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Seismic Performance Evaluation of Historic Temples

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Abstract

The Gorkha Earthquake 2015, including past earthquakes have damaged Nepalese heritage structures beyond recovery. The damage and survival of the historical structures have taught us a lesson on existing vulnerability of typical traditional Nepalese monuments. The paper presents the seismic evaluation of three representative multi-tiered temples with varying number of roofs, plinth area and stories, namely Maju Dega Temple, Changu Narayan Temple, and Chundevi Temple. Using Etabs, The analytical models were generated and optimized using the references from past research works. The structures were assessed for various load cases including gravity load and earthquake loads in terms of Seismic Coefficient Method and Response Spectrum Method as per NBC 105:2020. Results show that the selected three Nepalese Temples are stiff with natural period less than 0.36 seconds. The temples are vulnerable to earthquake forces. The temples fail under compresssive, tensile and shear stresses at various locations. The bottom story core wall, piers and spandrels around openings are the most vulnerable parts during an earthquake.

Keywords

Masonry, Response Spectrum, Heritage Structures, Multi-tiered Temples, Monuments, Seismic Vulnerability

1. Introduction

Geologically and historically,the Kathmandu Valley is designated as one of the most vulnerable places during earthquakes because of its dense population, unplanned settlement, highly vulnerable buildings, loose and unconsolidated surface geology. There are in total 8 cultural world heritage sites in the Kathmandu Valley listed under the UNESCO world heritage sites. Out of these 7 are inside the Kathmandu Valley.

Typolopgically our heritage structures can be divide in four typical types: Dome, Pagoda, Shikhara and Greco-Roman. Amongst them, Pagoda or the multi-tiered temples are the most common types of Nepalese heritage structures. This study deals with the seismic performance of Nepalese multi-tiered temples. Our past experiences show that the Nepalese heritage structures are not resistant to seismic actions. Nepal Bihar earthquake 1934 (M_w8.1) damaged 443 monuments in the Kathmandu Valley, most of which were reconstructed later. Similarly, the 2015 Gorkha Earthquake (M_w7.8) caused considerable damage to the heritage sites in the Kathmandu Valley. In total 2900 heritage structures were damaged by the main shock and after shocks of the 2015 Gorkha Earthquake. 228 of them suffered severe damage and collapsed. Almost all the heritage structures suffered damage with its extent varying from minor damage to complete collapse [1].

Most of the Nepalese multi-tiered temples were constructed following simple rules and construction details with least consideration for seismic resistance, during the period of Malla Dynasty (122-1768) [2]. The old worn out masonry Nepalese heritage structures built with lease seismic considerations have sustained a series of seismic events along with deterioration with age. Multi-tiered temples are historic structures, a heritage of the nation. The repair and restoration needs seismic interventions for which capacity assessment of topological structure is necessary. Since, the structures are highly vulnerable to future earthquakes that might have higher PGAs than the past earthquakes, we need to ensure the seismic safety of our structures by introducing immediate strengthening measures because the damage that occurred during Gorkha Earthquake had a PGA of only 0.2g: higher PGA are expected in major or near field earthquakes [1]. Since, seismic performance evaluation of Nepalese historic temples has not been carried out; it is of utmost importance to perform such evaluations. The objective of the study is to find out the performance of the masonry multi-tiered temples earthquake loading and determine the seismic vulnerability of the selected temples. Through understanding the response of the structures, engineering knowledge can be gathered into the response of the Pagoda style (multi-tiered) temples for potential retrofit schemes, to improve structural designs to minimize risk and losses, and ultimately preservation of cultural heritage. This is also in line with the mission of UNESCO's report that aims to reduce losses caused by earthquakes to heritage sites around the world [3].

2. Structural System

The structural system for majority of traditional temples is load-bearing system with brick masonry wall. They have considerably thick masonry walls, multi-tiered roof system, wide plinth, box-type configuration, timber floors, struts and columns with exceptional aesthetic appeal. Commonly, Nepalese temples are square or rectangular in plan or geometry. There is an erroneous perception regarding multi-roof tiers and multi-stories, as Nepalese temples are multi-tiered (with mere roofs only) but not actual habitable floors. Most Nepalese temples do not have equivalent number of functional floors, instead, they have mainly a cella (garbhagriha) on the ground floor above which there is an unused space, but varying number of roofs. However, in some cases where, the deity lies on the upper floor, there are multiple functional floors and subsequently, the description multi-storied is applicable [4].The load bearing masonry walls of the temples are thick (more than 45 cm, generally 1 m), layered construction with fire brick on outer face, sun-dried bricks on inner face and the middle core filled with rubble masonry. The walls rest on plinth mat built off the ground level. As described in [5], the foundation is wide as the plinth itself and raised (1 to 5 m) high to eliminate soft soil effects. Temples with shallow plinths have some depth below ground. The floor are simply laid using simple battens and joists. The floor finish is provided over the planks. The joists rest on the timber ring beam with timber pegs to lock their position [6]. The doors, windows and all other structural elements other than masonry are made up of timber. Some temples have timber framing in the first floor, some even have tower constructed resting on timber joists and timber columns along with timber beam supporting the wall above it [2]. High quality heartwood from Sal tree is used for timber elements. The temples can have one roof, two roofs, three roofs, and five roofs. The roofs are multi-tiered temples are symmetrical pitches that spring from the central point of the inner masonry core wall [7]. Roof rafters support the whole dead load of roofs (tile or metal), which is transferred to wall plates and purlins. Timber pegs are used to brace the rafters against the wall plates and purlins. More there are inclined timber struts that hold and transfer the roof load from purlins to the walls. There is no rigid connection of strut with purlin and the masonry wall of the temple [8].

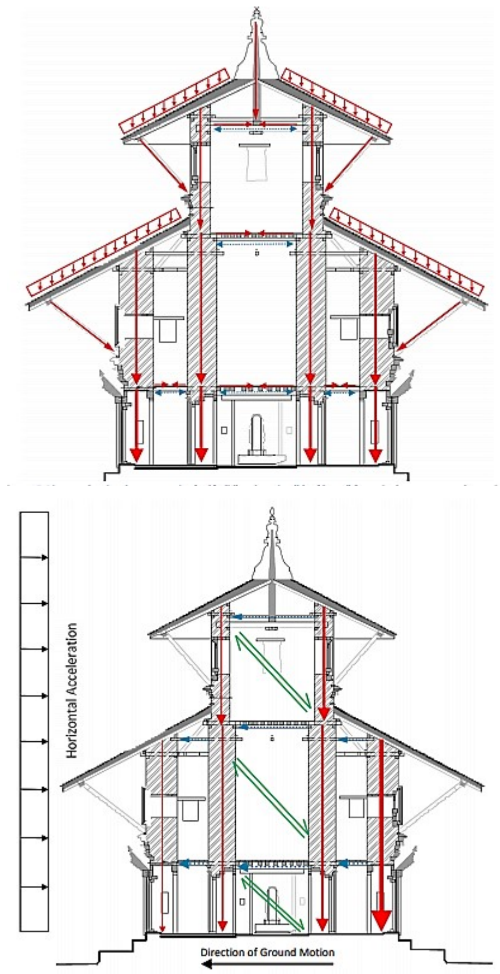

Figure 1: Diagrams showing compressive (red/solid), tension (blue/dotted) and shear (green) force in structure under vertical acceleration or gravity(top) and horizontal acceleration or earthquake (bottom) [9]

Historic multi-tiered temples in the Kathmandu valley typically have symmetrical layouts. The temples are symmetrical in plan as well as elevation in almost all directions, with least variations. The openings, walls and roofs are stretched symmetrically during construction. Symmetry is the basic principle of earthquake resistance. Symmetrical buildings distribute horizontal forces equally to the lateral stability elements and this leads to uniform displacement along height and prevent floor rotations. The torsional effects are kept insignificant via symmetry [10].

The above diagrams (Figure 1) show the load paths through the structure under both vertical and horizontal acceleration forces. In vertical acceleration, the forces follow a very logical layout, the loads transfer predominantly through compression, with its magnitude increasing downwards. Tension is present in timber beams only that transfer vertical forces laterally through bending. In horizontal acceleration case, the load path layout is quite different to that of the gravity case. Shear forces also develop in the masonry walls due to horizontal forces. This leads to the formation of diagonal cracks at an angle approximately 45 degrees in the walls, often propagating from re-entrant corners of openings like windows or putlog holes. In this case, the timber ring beam in the structure act as horizontal ties and help to transfer the lateral forces down to the foundations. The timber ring beams transfer the floor load from joists to the walls. These are bands on the wall circumference at levels where the vertical posts and beams are connected. These are also present at levels where multi-tiered roofs are connected to the walls through inclined supports. The presence of these beams add stability and stiffness during earthquake loading. During earthquake, the horizontal forces also exert an overturning force to the temple that causes compressive forces on one side of the structure and tensile forces on the other. This compressive force adds to the existing compression due to gravity loads and results in a net high compressive force on one side(large arrow) and a much lower compression (small arrow) on the other side[9].

2.1 Overview of selected temples

Maju Dega Temple (Basantapur, Kathmandu), Changu Narayan Temple (Changu, Bhaktapur), and Chundevi Temple (Balambu, Chandragiri, Kathmandu) are selected in the study. The Three temples were selected as the representatives of the most common types of multi-tiered temples in Nepal.

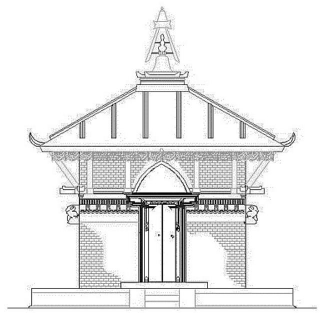

Figure 2: Chundevi Temple [11]

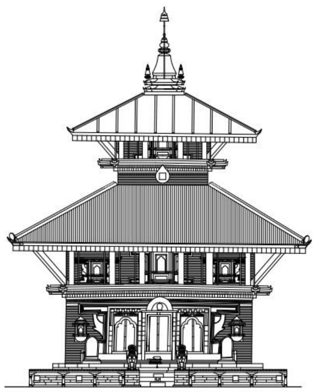

Figure 3: Changu Narayan Temple[11]

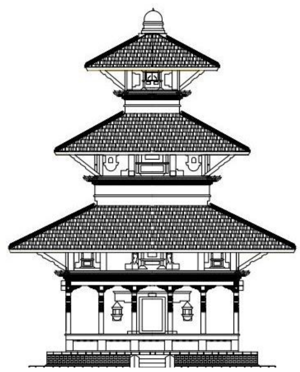

Figure 4: Maju Dega Temple[11]

It is a fact that every temple is unique and temples cannot be generalized, as they are different with each other in many aspects. The first selected temple is Maju Dega Temple, this temple is three tiered roof system, and represents few temples masonry. The temple is precious for its marvelous architecture, as it has been listed in UNESCO world heritage as well. The temple is of symmetrical plan, with extended gallery at base level, and standing on a high plinth. The interior wall, exterior wall and the top wall all have varying thickness; also, there is a double wall at the second story with a walkway between walls. This temple has a vertical load path discontinuity; the top tower rests on timber joists instead of wall. The second temple selected is Changu Narayan temple, a two-tiered roof system temple located at Changu

Municipality, Bhaktapur. This temple represents the most widely found temples in Nepal. The temple is symmetrical in plan and has two roofs. The wall thickness is uniform. The last one selected is Chundevi Temple, located at Balambu, Chandragiri Municipality, Kathmandu. The temple is the representation of one roof plan symmetrical temple with uniform wall thickness and low plinth level. The dimensions of the selected temples are presented in Table 1.

Table 1: Details of the selected temples

Temple	Chundevi	Changu Narayan	Maju Dega
Height (m)	4.064	14.249	14.833
Base Length (m)	3.200	8.992	8.484
Base Width (m)	3.200	8.992	8.484
Top Length (m)		4.674	2.642
Top Width (m)		4.674	2.642
Bottom Wall Thickness (m)	0.457	0.762	1.000
Top Wall Thickness (m)		0.762	0.610

3. Numerical Modeling of Nepalese multi-tiered temples

The complex temple structures have many uncertainties because of lack of adequate information on internal structural configuration, construction methods, materials and initial testing [12]. In this study, the base at the plinth level is considered rigid, assuming very stiff nature so that full seismic load is transferred to the structure from the ground motion. Bi-dimensional shell element is used to model masonry wall, considering only bending deformation in and out of plane [13]. Frame elements is used to model timber structures. Similarly, roof and floor structures are also modeled using shell element. The models are considered for variation in wall thickness at different levels. Masonry building with one way timber floors hinged at timber ring beams is used. The lateral direction timber provides stiffness in that direction of seismic force. The in plane bending of the timber joists is considered, as absolute rigid floor mechanism is not achieved in timber floors. Structures with flexible diaphragm can experience higher accelerations and displacements than structures with rigid diaphragms. In addition, their fundamental period of vibration can be higher. In temples, the timber joists are laid with planks above them, above which the floor finishing is used. In most temples, the floor is not even present but there is presence of cross beams that add stiffness to the structure at that level. The cross beams are heavy timber beams that rest on the timber ring beams on the walls. In this study, timber joists were laid in one way direction as found in the real structure. 100 x 150 mm joists spaced at 200 mm c/c were used. Similarly, 100 x 150 mm timber ring beams were used to connect the joists. The joists simply rest on these bands- timber ring beams and transfer the load via flexure. The timber ring beams are used to transfer the floor load from joists to the walls. These rings are the bands on the wall circumference at levels where the vertical posts and beams are connected. They are also present at levels where multi-tiered roofs are connected to the walls through inclined supports. These beams add stability and stiffness during earthquake. Similarly, the presence of openings are considered, whereas doors and windows frames itself are not considered in modeling. The pinnacle load has been considered whereas the pinnacle itself has not been modeled. The contribution of roofs in the global stiffness of structure as a whole has been taken into consideration, modeling of roofs has been included for analysis. Modeling of three tiered temple where the top tower has vertical load path discontinuity is done with the help of heavy timber cross beams (200 x 300) mm as found in the real structure. For Maju Dega temple, the walls of the top tower simply rest on those cross beams and the logical load path breaks with eccentricity between the two load paths. This makes the structure more vulnerable during earthquakes.

The modeling of the temple structures were done in Etabs v16. The models were optimized with verification against the results of previous related works related to experimental testing and analytical modal analysis by [14]. The materials were considered isotropic, homogeneous and linearly elastic. The material properties were taken from previous works presented in Table 2 and Table 3.

Table 2: Material Properties used in numerical modeling of Temple Structures [14, 2, 6]

Material	Density (kg/m³)	Young's Modulus (Mpa)	Poisson's Ratio
Timber	800	1250	0.12
Roof	1400	400	0.1
Masonry	2000	800	0.1

Table 3: Permissible Stress for Masonry [14]

Mode of failure	Permissible Stresses (Mpa)
Tension	0.05
Compression	0.606
Shear	0.201

4. Analysis and Results

The seismic analysis approach simply depends on the type of structures. Nepalese historic temples are masonry structures that possess high masses. In addition, brittle nature masonry has less ductility and over-strength. Therefore, masonry structures as temples attract high inertial forces during earthquake. Therefore, the masonry structures in Temples can be analyzed using linear elastic seismic analysis methods [15]. The methods of seismic analysis used are the Seismic Coefficient method and the Response Spectrum Method, based on [16].

From modal analysis, the fundamental time period of the three temples were found to be 0.076s, 0.364s and 0.32s for Chundevi, Changu Narayan and Maju Dega Temple respectively. Higher Maju Dega Temple has lesser time period than that of Changu Narayan temple, this is because of higher rigidity provided by thicker core wall and more number of roofs in Maju Dega Temple,for similar height temples. Time period of Nepalese temples suggests that Nepalese Temples are stiff structures [14]. Similiary, the drift ratios of the three temples also suggest excessive rigidity of historic traditional temple structures.

All three temples do not show any considerable in plane as well as out of plane displacement under gravity loading. However, under earthquake loading, Chundevi temple only shows very small displacement, 0.875mm. The other two temples show considerable deformation. The displacement increases with an increase in height as expected. The deformation is maximum under Response Spectra loading, in Y-direction , hence Y-direction is the most critical one. Figure 5 Shows comparison of displacements of the three temples under Response Spectrum in the Y-Direction. Single roof Chundevi temple, with low height, is stiff and less deformable during earthquake. Multi-tiered temples Changu Narayan and Maju Dega suffer differently during same earthquake. Changu Narayan Temple has a maximum displacmeent of 42.976mm and the same for Maju Dega Temple is 39.407mm. For Changu Narayan Temple, displacement in bottom stories is less in comparison to the displacement in upper stories. Figure 5 shows consistent flexibility with smooth changes in flexibility. For Maju Dega Temple, the bottom story has larger displacement exhibiting soft nature. The second story and fourth story has staggered nature with relative increase in rigidity. This is due to presence of double wall in the second story and cross beam in fourth story.It is seen that low height temples are stiff and they deform very less. For similar height temples, temples with logical load path has uniform flexibility distribution with smooth deformation profile. Temple where vertical load path irregularity is present, and the base story has framing arrangement exhibit staggered displacement profile due to relative variation in stiffness among stories. For Changu Narayan the deformation with respect to height is consistent and uniform than compared to Maju Dega. For same height, having timber columns in the first floor, and top tower resting on cross beams break continuity and consistency in deformation and rigidity of the stories. This might be the cause for collapse of Maju Dega Temple and similar temples e.g. Jaishi Dewal Temple during the 2015 earthquake. The Changu Narayan Temple suffered slight damage during the same.

Shell Stress analysis at various locations of the selected temples reveal that under gravity loading, the temples are safe in all stresses. However, under earthquake loading, various parts of the temple fail in compression, tension as well as shear stresses. The Chundevi temple experiences compressive stress of 0.1 MPa, tension 0.1 MPa and shear stress 0.005 MPa. The temple is safe in stresses except for tension stress during earthquake loading. There is a slight rise in tensile stress at the piers in door openings and window openings. For Changu Narayan temple, maximum compressive stress is 1.490 MPa, tensile stress 1.490 MPa and shear stress is 0.720 MPa. Maximum compression occurs at solid core wall in bottom story. Also, considerable compression and tension (0.73 MPa) occur at door opening at the bottom story. Maximum shear occurs at spandrel above door in bottom core wall. The core wall in the bottom story, and second story, and piers and spandrels fail under compression, tension and shear at various locations. For Maju Dega Temple, maximum compressive stress 1.140 MPa, tensile stress 1.140 MPa and shear stress 0.260 MPa , all occur at bottom story core wall. The core wall at bottom story fails under compression, tension as well as shear. Compression failure is limited to bottom story. The piers and spandrels around openings,in the core wall fail under compression, tension and shear, but they seem to be safe in the gallery wall. In general, Nepalese temple structures fail under compressive stress, tensile stress as well as shear stress.

The bottom portion of core walls fail under tension, compression and shear of both the multi-tiered temples. Shear failure is seen in core wall and at second story as well. The piers and spandrels fail in shear at almost every level of Maju Dega temple. Similar result is seen for Changu Narayan Temple. In addition, the shear stress concentration is more in piers than the spandrels, which indicates that the piers are more flexible than the spandrels.

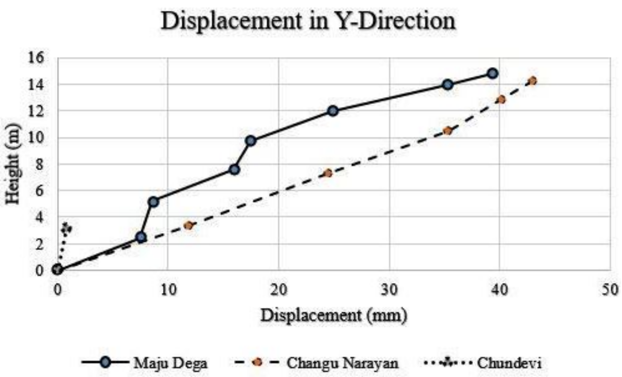

Figure 5: Maximum Displacement of Three Temples under Response Spectrum in Y Direction

Table 4: Modal Drift Ratio of Three Temples

Temple	Dislacement in Y-direction (m)	Height (m)	Modal Drift Ratio (x 10-3)
Chundevi	0.00086	3.162	0.27
Changu Narayan	0.04298	14.249	3.02
Maju Dega	0.03941	14.834	2.66

Table 5: Max Stress at Base of Temple from Seismic Coefficient Method (MPa)

S. No.	Temple	Tension	Compression
1	Chundevi	0.010	-0.100
2	Changu Narayan	0.120	-1.130
3	Maju Dega	0.110	-1.130

Table 6: Max Stress at Base of Temple from Response spectrum Method (MPa)

S. No.	Temple	Tension	Compression
1	Chundevi	0.100	-0.100
2	Changu Narayan	1.490	-1.490
3	Maju Dega	1.140	-1.140

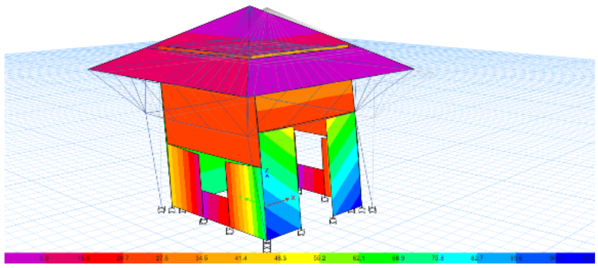

Figure 6: Deformed Chundevi Temple: Direct Stress under Response Spectra in Y-Direction

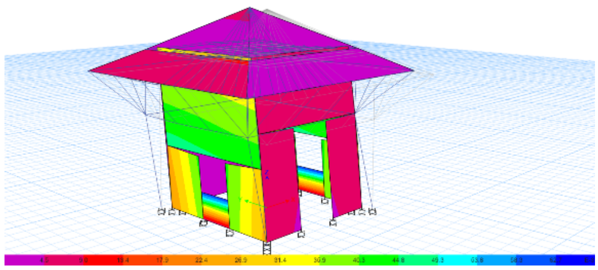

Figure 7: Deformed Chundevi Temple: Shear Stress under Response Spectra in Y-Direction

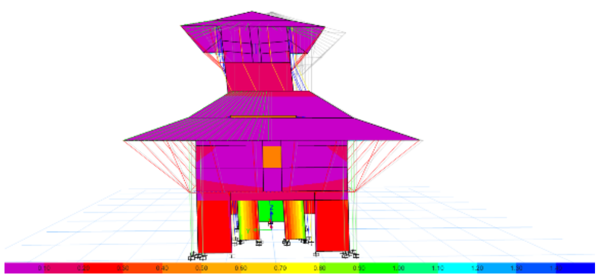

Figure 8: Deformed Changu Narayan Temple: Direct Stress under Response Spectra in Y-Direction

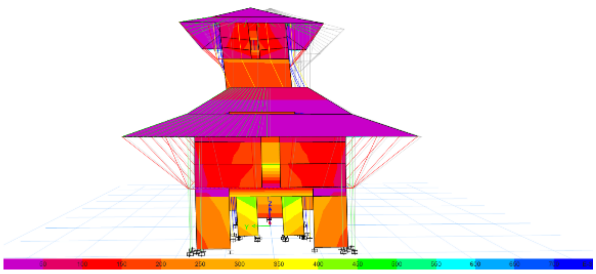

Figure 9: Deformed Changu Narayan Temple: Shear Stress under Response Spectra in Y-Direction

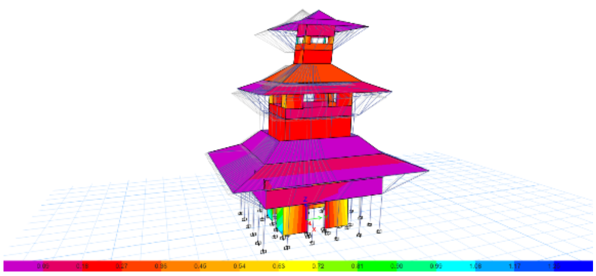

Figure 10: Deformed Maju Dega Temple: Direct Stress under Response Spectra in Y-Direction

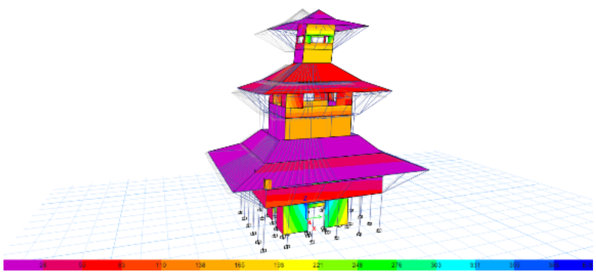

Figure 11: Deformed Maju Dega Temple: Shear Stress under Response Spectra in Y-Direction

5. Conclusion

The selected Nepalese temples are stiff masonry structures with fundamental period of vibration less than 0.4s. The seismic performance evaluation of historic Nepalese temples were performed using linear elastic seismic analysis methods: Seismic Coefficient method and Response Spectrum method.It is seen that Nepalese temples are vulnerable to earthquake forces. Temples with logical load path or vertical load path continuity show consistent floor deformation than temples with framing arrangement and walls resting on cross beams. Temples with framing arrangements exhibit soft story mechanism with staggered displacment profile, the staggering increases if there is presence of top tower resting on cross beams, not walls directly. The modes of failure is associated with compressive, tensile and shear stresses. The inner core walls of the multi-tiered temples are the most vulnerable part of temples, that fail under tension, compression and shear. The piers and spandrels also fail in tension, compression and shear. Piers are flexible than spandrels. The upper parts of the temple are safe in compression.

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