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DETERMINATION OF THE DYNAMIC CHARACTERISTIC OF THE MULTI-TIERED BHAIRABNATH TEMPLE IN DAMAGED AND POST-RECONSTRUCTION STATE USING MICROTREMOR

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Abstract

Historical structures that have endured for centuries present unique challenges for seismic assessment due to uncertainties in material properties, construction techniques, and the cumulative effects of past modifications and damage. Dealing with such complexity can be time-consuming and challenging. However, using a non-destructive vibration test for seismic assessment of the historical structure is a widely adopted and reliable method for understanding global behaviour. This study performed the ambient vibration tests of the Bhairabnath temple of Bhaktapur, Nepal, to investigate its dynamic characteristics. The vibration tests were conducted in the damaged and post-reconstruction phases. It shows the identified predominant frequency of X and Y direction of the structure in the damaged state are 1.51 and 2.29 Hz, respectively, slightly lower than the post-reconstruction state, which are 1.59 and 2.5 Hz, respectively. This reduction in the structural frequency is attributed to the reduction in the global stiffness, demonstrating the increased structural flexibility. In the post-reconstruction state, operational modal analysis was performed using enhanced frequency domain decomposition and stochastic subspace identification to obtain its dynamic characteristics. The reliability between the two techniques was evaluated using the cross-matrix assurance criteria, which demonstrate a strong correlation between the obtained frequencies and mode shapes. Similarly, the discrepancies in principal directions are 5.3% and 9.17% correspond to the different structural states, which indicate a reduction of 10% and 17% structural stiffness in the damaged state. Hence, the study underscores the significance of vibration test in determining the dynamic properties of the structure and highlights the necessity of structural health monitoring in historical structures.

Keywords: Historical structure; Ambient vibration test; Dynamic characteristic; Operational modal analysis.

1. Introduction

Historical structures are endowed with significant physical records of past civilizations, synthesizing architecture, archaeology, engineering, history, and cultural studies. Their preservation, however, presents a considerable challenge, particularly in seismically active regions. The repeated seismic events often subject these edifices to cycles of damage and repair. With this phenomenon, it loses its strength through material degradation and long-term exposure to the outer environment. Moreover, understanding its seismic behaviour is difficult to interpret due to its construction technique, which usually considers gravity loads (Yavartanoo and Kang, 2022). For understanding its structural behavior, a non-destructive ambient vibration test offers critical insights into the identification of the dynamic behavior of existing historical structures. The dynamic characteristics of the historical structure in operational condition are determined using the operational modal analysis (OMA) technique, particularly in the context of health monitoring (Reynders and De Roeck, 2014). It identifies key parameters such as resonant frequencies, mode shapes, and damping ratios, offering insights

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into the structure's dynamic behavior under operational conditions (Capanna et al., 2021). Such analysis is crucial for evaluating global structural performance, stability, and integrity of historical structures that rely solely on measuring structural response. Further, the operational model analysis results calibrate the structural material properties, reducing discrepancies between the dynamic properties of numerical models and real structures (Altunişik et al., 2024). This technique evaluates the recorded vibration in the frequency domain and time domain methods. Frequency domain includes peak picking and frequency domain decomposition, and enhanced frequency domain decomposition, and the time domain method includes stochastic subspace identification for model identification. The application of OMA techniques in the identification of dynamic properties has been widely applied in the existing structure(Lorenzoni et al., 2019; Standoli et al., 2020). Zahid et al., 2020 reviewed the development of the OMA techniques in structural health monitoring and discussed their advantages and disadvantages. The dynamic characteristic deduced from the OMA in the historical structure provides a benchmark for the material properties calibration in the numerical simulation (Capanna et al., 2021; Standoli et al., 2020). The study conducted the experimental vibration test on the structure in damaged and post-reconstruction states, which conducted operational modal analysis technique to assess the dynamic behavior of the existing historical Bhairabnath temple. In the damaged state, the predominant frequency was identified using only a single velocity sensor, whereas the structural dynamic characteristics were identified using multiple sensors in the post-reconstruction state. The result indicates the observed decrease in natural frequencies in the damaged state confirmed a loss of global stiffness due to the damage and cracking in the structure. The subsequent recovery of higher frequencies in post-reconstruction validated the effectiveness of the reconstruction. Further, the strong correlation between the mode shapes identified by the EFDD and SSI techniques, verified through the Cross MAC, attests to the robustness of the findings. Consequently, the work establishes OMA as a powerful non-destructive method for the condition assessment and long-term health monitoring of significant historical structures.

2. Case Study

Bhairabnath temple is a historical multi-tiered pagoda structure, a traditional architectural typology commonly found in Nepal. Such a typological structure has a large overhanging roof, which makes it a distinct structure from other types of historical structures. The temple is located in the very soft soil of the Kathmandu valley and is situated in a high seismic area of Nepal. Due to the high seismic region, the Bhairabnath temple experienced and sustained significant seismic damage over the years. Historical records indicate a complete collapse of the structure during the 1934 Nepal-Bihar earthquake. Later, in the 1989 Udyapur earthquake and the 2015 Gorkha earthquake, the major damage documented was only on the upper floor of the temple. This cycle of extensive damage and reconstruction due to the major seismic events highlights the vulnerability of the temple (Kc et al., 2017; Shilpakar et al., 2021).

Following the Gorkha earthquake in 2015, a condition assessment was conducted by a team of experts from the Bhaktapur Municipality for detailed documentation of structural damages and assessment before reconstruction efforts (Condition Assessment of Bhairavnath Temple, 2019). The intensive assessment illustrates the floor-wise damage of the structure, and found that the top floor experiences the most severe damage, which tends to collapse. It was slightly tilted due to the seismic forces, and most struts supporting the roof had fallen, as shown in Figure 1. In the lower floor, vertical cracks were observed, likely due to the compression forces exerted by the upper floors. Similarly, shear cracks, wall toe crushing, and corner separation between walls, which are common forms of damage in the masonry structures caused by seismic forces, were also observed in the temple.


Figure 1. Damaged state after the 2016 Gorkha earthquake

3. Ambient Vibration Test

3.1. Single Point Measurement

A single-point ambient vibration measurements were conducted on the Bhairabnath temple using a Portable Intelligent Collector (PIC) 1016 velocity sensor, as shown in Figure 2. The survey was performed on 2018-10-08, following the 2015 Gorkha earthquake, to assess the structure's condition in its post-earthquake damaged state. The sensor was deployed at the center of the top floor to capture low–frequency vibrations over a 15-minute recording period. The recorded raw signals by the velocity sensor are corrected and reviewed for any transient signals that are manually removed. Each signals are customized to 8-14 segments of 2048 samples using 20.48s and segregated into individual (X, Y, Z) components. Each segment undergoes a fast Fourier transform to obtain the Fourier spectra. Subsequently, the Floor spectral ratio is a reliable parameter for obtaining the fundamental frequency of the structure (Kawan et al., 2024; Sakhakarmi et al., 2024). It is a ratio of the horizontal spectral component of the top floor to the bottom floor. The floor spectral ratio was computed to identify the predominant frequency of the structure.

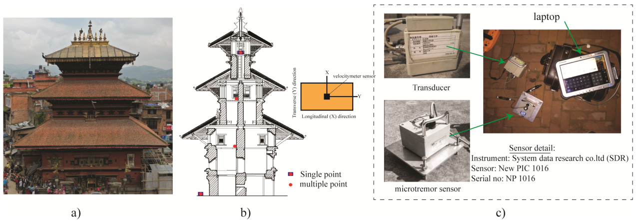

Figure 2. a) and b) Single point measurement location, and c) instrument used

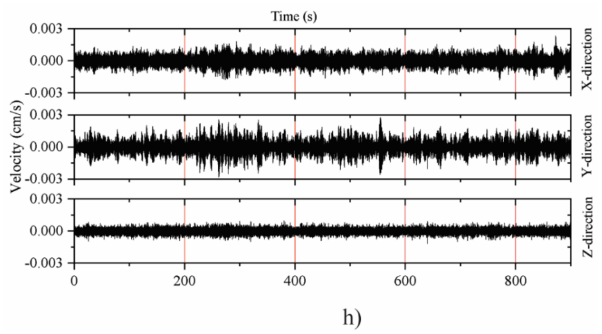

Figure 3. Three-component (X,Y,Z) velocity time series recorded in Bhairabnath temple

3.2. Multiple Point Measurement

After the reconstruction of the structure, the vibration recording was performed with multiple velocity meter sensors, as shown in Figure 4. Later on, date 2024-08-14, a three-component velocity sensor, McSEIS-AT, manufactured by OYO corporation, was deployed. All the sensors were positioned at the center of the ground, second, fourth, and sixth floors. The simultaneous recording of all the sensors was achieved using a built-in GPS sensor that was recorded for 15 min with a sampling frequency rate of 250 Hz. The simultaneous recording enabled the identification of the dynamic parameters of the structure, such as predominant frequency, mode shapes, and damping ratio.

Figure 4. Multiple point measurement a) Illustrative diagram of the measured location, b) free-field, c) second floor, d) fourth floor, and e) sixth floor

4. Result and Discussion

4.1. Horizontal Spectral Ratio

In the historical Bhairabnath temple,, single-point ambient vibration test was conducted with the velocity sensor after the 2015 Gorkha Earthquake. The uppermost part of the structure was extensively damaged when the measurement was performed. For the identification of the dynamic characteristic of the structure by single-point measurement, a horizontal spectral ratio is computed between the top floor of the ground and the structure. The examined experimental analysis indicates the predominant frequency of the structure in X-direction and Y-direction as 1.51 and 2.29 Hz, as presented in Figure 5. The X-direction and Y-direction frequency is considered as the first and second modes of the structure, which is generally a translation mode. This method is very conservative for higher modes, which cannot be clearly defined.

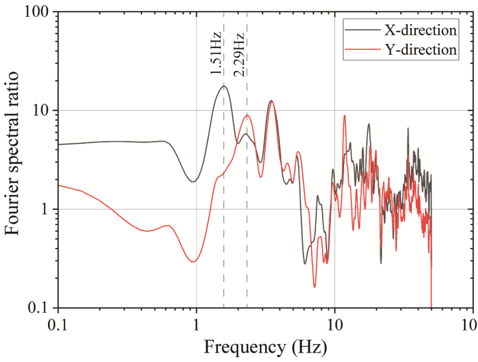

Figure 5. Predominant frequency of the structure in the X and Y direction of the structure using the horizontal fourier spectral ratio.

4.2. Operational Modal Analysis

The simultaneous recording of ambient vibration at multiple points of the structure provides a better understanding of the dynamic characteristics of the structure in its operational state. In the study, four velocity sensors were deployed at the center of the floor to capture the low-frequency vibration of the structure. The experiment was conducted after the reconstruction of the structure that was damaged by the 2015 Gorkha earthquake. This method was widely adopted in identifying the structural behavior at the operational state since it is non-destructive and does not harm the structure. Operational model analysis is performed to capture different modes and predominant frequencies associated with the ambient vibration test. It was performed using Python-based tools that compute enhanced frequency domain decomposition and Stochastic subspace identification methods from the output signals (Pasca et al., 2022). The singular value plot and stabilization plot from the EFFD and SSI techniques are shown in Figure 6 a and b. The first three peaks of the singular plot are a clear identification of three mode frequencies for the EFFD, whereas the higher order value concentrated at the low frequency shows the clear indication of three frequency modes. As shown in Figure 6, only the first three modes that profoundly influence the structural responses were taken into consideration for the study. The first and second modes correspond to translation in longitudinal and transverse direction, whereas the third mode exhibits rotational behavior, as illustrated in Figure 6 c, d, and e.

Table 1 shows the computed frequency for the first three modes using operational modal analysis. It presented the first three fundamental mode frequencies for EFFD are 1.594, 2.501, and 2.973 Hz, respectively. And from the SSI technique, the first three frequencies are 1.595, 2.505, and 2.992 Hz, respectively. Similarly, it presented the damping ratio for the studied modes.

The reliability of the mode shapes between two different techniques was assessed using CrossMAC. In Table 2, the diagonal matrix is nearly 1, which shows a good correlation between the modes. Similarly, lower values in the off-diagonal matrix indicate all modes are distinct from one another. The results of the MAC demonstrate the consistency in the mode shapes performed using the EFDD and SSI technique.

The experimental results were compared with the fundamental period formulation proposed by Fujita et al., 2020. The formulation was proposed especially for the Nepalese multi-tiered structure; it presents the relation between the fundamental period and height of the structure. The experiment period from the EFDD and SSI techniques was determined from the inverse relation, which is 0.627s for both. As shown in Figure 7, the obtained periods are fitted with the Fujita et al., 2020 formulation, showing proper validation of the test results. It shows that the test results matched the period of the multi-tiered historical structures commonly found in Nepal.

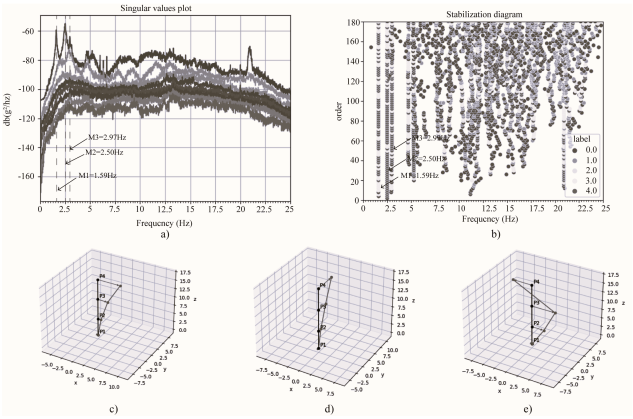

Figure 6. a) and b) SVD and stabilization plot from the EFFD and SSI technique for the identification of natural frequency, c) First three mode shapes

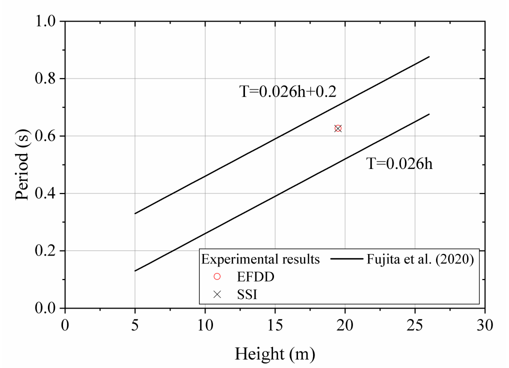

Figure 7. Comparison of experimental (EFDD and SSI) periods with the Fujita et al. (2020) equation.

Table 1. Frequency and damping ratio of EFFD and SSI analysis

Mode	EFFD		SSI	
	Freq. (Hz)	Damp. (%)	Freq. (Hz)	Damp. (%)
1	1.594	1.76	1.595	1.86
2	2.501	2.00	2.505	1.80
3	2.973	0.37	2.992	2.53

Table 2. Matrix assurance criteria

OMA		EFDD		
		M1	M2	M3
SSI	M1	0.9954	0.0003	0.1230
	M2	0.0005	0.9994	0.0008
	M3	0.0231	0.0014	0.9706

4.3. Frequency Comparision (Damaged and Post-reconstruction State)

After the 2015 Gorkha earthquake, the Bhairabnath temple was severely damaged. During the damaged state, a non-destructive experiment was conducted to assess the structural health of the structure. Later, after the reconstruction, the vibration of the structure was monitored at multiple points. From two different phase measurements, there seems slight deviation in the frequency. In both X and Y directions, the frequency obtained during damaged conditions was lower than that after reconstruction, as shown in Table 3. The lower frequency obtained is due to the fall of the roof structure, cracks, and damage in the structure, making the structure slightly flexible. Due to this, the global stiffness in the structure is relatively lower compared to the post-reconstruction phase.

Table 3. Difference in frequencies before and after reconstruction

	X-direction (Hz)	Y-direction (Hz)
Before reconstruction	1.51	2.29
After reconstruction	1.59	2.50
Difference (%)	5.20	9.17

4.4. Change in Structural Stiffness

The Bhairabnath temple demonstrated a discrepancy in the structural frequencies while conducting experimental tests in the damaged and post-reconstruction state, as presented in Table 3. The change in frequency reveals the alternation of structural stiffness due to damage in the masonry wall (Shakya et al., 2013). After the 2015 Gorkha earthquake, the top floor of the structure was heavily damaged, as shown in Figure 1. The alteration of the structural stiffness in can be attributed to the frequency and stiffness relation, as indicated in Equation. (1):

$$\frac{f_d}{f_r} = \sqrt{\frac{k_d}{k_r}} \quad \Rightarrow \quad k_d = k_r \left(\frac{f_d}{f_r}\right)^2 \tag{1}$$

Fd, Kd, and Fr, Kr are the frequency and stiffness of the damaged state and post-reconstruction state, respectively. Assuming the minimal changes in the mass of the structure, mr and md are equal. Hence, the stiffness relation for X and Y directions is reduced as shown in Equations (2) and (3).

$$k_{dx} = 0.90\, k_{rx} \tag{2}$$

$$k_{dy} = 0.83\, k_{ry} \tag{3}$$

Equations (2) and (3) indicate a 10% and 17% reduction in the stiffness attributed to the principal (X and Y) directions of the structure in the damaged state, due to the heavy destruction of the top floor and the major structural damage to the masonry walls on the other floors.

5. Conclusion

This study investigates the dynamic properties of the Bhairabnath temple through ambient vibration testing in two distinct phases: a post-earthquake damaged and a post-reconstruction state. The experiment program initially performed a single-point measurement after the earthquake to capture the structure's behaviour. Following the reconstruction of the structure, an extensive multi-sensor experiment was conducted, enabling the identification of predominant natural frequencies, damping ratios, and mode shapes. For determining the dynamic characteristic, operational modal analysis was executed using Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI) methods. The subsequent recovery of the natural frequency indicates the effectiveness of the repair during reconstruction. The knowledge regarding the historical structure is limited, such as an experimental test to assess its dynamic characteristics. Hence, the obtained result can be set as a benchmark for the upcoming experiment test, which could help in health monitoring.

The analysis draws the following key findings:

1. Predominant natural frequency determined from the single point measurement during damaged condition is 1.51 and 2.29 Hz for the first two modes. Whereas the multi-point measurement provides slightly higher frequency for the first two modes at 1.59 and 2.5 Hz, respectively.
2. Enhanced frequency domain decomposition and stochastic subspace identification analysis show similar results for the first three modes, and their complexity shape factor is also very low. The low values indicate that the performance of the nodes in the mode shapes is acceptable.
3. The reliability of the mode shapes from two different techniques was checked through CrossMAC shows the diagonal matrix is nearly 1 and the off-diagonal matrix is very low, showing good correlation between modes from different techniques.
4. Frequency before construction is lower than that after the construction state, indicating a 10% and 17% reduction in stiffness of the structure during the damaged state in the first two modes of the structure.
5. The ambient vibration test is a major tool for structural health monitoring that identifies changes in stiffness, indicating damage in the structure in different states.

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