Published by JScE as Proceedings of 4^{th} International Conference on Earthquake Engineering and Post-Disaster Reconstruction Planning (ICEE-PDRP), 19-21 Jan. 2026, Bhaktapur, Nepal

SEISMIC FLOOR RESPONSE CHARACTERISTICS OF SLOPED ROOF IN TRADITIONAL MASONRY STRUCTURAL SYSTEM DUE TO STRONG BI-DIRECTIONAL GROUND MOTIONS

Bidhek Thusa[1]*, Bidhan Thusa[2], Amit Prajapati[3]

[1] Heaven Consultant, Bhaktapur, Nepal
[2] PG Department of Earthquake Engineering, Khwopa Engineering College,
Purbanchal University, Nepal
[3] Department of Civil Engineering, Tongji University, Shanghai, China

Abstract

The recent failure of the sloped roof of the ancient pagoda, Fengyang Drum Tower in eastern China, has raised major concerns about the safety of such a structure. The primary objective of this study is to investigate the engineering demand parameter of a sloping roof in a traditional pagoda masonry structure. Generally, most traditional masonry structures consist of steep, sloping roofs with an angle ranging from 25 to 30 degrees. These roofs carry a large amount of self-weight as well as are supported by the wooden roofing system. These roof systems are critical in terms of public safety during the earthquake evacuation process. They are highly vulnerable to damage due to their location and experience maximum acceleration during earthquakes. The damage on sloped roofs is a critical hazard scenario for a traditionally dense city like Bhaktapur. This study selects a typical pagoda masonry structure for simulating the seismic response of such structures and locates the critical local and global locations of importance. The numerical model is developed utilizing three-dimensional nonlinear shell elements in SAP2000. This study utilizes 10 strong bi-directional natural ground motions for the time history analyses. The global and local structural response due to input strong bi-directional ground motion is investigated. The uni-directional and bi-directional responses are compared to investigate the effect of bi-directional ground motions on response characteristics. Additionally, this study investigates the global response trajectory of the system due to bi-directional ground motion for the precise seismic response characterization. The critical angle of incidence of the traditional pagoda structures is also investigated. This study points out the importance of considering bi-directional ground motions for efficient seismic performance evaluation of such structures. This study recommends updating design code and provisions to address the bi-directional effect of ground motions during structural analysis and seismic performance evaluations of existing structures.

Keywords: Masonry structure, Bi-directional ground motions, Seismic response characteristics, Sloped roofing system, Seismic performance evaluation

1. Introduction

UNESCO started the heritage conservation initiative back in 1960s with a moto to preserve the remarkable human ingenuity and serves as evidence of Human civilization as a time capsule for the future generations. However, due to aging monuments and major uncertainty in natural and artificial disasters, these living monuments are in the verge of critical conservation issues. For example, the recent failure of sloped roof of ancient pagoda Fengyang Drum Tower in eastern China due to aging and rule out of timely structural safety evaluations. Similarly, the 2015 Gorkha Earthquake in Nepal cause significant damage in heritage sites of Kathmandu Valley with more than 745 monuments being damaged (DoA, 2015). After The Gorkha Earthquake 2015 in Nepal, several research has been carried out on the damage assessment and the seismic performance investigation of Pagoda temples and monuments (Shakya and Kawan, 2016; Shakya and Kawan, 2016; Gautam, 2017; Weise et al., 2018;

---

*Corresponding author: Bidhek Thusa
Heaven Consultant, Nepal
Email: letterbdhek@gmail.com
https://doi.org/10.3126/jsce.v13i1.89570

Endo and Hanazato, 2020). Several researchers utilized the finite element modelling techniques for the numerical simulation of the masonry structures i.e. meso-scale modelling (Aref and Dolatshahi, 2013; Endo and Miyoshi, 2023), URM modelling (Cattari et al., 2022), distinct element method (Tra et al., 2024) and so on. However, the study of roof system has not been investigated so far. Despite not being the structural component of the Pagoda Temple, the roof system is very critical and vulnerable during seismic activities. The roof system is significantly accelerated during earthquake due to its structural system and being interlocked in the wall through wooden beam truss elements. While the terracotta tiles attached by mud mortar on the roof are highly vulnerable during earthquake and can cause life losses during evacuation process. Additionally, the recent earthquake in turkey Syria 2023 raises the concern of strong ground bi-directional ground motions. Strong bi-directional motions are even extremely challenging to most robust structures like Auxiliary Building of nuclear power plants (Thusa et al., 2025). This strongly points out how critical bi-directional motion could be for the aging heritage structures. Hence this study is carried out for addressing the significant research gap in bi-directional ground motions on masonry structures.

The main objective of this investigation is to study the floor acceleration of the roof system and performance of roof connection with the main structural element of a typical rectangular Pagoda temple due to strong bi-directional earthquakes. A set of 10 strongest bi-directional earthquake ever recorded is utilized to perform a nonlinear time history analysis of a typical rectangular Pagoda Temple. The bi-directional motions are selected in such a way that the motions hold almost same level of response spectrum along X and Y direction. The roof acceleration at 4 typical nodes of connection with the main structure is selected in each floor. The floor response spectrum is investigated along X and Y direction of structure and results bi-directional response is computed utilizing the wave theory. Additionally, the axial force developed on the connection system of roof and main beam in the floor is also investigated in this study to understand the seismic response characteristics of the roof system. This study holds a significant advancement in seismic performance evaluation concept of pagoda temples.

2. Numerical Modelling

A typical rectangular Pagoda temple numerically constructed using multilayer shell element model (MLSM) in SAP2000 (SAP2000, 2019). The adopted dimension of the Pagoda temple in this study is 12.86m in length and 7.24 m in width. While the roof system consists of three roofs making the temple height to 18.5 m. The numerical model is presented in Figure **??**. The mechanical properties of the masonry structure is listed in the Table **??**. Furthermore, Eigenvalue analysis is conducted to investigate the mode shapes and modal vibration frequency of the structure. The modal analysis result with mode shape with respective modal frequency is presented in Figure **??**.

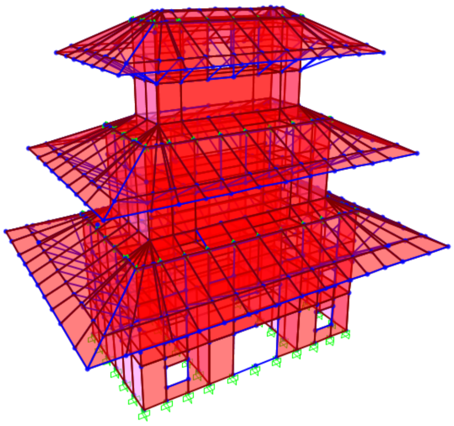


Figure 1: Numerical model using MLSM

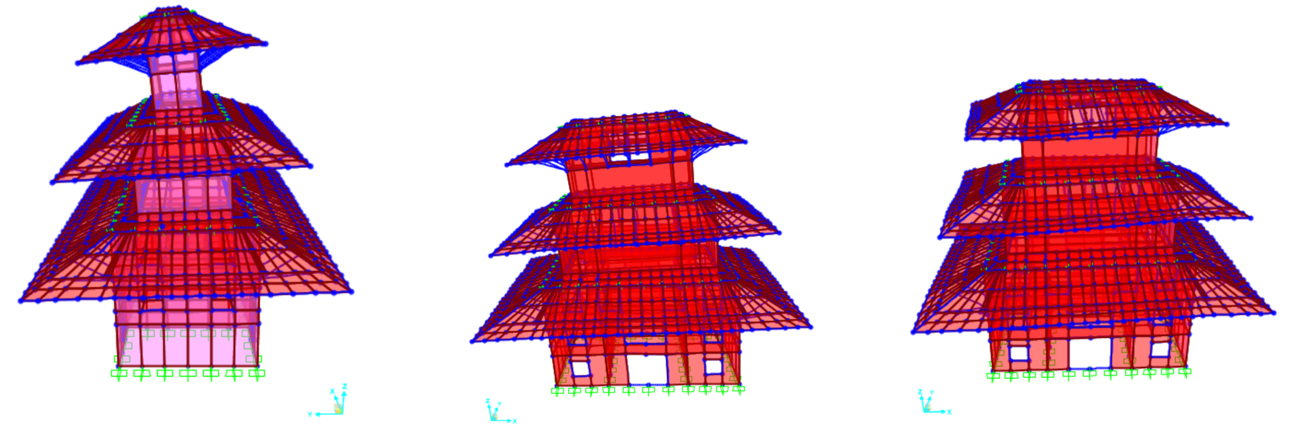
Table 1: Material properties

	Brick Masonry	Timber
Density (kg/m^3)	1800	900
Compressive strength (MPa)	1.6	40
Modulus of Elasticity (MPa)	160	10000
Tensile strength (MPa)	0.08	40

3. Floor Response Characteristics of Roof System

The floor response characteristic of the study model is investigated through a series of nonlinear time history analyses. The Response input strong bi-directional ground motions are presented in Figure **??**. The Rayleigh damping is generally utilized in dynamic analyses. This study also utilized the Rayleigh damping model for the structural damping value during the numerical analysis. The node for accelerometer is selected at the location of link element which connect the slanted roof purlins and the wooden beam on the top of the wall to hold the roofing system. The link element is modelled as nonlinear wooden links. Four nodes are selected along the four diagonal roof members. The basic sectional view is presented in Figure **??**.

The mean floor response spectrum (FRS) for each node of each roof is numbered as R1P1 to R3P4, where R1 represents Roof 1 node point 1. The output response spectrum for all the 12 nodes (4 node from each roof) is presented in Figure **??**. It is observed that the response



(a) Mode 1, f1 = 1.456Hz, translation along X

(b) Mode 1, f1 = 1.900Hz, translation along Y

(c) Mode 1, f1 = 2.960Hz, torsional mode shape

Figure 2: Eigenvalue analysis results.

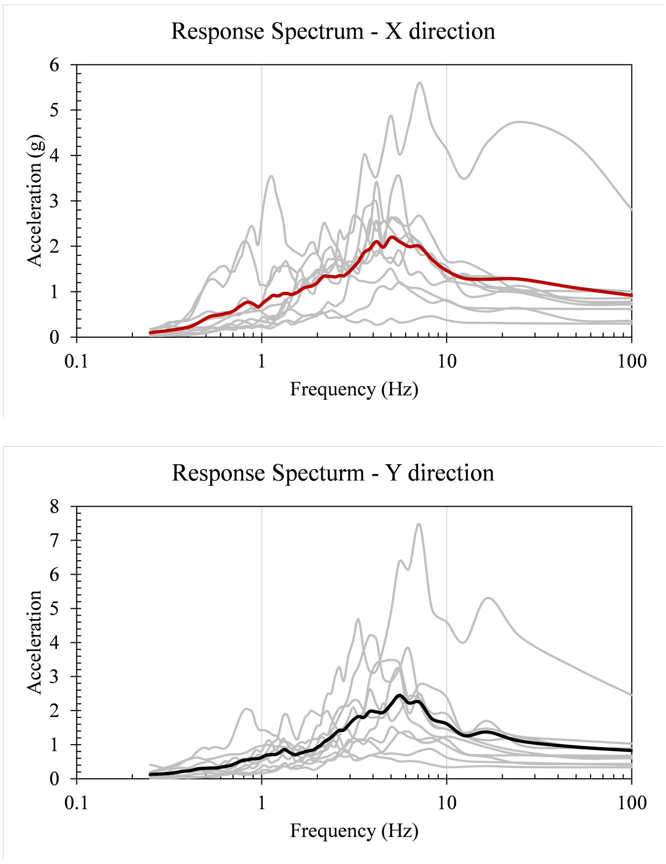


Figure 3: Input Strong bi-directional ground motion

spectrum is consistent and spectrum rises as we move to higher roof which is obvious. However, from close observation, the higher peak is observed at higher frequency ranges.

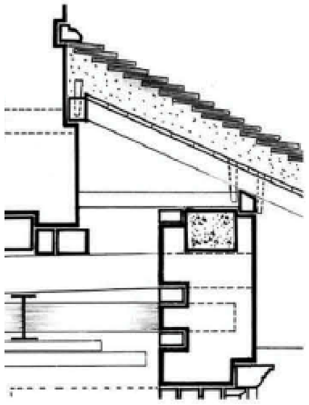


Figure 4: Roof connection system (from Theophile and Ranjitkar, 1994)

The higher peak response at higher frequency range in the roof can be attributed to the significant sensitivity of the roof connection joints to the high frequency content of the strong bi-directional motions. Hence, the roof is highly susceptible for the damage during strong earthquake with higher frequency contents. This result pointed out the need of consideration of bi-directional ground motions during seismic safety evaluations of heritage structures, and this strongly recommends the need for consideration of

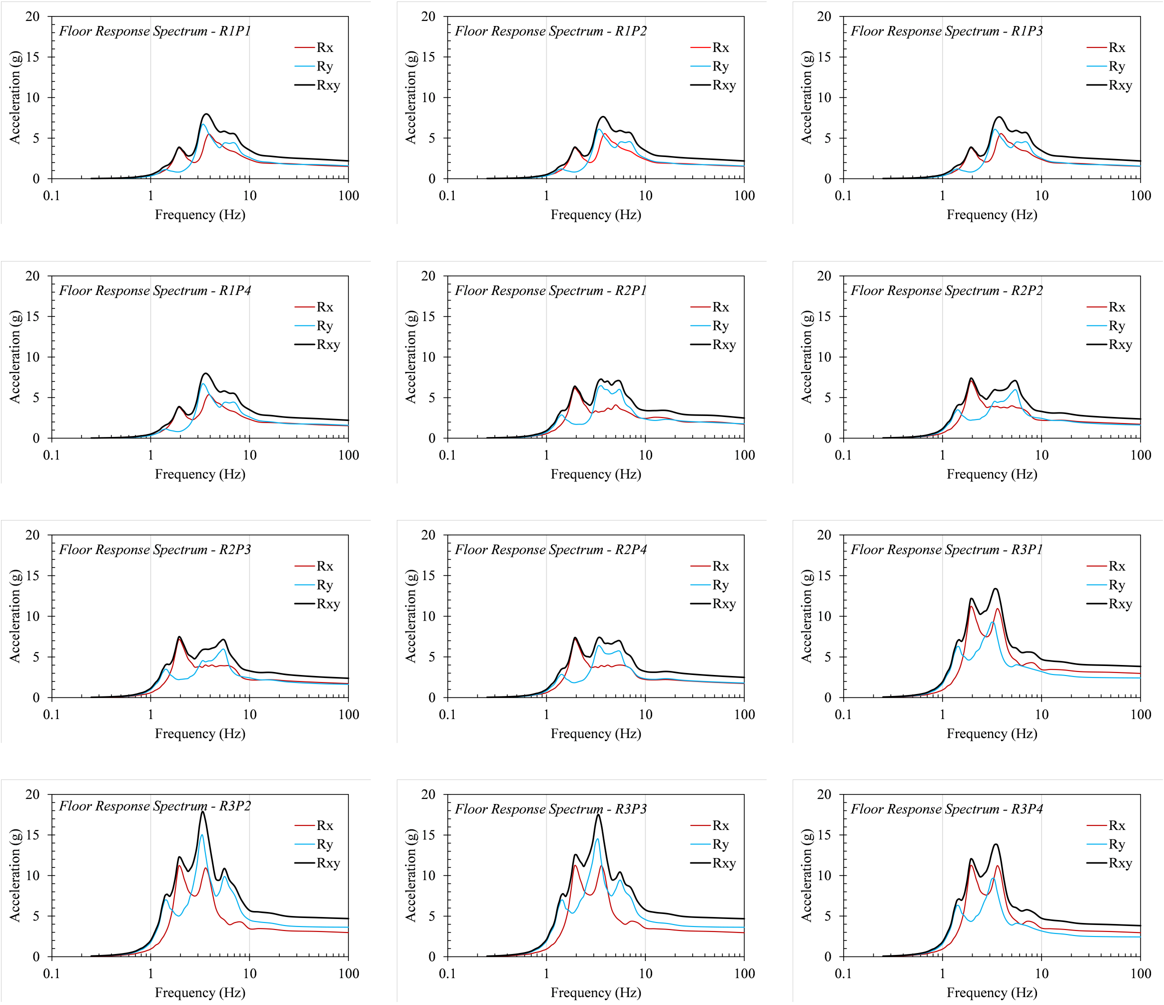


Figure 5: Mean FRS at the three roof levels due to strong bi-directional ground motions

bi-directional ground motions building codes.

This study also investigated the axial force developed in the joint element of the room and the main structure. The mean force generated in the link element due to strong bi-directional ground motion is presented in Table **??**.

From Table **??**, the observed force in the link element for the roof purlins and main beam on the wall presents maximum force is observed in the first roof and second roof, while the topmost third roof link elements exhibit minimum force. This may be due the mass of roof for the first and second roof being significantly higher than the third roof. The further extension of this study will be conducted to hold experiments to address the bond capacity of the connection system and estimate the damage state of the connections system for the pagoda temple.

4. Conclusion

This study investigates the floor response characteristics of the roof system of a typical rectangular pagoda temple. The nonlinear FEM model is developed by using MLSM. A series of nonlinear time history analysis is performed for 10 strong bi-directional ground motions. The seismic floor response is studied at various critical four locations of each roof. The following conclusion can be drawn from the numerical analyses.

- Strong bi-directional earthquake has significant effect on the floor acceleration of the roof.
- The bi-directional motion has a significant effect on the structural purlins and the major structural beams of the connecting the roof and the entire main structure.
- The significant second peak on the roof nodes at the

Table 2: Axial force in the link elements between the roof and structure

Node Number	Mean Axial Force (N)	Average per Roof (N)
R1P1	219.695	230.036
R1P2	239.098	
R1P3	226.436	
R1P4	234.917	
R2P1	246.750	249.372
R2P2	251.615	
R2P3	235.937	
R2P4	263.184	
R3P1	42.884	41.491
R3P2	37.460	
R3P3	38.776	
R3P4	46.845	

connecting element provide significant insight into the connections system of the roof system of pagoda temple being significantly sensitive to high frequency contents of the earthquake.

- Integration of bi-directional ground motions during the seismic safety investigation is strongly recommended in design codes and engineering practice.

References

Aref, A. J., & Dolatshahi, K. M. (2013). A three-dimensional cyclic meso-scale numerical procedure for simulation of unreinforced masonry structures. *Computers & Structures*, *120*, 9–23. https://doi.org/10.1016/j.compstruc.2013.02.009

Cattari, S., Calderoni, B., Caliò, I., Camata, G., de Miranda, S., Magenes, G., Milani, G., & Saetta, A. (2022). Nonlinear modeling of the seismic response of masonry structures: Critical review and open issues towards engineering practice. *Bulletin of Earthquake Engineering*, *20*(4), 1939–1997. https://doi.org/10.1007/s10518-021-01263-1

DoA. (2015). *Preliminary list of affected monuments of nepal by gorkha earthquake 2015* (Report). Department of Archaeology, Government of Nepal. Kathmandu, Nepal.

Endo, Y., & Hanazato, T. (2020). Seismic analysis of a three-tiered pagoda temple affected by the 2015 Gorkha earthquake. *International Journal of Architectural Heritage*, *14*(3), 457–470. https://doi.org/10.1080/15583058.2018.1550536

Endo, Y., & Miyoshi, K. (2023). Meso-scale numerical simulation of the mechanical behaviour of brick masonry in earth mortar. *Journal of Building Engineering*, *74*, 106890. https://doi.org/10.1016/j.jobe.2023.106890

Gautam, D. (2017). Seismic performance of world heritage sites in Kathmandu valley during Gorkha seismic sequence of April–May 2015. *Journal of Performance of Constructed Facilities*, *31*(5), 06017003. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001040

SAP2000, 2. (2019). *SAP2000: Integrated software for structural analysis and design* [Version used in this study (e.g., v21 or as applicable)]. Berkeley, CA, USA, Computers; Structures, Inc.

Shakya, M., & Kawan, C. K. (2016). Reconnaissance based damage survey of buildings in Kathmandu valley: An aftermath of 7.8 Mw, 25 April 2015 Gorkha (Nepal) earthquake. *Engineering Failure Analysis*, *59*, 161–184. https://doi.org/10.1016/j.engfailanal.2015.10.003

Thusa, B., Nguyen, D. D., Azad, M. S., & Lee, T.-H. (2025). Floor response characteristics of NPP auxiliary building subjected to bi-directional ground motions. *Nuclear Engineering and Technology*, *57*(8), 103599. https://doi.org/10.1016/j.net.2025.103599

Tra, S.-N., Kim, S.-H., Shin, J., Lee, D.-H., Park, H.-J., & Lee, K. (2024). Seismic fragility analysis and reliability evaluation for ancient stone pagoda using distinct element method. *Results in Engineering*, *23*, 102783. https://doi.org/10.1016/j.rineng.2024.102783

Weise, K., Gautam, D., & Rodrigues, H. (2018). Response and rehabilitation of historic monuments after the Gorkha earthquake. In D. Gautam & H. Rodrigues (Eds.), *Impacts and insights of the Gorkha earthquake* (pp. 65–94). Elsevier. https://doi.org/10.1016/B978-0-12-812808-4.00004-3

This page is intentionally left blank.