Seismic Vulnerability of Buddhist Monasteries: Evidences from the 2011 Sikkim Earthquake and Dynamic Analyses

T. Pradhan, V. Singhal, G. Mondal, N. Parool & D.C. Rai
Dept. of Civil Engineering, Indian Institute of Technology Kanpur, India

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SUMMARY:
Buddhist monasteries share a rich history in the culture and tradition of the Sikkimese Himalayan region. These monasteries, some dating back to 300 years, have played a significant role in portraying and conserving the architectural style of the Tibetan and Chinese construction. The M6.9 September 18, 2011 earthquake affected most of these historical structures causing damages of varying degree. Post-earthquake ambient vibration measurements of main temple were made at three monasteries, which establishes them as short period structures with the fundamental period ranging from 0.23 to 0.37 s. A finite element analysis of one of the temples was carried out to study its dynamic behaviour and predict its seismic vulnerability. Response spectrum analysis and static lateral load analysis were performed which identified the wall openings as critical areas with tensile stresses exceeding the permissible value, which was supported by the observed damage.

Keywords: Monastery, Seismic vulnerability, Stone masonry, Ambient Vibration

1. INTRODUCTION

The Himalayan state of Sikkim is dotted with monasteries, some dating back to the 17th century and serve as centres of meditation and institution for learning Buddhist philosophy. These monastic structures showcases intricate timber carvings, life-like frescos of hoary Buddhist legends and illustrative paintings which are of great historical significance and act as a symbol of the rich cultural heritage. The monasteries in Sikkim are of three types: (*a*) *Tak-phu* meaning rock-cave or cave hermitage, (*b*) *Gompa* which is a place of solitude, a religious escape where the monks are trained in the finer aspects of Tibetan Buddhism practice, and (*c*) *Mani Lakhangs* are temples without any schools which are administered by few monks (Risley, 1894; Gulia, 2005).

A typical monastery consists of a spacious courtyard, a main temple or shrine hall and dwellings or schools for the monks as shown in Fig. 1.1. The shrine halls are simple one to three-tiered structure having symmetrical plan and reduced floor area on the upper stories. The temple is constructed traditionally using stone masonry walls on the exterior and timber beam-column frame on the inside to support the timber floor diaphragm. The hipped timber roofs covered with corrugated metal sheets are provided at one or more levels. The overhangs extend up to 2 to 3 m protecting the exterior walls from the rain. The schools, dwellings and other units are constructed either in traditional *Ikra* style or modern RC frame with masonry infills.

Sikkim lies in the seismic zone IV of IS 1893 (BIS, 2002) with an expected shaking intensity of VIII (MSK scale). The M6.9 earthquake hit Sikkim on September 18, 2011 at 6:11 PM IST with its epicentre located near Nepal-Sikkim border. The event caused widespread destruction and affected these historical structures causing varying degree of damage mostly to their exterior walls (Rai et al., 2012). To understand the dynamic behaviour of the main temple, ambient vibration measurements were made at three monasteries and subsequently, finite element analysis was performed for dynamic and static lateral loads to predict the expected seismic demand and its vulnerability.

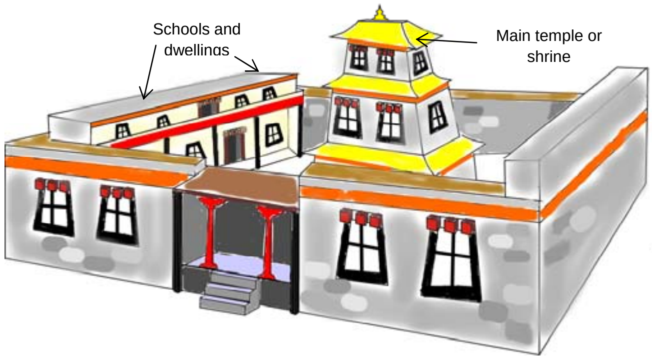


Figure 1.1. (a) Layout of a typical monastery showing the courtyard, main temple and school

2. STRUCTURAL SYSTEM OF THE MAIN TEMPLE

The main temple is a two or three storey structure with load bearing exterior walls and an inner timber frame which supports the wooden diaphragm. Fig. 2.1 shows an exterior view of a typical main temple in a monastery. The exterior walls are thick, tapered and built using dressed or semi-dressed or random rubble (R/R) stone masonry laid in mud or lime or cement mortar. The thickness of the wall varies from 0.5 to 1 m which gradually reduces in the upper stories. Doors and windows are an important part of the Buddhist construction from both functional and religious point of view. Openings are provided on all the three sides except on the side opposite to the main entrance where the idols of the deities are placed. These openings are large in size and number, and significantly influence the overall strength of the wall.

Figure 2.1. View of main temple at Pubyuk monastery

The timber framing system comprises of grid of columns and beams arranged in the central portion of the room. The main beam runs from one wall to the other in the direction parallel to the main entrance or *Tsomchhen*. The columns are not continuous from bottom to top in a multi-level frame but they are constructed in such a manner that their centre-line is maintained at all the floor levels. These columns are tapered and made from solid timber logs which extend from the base of the floor to the capital (Fig. 2.2a). The capitals known as bows have elaborate carvings and are placed in either two or three layers depending upon the height of the floor. The floor is made of wooden planks placed on wooden rafters supported between the main beam and the wall (Virtanen, 2001). Hipped timber roofs covered with corrugated galvanised iron sheet are provided at one or multiple levels resting on trussed rafters as shown in Fig. 2.2b.

In the newly constructed monasteries the traditional timber frames are replaced by RC frames. In addition, appendages to the existing structure such as, pavilions, extended prayer halls, corridors etc., are constructed in reinforced concrete and brick/block masonry to accommodate the expanding congregation and also occasionally to support the weight of the aging structure in several monasteries.

(a) (b)

Figure 2.2. Details of (a) wooden timber frame and floor diaphragm supported on rafters and (b) hipped roof construction.

3. SEISMIC PERFORMANCE

The monasteries have poor lateral load resistance capacity as the stone masonry walls have low in-plane and out-of-plane strength. In addition the timber floors under lateral loads act as a flexible diaphragm and undergo excessive deflection, pushing the walls outwards. Moreover, such heavy walls attract a large amount of inertial forces and are easily overwhelmed by such forces and displacement demands imposed on them.

In the September 18, 2011 event several monasteries suffered varying degree of damages ranging from cracked walls to total collapse. Heavy damages were observed to exterior walls at several monasteries, e.g., total collapse of a village temple at Lachung, partial collapse at Ringhem Choling monastery at Mangan, delamination of walls and cracks in Samten Choling monastery temple, Lachung (Fig. 3.1).

(a) (b)

Figure 3.1. Common damages observed (a) Partial collapse of wall of Ringhem Choling monastery due to forces imposed by the roof deflection and (b) Shear cracks and delaminated wall painting at Samten Choling monastery.

Enchey monastery at Gangtok, retrofitted after the 2006 Sikkim Earhtquake (Kaushik et al., 2006; Dutta et al. 2006) suffered moderate damages in the 2011 event. The out-of-plane failure around the opening was observed in the unretrofitted portion of third-storey wall as shown in Fig. 3.2. Similar damage to the exterior wall built in stone laminates was also observed at Labrang monastery (Fig. 3.3). After the 2006 earthquake, the collapsed roof was replaced by a truss roofing system supported on steel columns erected around the shrine room. Steel joists connected to columns were also inserted below the timber floor to relieve the load on the timber beams and walls.

Figure 3.2. Damages observed on the front wall of third storey at Enchey monastery

(a) (b)

Figure 3.3. (a) Cracks on the exterior wall of Labrang monastery and (b) Exposed stone laminates during the recent damage and steel columns and joists used in the retrofit

Phodong monastery which is a mixed construction of RC frames and load bearing masonry walls suffered no damages to the exterior walls (Fig. 3.4a). However, the RC columns were severely affected because of short-column effect due to the presence of deep haunches at the beam-column junctions as shown in Fig. 3.4b. The modified configuration which were supposedly provided to increase the lateral load resisting capacity of the frame, in turn created a short-column effect causing brittle shear failure of the columns.

Tsug-lakhang also referred to as the royal chapel, a two storey building with a regular plan area, constructed in dressed stone masonry, is a hallmark of excellent workmanship and building technology of the Buddhist architecture (Fig. 3.5a). No significant damage was observed to the structure during the Sept. 18, 2011 earthquake. In the Rikzing Choeling monastery, strengthening of the existing masonry walls by constructing RC columns at the corners prevented the walls from complete collapse (Fig. 3.5b). These efforts can be expanded into a comprehensive strengthening and retrofitting measures of such structures so that their performance is satisfactory in future earthquakes.

(a) (b)

Figure 3.4. (a) Phodong monastery, interior RC frame with exterior stone masonry wall and (b) Damaged column due to short-column effect induced by the presence of deep haunches at beam-column junctions.

(a) (b)

Figure 3.5. (a) Tsug-lakhang monastery and (b) Rikzing Choeling Monastery with RC confinement at corners

4. POST-EARTHQUAKE AMBIENT VIBRATION TEST

Ambient vibration measurements of main temple were made at three monasteries namely Enchey, Labrang and Phodong to obtain the dynamic properties of these structures. The vibration measurements were performed in two directions, i.e., parallel to the main entrance (*x*-direction) and perpendicular to the main entrance (*y*-direction), using SS-1 Ranger seismometer (Kinemetrics, USA). The set up of sensor and data acquisition system at Enchey monastery and Labrang monastery are shown in Fig. 4.1. The measurement was taken at every floor and at different locations, chosen depending on the ease of placing the sensor. The sampling frequency was 2000 Hz which was recorded for about 150 s each time. The recorded time-history in both the direction and its corresponding Fourier spectrum is shown in Fig. 4.2. The data are filtered and re-sampled to remove the high frequency content. The frequencies of the three temple sites as obtained from ambient vibration test are listed in Table 4.1. It was observed that all the three temples were short period structures and fall in the acceleration sensitive region of the seismic design response spectrum. In addition the floor vibrations were also measured by placing the seismometer in upright position and creating vibration by tapping the floor.

Table 4.1. Frequency measurement by ambient vibration testing

Frequency	***x*-direction (Hz)**	***y*-direction (Hz)**
Enchey	4.1	4.4
Labarang	3.1	3.5
Phodong	3.0	2.7

Figure 4.1. Experimental setup consisting of seismometer and data acquisition system at Enchey monastery and Labrang monastery.

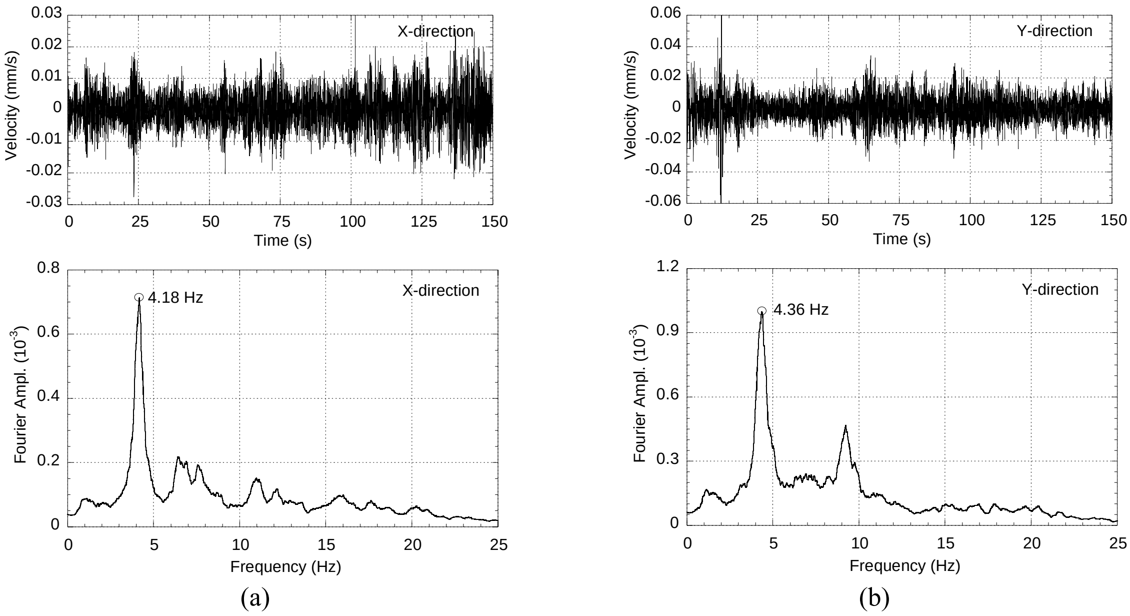


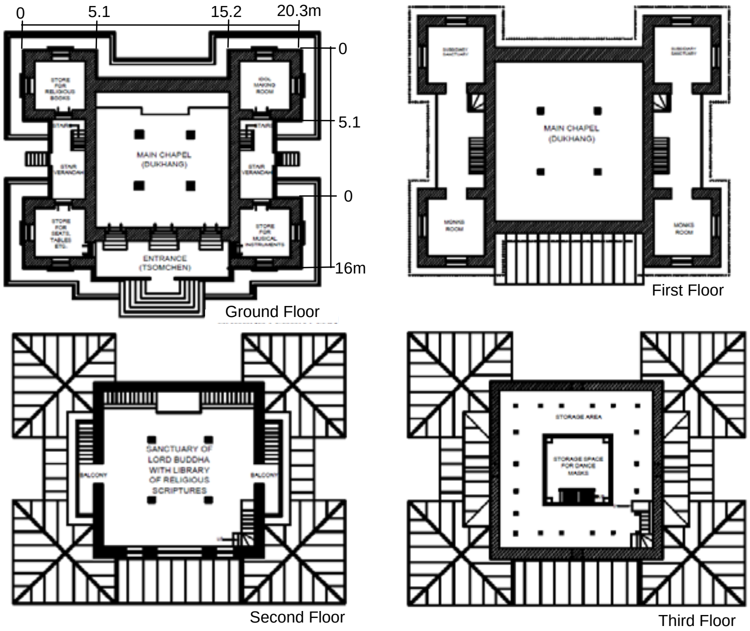
Figure 4.2. Recorded time-history and Fourier spectrums at the top floor of Enchey monastry (a) in *x*-direction parallel (b) *y*-direction perpendicular to the main entrance

5. SEISMIC VULNERABILITY ASSESMENT

To further understand the behaviour of the monastery temples and also to predict their seismic vulnerability, the main temple at Enchey monastery was studied using Finite Element (FE) analysis in Abaqus environment (Simulia, 2010). Modal analysis and response spectrum analysis (RSA) was carried out to know the dynamic properties of the structure and determine the seismic demands in terms of stresses in the various structural components. In addition, static horizontal loads proportional to the weight of structure were applied in the two orthogonal directions which showed higher stresses in the areas around the opening where the damage was observed.

Enchey monastery is one of the most important monasteries of the *Nyingma* sect and was built by Sikyong Tulku in 1909 (Gurung, 2008). The architectural style is distinctive to the *Peiching* (Beijing) school of *Gyan-Ryuchinqa* meaning 'the five pinnacles'. The main temple is a four-tiered construction with semi-dressed stone masonry walls on the outside and roof at three levels as shown in Fig. 5.1a. The plan is symmetric with a rectangular opening at the centre and four square sections connected at the four edges as shown in Fig.5.1b. The central portion serves as the *dukhang* or the assembly hall and extends up to the second storey. The frame comprises of four columns arranged in a rectangular grid with main beams running parallel to the entrance and a transverse second beam in the perpendicular direction between the two columns.

(a)



(b)

Figure 5.1. (a) A view of the main temple at Enchey Monastery and (b) Floor plans at different floor level (Gurung, 2008)

5.1 Finite Element Modeling

A three dimensional FE model was developed for Enchey monastery using the general purpose program Abaqus (Simulia, 2010). At this stage, no material characterization could be possible due to insufficient data on the strength of the masonry walls. The properties of the stone masonry, corrugated GI sheets and timber used for analysis are mentioned in Table 5.1. The typical value of Young's modulus for stone masonry ranges from 200 to 1000 MPa has been reported by (Tomazevic, 1999). A modulus of 300 MPa near lower values of the range was chosen considering the age, quality and type of masonry construction. The masonry walls and timber frame were modelled as 3D solid element while the floor and roof components were modelled as 3D shell element. The second and third storey floors were modelled as isotropic shell of thickness 145 and 210 mm to match the frequencies of two floors (9.4 Hz and 13.5 Hz) as obtained by the ambient vibration test in the vertical direction. The discretization of masonry walls and timber frame was achieved by 4-noded linear tetrahedron elements (C3D4) whereas 3-noded triangular shell elements (S3) of the Abaqus element library were used for roof and timber floors. Monolithic connection was assumed between the column and beam joints and between frame and diaphragm. A view of the model and the meshing used is shown in Fig. 5.2.

Table 5.1. Mechanical properties of materials used in the FE modeling

Material	Density (kN/m^3)	Young's Modulus (GPa)	Poisson's Ratio
R/R stone masonry	20.0	0.30	0.20
GI sheet	78.5	210	0.30
Timber frame	8.0	7	0.12
Timber floor	8.0	12	0.12

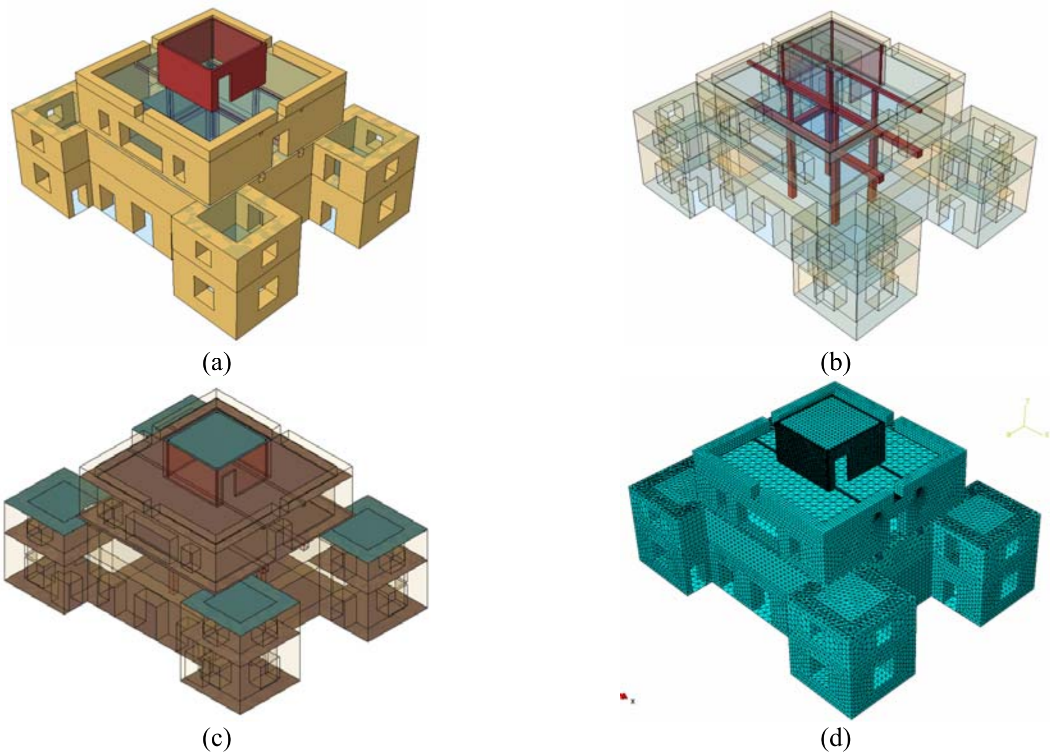
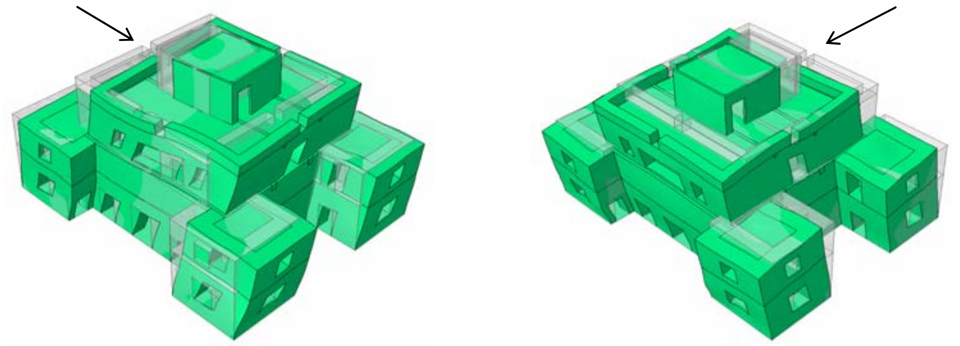


Figure 5.2. View of model showing (a) Exterior masonry walls and small wooden cabin (b) Frame system of the structure comprising of wooden beams and columns (c) Roof and floor diaphragms modeled as flat slabs using solid shell elements and (d) Discretization of model using tetrahedral and triangular elements.

5.2 Modal Analysis and Seismic Response under Lateral Loads

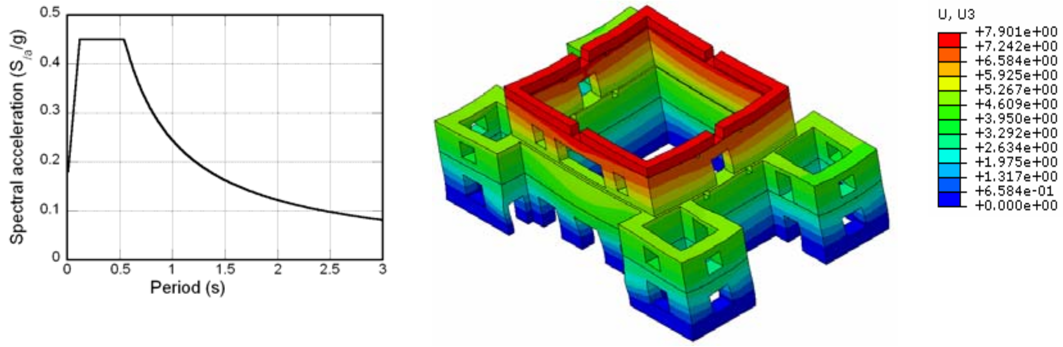
The modal analysis of the structure was performed by assuming fixed translational and rotational boundary conditions at the base of the structure. The frequency in the orthogonal direction: parallel (*x*-direction) and perpendicular (*y*-direction) to the entrance was found to be 4.5 Hz and 4.8 Hz, respectively as shown in Fig. 5.3. These obtained frequencies are in a good agreement with the observed values of 4.1 and 4.4 Hz measured by ambient vibration tests.

Response spectrum analysis (RSA) considering all significant modes in both the direction was performed to predict the seismic demand for Zone IV (zone factor of 0.24*g*). For the design basis earthquake (DBE), 5% damped elastic design response spectrum for soil type II was scaled so that the zero period acceleration (ZPA) is 0.18*g* which includes a load factor of 1.5 (Fig. 5.4a). The total base shear was calculated which was found to be 29% and 31% of the self weight in *x*- and *y*- direction, respectively. The obtained base shear was divided by the net wall area in both directions at the window level to estimate the average wall shear stress. Fig 5.4b shows the displacement contour for loading in *y*-direction as obtained from the response spectrum analysis.



(a) (b)

Figure 5.3. Mode shapes for natural frequency in (a) *x*-direction and (b) *y*-direction



(a) (b)

Figure 5.4. (a) Response spectrum for zone IV soil type II with 5% damping and (b) Displacement contour for loading in *y*-direction as obtained by RSA

In order to identify the stress critical zone in the structure, a uniform static horizontal load taken as 20% of the weight as per the Indian seismic code was applied in both the directions. Table 5.2 summarizes the stresses obtained by response spectrum analysis and lateral load analysis. The maximum tensile stresses observed at the corner of openings exceeded the lower bound permissible value of 0.08 MPa (Tomaževič, 1999) (Fig. 5.5). The location of maximum stresses was same as the location of damage observed during the 2011 earthquake (Fig. 3.2).

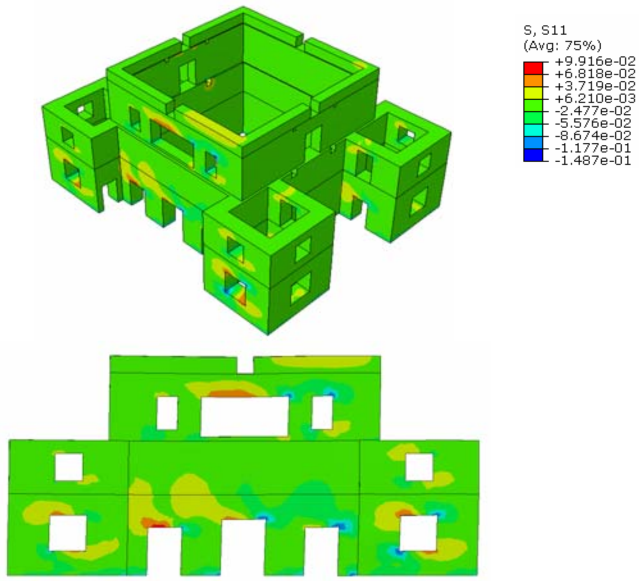


Figure 5.5. Areas identified with critical stresses (*x*-direction)

Table 5.2. Results of the response spectrum and lateral load analyses for stresses in walls

Excitation direction	Shear stress from RSA (MPa)	Lateral Load Analysis			
		Tensile Stress (MPa)		Compressive Stress (MPa)	
		x-dir.	*y*-dir.	*x*-dir.	*y*-dir.
x-dir.	0.08	0.10	0.07	0.14	0.12
y-dir.	0.09	0.07	0.10	0.32	0.12

6. CONCLUSIONS

The heavy damages caused to the monasteries during the 2011 Sikkim earthquake highlighted the seismic vulnerabilities of these heritage structures. Major damages were observed in the exterior stone masonry walls due to their poor lateral load resisting capacity. The ambient vibration tests performed on main temples at three monasteries showed that they were short period structures with the fundamental period ranging from 0.23 to 0.37 s. The FE model of the temple was able to simulate the observed frequencies and the dynamic behaviour was dominated by massive and relatively stiff masonry walls. The model was used to estimate seismic demands imposed on various components of the structure for a design level earthquake. The lateral load analyses showed that the tensile stresses around the wall openings exceeded the permissible values and are, therefore, susceptible to damage. These predictive vulnerabilities compare well with the damages observed in the recent earthquake, however, these preliminary results needs to be further supported with detailed analyses.

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REFERENCES:

Simulia (2010). ABAQUS v6.9-1, Dassault Systems Simulia Corporation, Providence, RI, USA.

BIS. (2002). IS1893: Indian Standard Criteria for Earthquake Resistant Design of Structures: Part 1– General Provisions and Buildings. Bureau of Indian Standards, New Delhi.

Dutta, S. C., Guha, A. L., Guha Niogi, J., and Mukhopadhyay, P. (2006). A Reconnaissance Based Vulnerability and Damage Survey Report The Sikkim Earthquake of 14th February 2006. School of Community Science and Technology, Bengal Engineering and Science University.

Gulia, K. S. (2005). Human Ecology of Sikkim: A Case Study of Upper Rangit Basin. Kalpaz Publications, New Delhi.

Gurung, U. (2008). Buddhist Monastery with Emphasis on Vernacular Material. *Project report* submitted to Priyadarshini Institute of Architecture and Design Studies, Nagpur.

Kaushik, H. B., Dasgupta, K., Sahoo, D. R. and Kharel, G. (2006). Performance of Structure during the Sikkim Earthquake of 14 February 2006. *Current Science*, **91:4**, 449-455.

Rai, D. C., Mondal, G., Singhal, V., Parool, N., Pradhan, T., and Mitra, K. (2012). Reconnaissance report of the M6.9 Sikkim (India–Nepal border) Earthquake of 18 September 2011. *Geomatics, Natural Hazards and Risk*. **3:2**, 99-111.

Risley, H. H. (ed.) (1894). Gazetteer of Sikkim, Bengal Govt. Secretariat, Calcutta.

Tomaževič, M. (1999). Earthquake-Resistant Design of Masonry Building, Imperial College Press.

Virtanen, K. (2001). Future Plan of the Main Temple Complex, Beri Monastery, *Masters Thesis* submitted to The Royal Institute of Technology, Sweden.