stiffness. The three numerical models of three different temples are analyzed simultaneously to understand their structural fragilities.

Modal analysis results of show that due to symmetry of the structure in both directions, first and second mode, also fourth and fifth mode has same frequency with flexural mode shape in either direction while the third mode is a torsional mode shape in all of the three models (see Table 3). Due to this fact, in all parametric analysis, first, third and fourth modes are only considered excluding second and fifth mode.

Table 3. Analytical frequency for three temples

Temple	Frequency (Hz)				
	First mode (bending xx)	Second mode (bending yy)	Third mode (torsion)	Fourth mode (bending xx)	Fifth mode (bending yy)
Shiva	7.81	7.81	10.09	17.51	17.51
Lakshmi Narayan	6.42	6.42	10.10	13.53	13.53
Radha Krishna	3.16	3.16	4.59	7.19	7.19

The first analysis was performed to understand, what percentage change in frequency is expected, if the timber strut is modelled as a rigid connection to wall and purlin or if connected with pin connection. But the analytical result show no change in frequency in none of the three models was attained, which means it is difficult to find the local effect of these members in global stiffness of model. Exactly the same result was obtained in case of Radha Krisna temple where a timber column was pin connected at the ends. Another analysis was directed towards understanding the percentage change in frequency or indirectly understanding the effect on global stiffness of temple structure, when the temple is modelled with roofs and the same without roofs, but considering its mass, which is nearly 15-20% of overall mass of the temple.

Table 4. Percentage change in fundamental frequency with roof and without roof structure

Temple	Mode	Frequency with roofs (Hz)	Frequency without roofs (Hz)	Percentage change (%)
Shiva	First (bending xx)	7.81	6.17	20.86
	Third (torsion)	10.09	9.04	10.35
	Fourth (bending xx)	17.51	19.74	-13.36
Lashmi Narayan	First (bending xx)	6.42	2.25	64.91
	Third (torsion)	10.10	5.04	50.09
	Fourth (bending xx)	13.53	4.81	64.43
Radha Krishna	First (bending xx)	3.16	1.83	42.07
	Third (torsion)	4.59	2.72	40.73
	Fourth (bending xx)	7.19	3.61	49.73

Results in Table 4, reveal a decrease of the fundamental frequency from models with roofs to model without roofs concluding that the roofs have a significant effect in the global stiffness of the structure, although the mass of roofs is considered. Temple models with roofs are stiffer than without roofs. Moreover, variation is significant in first and fourth mode than on the third mode in all of the three selected temples. The change in frequency is significant for the Lashmi Narayan and Radha Krishna temple, with two and three roofs respectively, in comparison to Shiva temple with a single roof. Shiva temple also shows negative change in frequency for the fourth mode. The absence of the top tower resting on timber joists on Shiva temple as others do, affects the result attained for this temple. The mode shapes obtained after modal analysis is shown in Fig. 6. The mode shapes for all of the three temples in each mode are the same for both cases (i.e. consideration or not consideration of roofs).

The next step of analysis is carried out to understand the effect of damage or degradation in fundamental frequency of the temple structure. Analysis is carried out after selecting some of the fragile members in both timber and masonry elements, which are prone to damage.

Timber members selected for parametric analysis are struts, columns and floor, which are liable to damage. A physical cause of damages in timber members considered as the reduction of cross-section due to material degradation, decay, fungal attack, moisture attack etc. Moreover timber column can decay rapidly due to lack of damp proof course and up-splashing rain water. Floor joists are at more risk from fungal attack particularly where they are inserted through brick walls.

Similarly, masonry wall portions selected for parametric analysis are wall corner joints, one third portion of total wall height at base storey and also the portion of walls where timber joists are heavily inserted. Parametric analysis of wall corner joints is carried out to understand the effects of damages seen in traditional brick masonry walls such as corner cracks or separating of wall faces with slight movement or settlement due to the lack of seismic bands. Analysis of base storey wall is important to understand the effect of damages caused due to bulging of wall after water penetration and also erosion due to up splashing rain water or insufficient damp proof course. Another portion of damages in masonry wall analyzed is reduction in cross-section of masonry wall where insertion of timber joists are heavily done such as, at floor level or at portions where joists are inserted to hold wall plates in position.

Lastly analysis is made for accumulation of all type of damages at once. Hence, in this parametric analysis the reduction in stiffness due to damage of fragile members selected for analysis is introduced in the model by reducing its Young’s modulus (E value). This parametric analysis, studies the effect of damages over the fundamental frequency for three selected temples. Percentage change in fundamental frequency due to induced damages in terms of reduced E values, for various fragile members are summarized in Table 5.

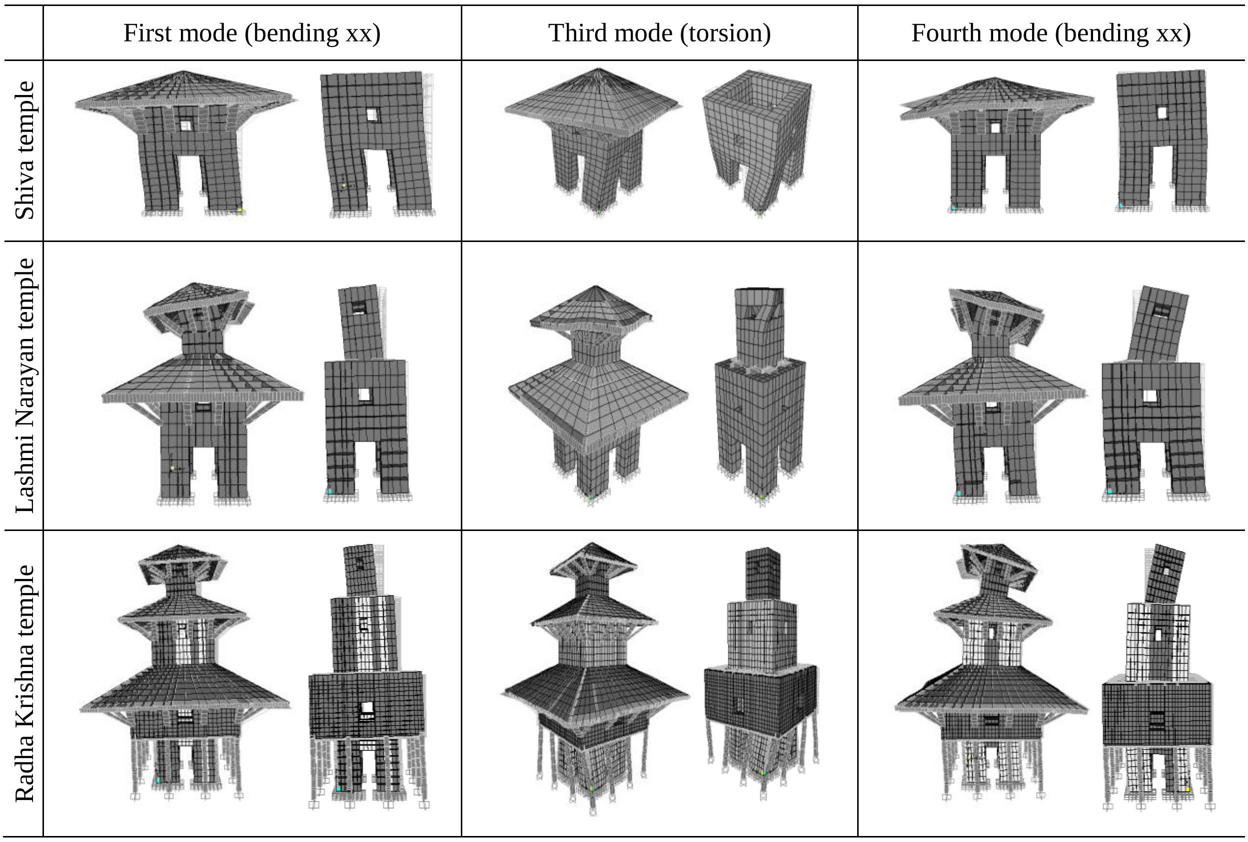


Figure 6. Three modes for each three selected temples with and without roofs

Damages in fragile members cause fundamental frequency to decrease due to reduction of stiffness. The results of parametric analysis shows that the damages in masonry wall is the major cause to bring change in frequency than damages in timber elements but the timber columns holding the wall above it, in case of Radha Krishna temple, definitely shows some changes.

The damage in masonry wall at base storey is most crucial as its damage leads to a significant reduction in frequency than any other portion on wall. Percentage decrease in frequency is mostly similar in Shiva and Lashmi Narayan temple. It can also be noticed that Radha Krishna temple has lowest decrease in percentage of frequency than other two due to the considerable wall thickness and also having timber gallery at the base storey. Frequency is nearly reduced by double percentage in every 20% reduction of the E value for almost all temples. The damage introduced in masonry wall corners angles is another important parametric analysis, whose results are more or less same for all three temples. However more precisely, Lashmi Narayan temple shows slightly higher and Radha Krishna temple presents a slightly low decrease in frequency than Shiva temple. The rate of change of frequency is uniform in this case also as it was for base storey damage analysis for all three temples.

Similarly, the result of analysis made to understand the effect of damage in masonry walls due to insertion of timber joists shows significant decrease in frequency percentage in Shiva and Lashmi Narayan temples in comparison to third temple. Even though the volume of surface area inflicted by damage is highest in case of Radha Krishna temple due to higher volume of timber inserted portion in wall section than the other two, but it also shows lowest percentage decrease in frequency. Regarding masonry wall damage, here also the considerable wall thickness of Radha Krishna temple plays a role in the lowest reduction of global stiffness, resulting in smallest reduction in percentage of frequency than rest of two temples. It is also noticeable that the frequency reduction shows a uniform reduction till 70% but it abruptly changes going to 90% for all three temples.

Table 5. Percentage reduction in fundamental frequency due to various damage scenarios

Fragile / degraded / damaged member	Temple	Percent Reduction of E value				
		10%	30%	50%	70%	90%
Base storey wall	Shiva	2.13%	7.29%	14.31%	24.88%	46.32%
	Lashmi Narayan	1.83%	6.44%	13.10%	23.92%	47.41%
	Radha Krishna	0.88%	3.13%	6.54%	12.33%	25.64%
Wall corner joint	Shiva	1.42%	4.55%	8.16%	12.48%	18.03%
	Lashmi Narayan	1.95%	6.24%	11.21%	17.33%	26.49%
	Radha Krishna	1.20%	3.79%	6.80%	10.53%	16.03%
Timber inserted wall	Shiva	0.46%	1.55%	3.30%	6.68%	17.60%
	Lashmi Narayan	0.68%	2.48%	5.34%	10.72%	26.70%
	Radha Krishna	0.15%	0.57%	1.26%	2.72%	8.53%
Timber strut	Shiva	0.00%	0.00%	0.01%	0.01%	0.02%
	Lashmi Narayan	0.00%	0.01%	0.01%	0.02%	0.05%
	Radha Krishna	0.00%	0.01%	0.01%	0.02%	0.04%
Floor	Shiva	0.00%	0.00%	0.00%	0.00%	0.00%
	Lashmi Narayan	0.00%	0.00%	0.00%	0.00%	0.00%
	Radha Krishna	0.00%	0.00%	0.00%	0.00%	0.00%
Timber Column	Radha Krishna	1.01%	3.35%	6.38%	10.34%	15.87%
Cumulative of all above	Shiva	3.07%	10.01%	18.84%	31.28%	54.16%
	Lashmi Narayan	3.19%	10.50%	19.68%	32.48%	55.49%
	Radha Krishna	2.75%	9.07%	17.04%	28.17%	48.59%

Timber strut supporting a heavy roof structure does not shows appreciable change in frequency due to damage, in term of young's modulus reduction. Also the damage in floor wood batten shows no change in frequency. The result shows there is no effect of strut and floor damage on the global stiffness of the temple structures. Results regarding the analysis made with a concept that if all of the fragile member's damage is accumulated (represented by equal percentage of E value reduction), reveal the highest percentage of reduction in frequency than individual damages for all three selected temples. This result also indicates that there is a uniform rate of decrease in percentage of fundamental frequency with the increase in damages percentage.

5. CONCLUSIONS

In the first part of this paper, a description has been given on seismology of Nepal where these historic temples exists, history of these temples, traditional construction method, and its conservation significance as a part of world cultural heritage. The second part includes a review on construction components of these structures and also emphasis on experimental testing of material properties to use in numerical modeling. It also identifies and discusses the uncertainties and difficulties in numerical modeling of temple structures, which is able to reproduce the actual structural behaviours. Finally it presents the modeling techniques applied, parametric study carried out and results.

The objective of parametric analysis carried out in this paper, on three Nepalese pagoda temples was to understand the seismic vulnerability of structural component and its damage effect on fundamental frequency, or which ultimately means the global stiffness of the structure. Results show, masonry that represents 70-80% of total mass of temple, as the most vulnerable structural components to be protected from damage. More precisely, base storey masonry wall is fundamental in the reduction of global stiffness of the structure. Considerable wall thickness of temples with roof structures has made these structures stiffer. In summary, it can be concluded that it is difficult to understand the local behaviour of timber components with resource to a global numerical model analysis of the temple structures and therefore it should be separately modeled and analyzed to understand its structural vulnerability.

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REFERENCES

Bonapace, C. and Sestini, V. (2003). Traditional materials and construction technologies used in the Kathmandu valley. *Paragraphic for the United Nations Educational, Scientific and Cultural,* 7 Place de Fontenoy, 75352 Paris 07 SP, France.

Jaishi, B., Wei-Xin, R., Zhou-Hong, Z. and Maskey, P.N. (2003). Dynamic and seismic performance of old multi-tiered temples in Nepal. *Journal of Engineering Structures* **25:3**, 1827-1839.

MoHA and DPNet. (2009). Nepal Disaster Report 2009: *The Hazardscape and Vulnerability*, Ministry of Home Affairs and Nepal Disaster Preparedness Network-Nepal. ISBN: 9937-2-1301-1.

Neves, F., Costa, A., Vicente, R., Oliveira, C.S. and Varum, H. (2011). Seismic vulnerability assessment and characterization of the buildings on Faial Island, Azores. *Bull Earthquake Eng*, doi 10.1007/s10518-011-9276-0.

Nienhuys, S. (2003). Options for reconstruction and retrofitting of historic pagoda Temples. Options for reconstruction and retrofitting of historic pagoda Temples, *Reconstruction of Temples in Kathmandu*, HUYS ADVIES.

Parajuli, Y.K. (1986). Bhaktapur Development Project (BDP): *Experiences in preservation and restoration in medieval town (1974-1985)*. Frankfurt: Deutsche Gesellschaft fuer Technisches Zuzammenarbeit (GTZ*).*

Ranjitkar, R.K. (2000). Seismic Strengthening of the Nepalese Pagoda: Progress report. *Earthquake-Safe: Lessons to Be Learned from Traditional Construction: International Conference on the Seismic Performance of Traditional Building*s: Istanbul, Turkey, Nov. 16–18, 2000. Istanbul: ICOMOS International Wood Committee (IIWC).

Ranjitkar, R.K. (2006). Heritage homeowner's preservation manual. Kathmandu Valley World Heritage site, Nepal: advice for maintenance of historic houses in the Kathmandu Valley, *Integrated Community Development and Cultural Heritage Site Preservation in Asia and the Pacific through Local Effort Programme (LEAP)*, UNESCO Kathmandu, Nepal.

Thapa, J.B. (2011). Test and simulation of brick masonry wall of historic buildings. *Partial fulfillment of the requirements for the Degree of Master of Science in structural engineering. Institute of Engineering*, Pulchowk campus, Tribhuvan University, Nepal.

Theophile, E. and Ranjitkar, R.K. (1992). Timber conservation problem of the Nepalese pagoda temple. *ICOMOS International Wood Committee (IIWC), 8th International Symposium*, Kathmandu, Patan and Bhaktapur, Nepal. Edited by Larsen and Marstein, Tapir publishers, Norway. pp. 85-124.

Tiwari, S.R. (2009). Temples of the Nepal Valley. *Himal Books, Kathmandu, Nepal.* ISBN: 9789937814430.

UNDP/BCPR. (2004). *Reducing Disaster Risk: A Challenge for Development A Global Report.* New York: United Nations Development Programme/Bureau for Crisis Prevention and Recovery.