

Combined ND Techniques for Structural Assessment: The Case of Historic Nepali Constructions after the 2015 Gorkha Earthquake [†]

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[†] Presented at the 18th International Conference on Experimental Mechanics, Brussels, Belgium, 1–5 July 2018.

Published: 27 May 2018

Abstract: Combined non-destructive in situ techniques—namely sonic tests and ambient vibration measurements—are applied on two Nepali Pagoda temples damaged by the 2015 Gorkha earthquake, providing the dynamic elastic modulus of masonry and the buildings’ frequencies.

Keywords: non-destructive combined techniques; sonic test; ambient vibrations; earthquake damage

1. Introduction and Methods

Nepal has a long seismic history due to its location on a very active tectonic zone, as the result of the subduction of the Indian plate under the Eurasian Plate. Major earthquakes were reported in 1255, 1810, 1866, 1934, 1980, 1988 and 2015. The 1934 Nepal-Bihar earthquake (M_w 8.0) destroyed more than 80,000 buildings and claimed 8500 lives [1,2]. The 2015 Gorkha earthquake (M_w 7.8) destroyed half million homes, causing more than 8790 deaths and 22,300 injuries [3]. Cultural heritage, mainly consisting of temples and palaces, suffered heavy damage as well [4].

Nepali Pagoda temples appeared around the middle of 14th century during the Malla Dynasty. They consist of brick masonry and timber members. The main features of Pagoda temples are their considerable wall thickness, multi-tiered roof and box type configuration [5,6]. The main weaknesses of Pagoda temples under seismic actions are: (a) lack of transverse connection in multi-leaf brick masonry; (b) lack of vertical continuity of the walls—upper walls rest on timber beams to form a kind of inward cantilever; (c) large weight of the top roof, arcades at the base resulting in soft ground floor [7].

This study presents an experimental investigation on two Nepali Pagoda temples damaged by the 2015 Gorkha Earthquake, namely Jagannath Temple in Kathmandu Durbar Square and Krishna Temple in Bhaktapur Durbar Square.

Non-destructive techniques (NDTs) for the in situ evaluation of civil structures are well known and widely used with the aim of identifying hidden construction elements, calibrating mechanical parameters, assessing the level of damage and/or the state of preservation [8,9]. Currently, the most used NDTs are: sonic and ultrasonic tests, ground-penetrating radar, pachometer, rebound hammer, thermography and dynamic monitoring under an exciting device or ambient vibrations measurements (AVMs) [10,11]. Minor-destructive in situ tests, e.g., mortar penetration tests and flat jacks, or sampling for laboratory tests, are very common as well.

The research field of NDTs is rather complex from the scientific point of view and there is still the need to understand the potential of combining a number of different techniques. The aim of this

research is to investigate the interaction of AVMs and sonic tests (STs), with special emphasis on damage level assessment and on expected seismic collapse mechanism.

2. Results

The experimental results related to STs to evaluate the level of compactness in damaged and undamaged parts of masonry, and to AVMs on historic temples are presented. Specifically, the experimental investigation was carried out on Jagannath Temple in Kathmandu Durbar Square [12,13] and Krishna Temple in Bhaktapur Durbar Square.

2.1. The Case of Jagannath Temple in Kathmandu Durbar Square

The first historic construction investigated with both STs and AVMs is Jagannath Temple (Figure 1). STs have been applied in four zones, as indicated again in Figure 1. Some results are reported in Table 1 for zone A. Masonry density has been assumed according to [14].

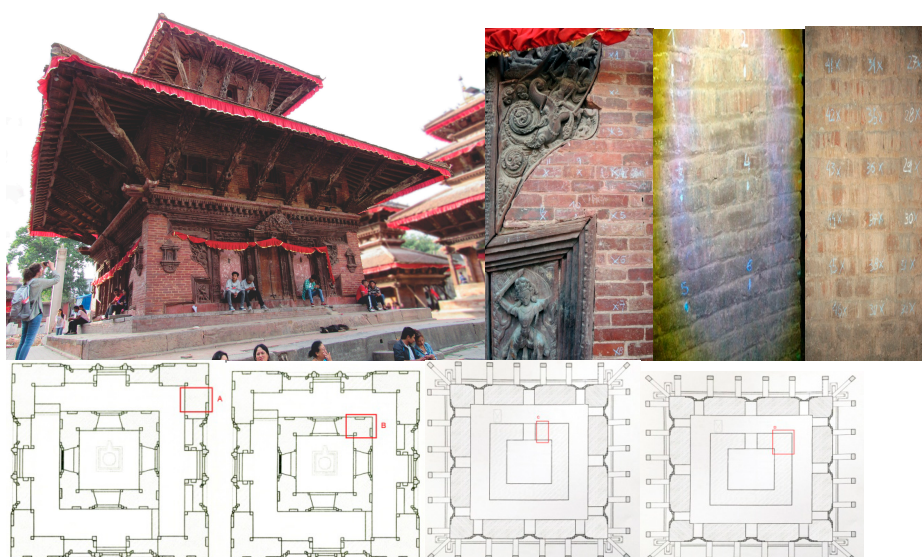


Figure 1. Jagannath Temple, Kathmandu.

Table 1. Results of STs, Jagannath Temple.

	t_1 (s, Hammer)	t_2 (s, acc.)	Δt (s)	Wall Thick. (m)	Velocity tr (m/s)	Velocity Long (m/s)	Poisson Ratio	Density (kg/m ³)	Dynamic el. mod. (MPa)
P1	13.206146	13.20750	0.001354	1.00	738.55	1273.37	0.2465	1750	1571
P3	6.613073	6.613906	0.000833	1.00	1200.48	2069.79	0.2465	1750	4150
P5	4.979010	4.979844	0.000834	1.00	1199.04	2067.31	0.2465	1750	4140
P7	2.874219	2.874896	0.000677	1.00	1477.10	2546.73	0.2465	1750	6282
P9	2.445260	2.446094	0.000834	1.00	1199.04	2067.31	0.2465	1750	4140

In detail, the analysis of the results confirms the effects of damage and its distribution. In particular, it is evident from Table 1 that the zone in correspondence of the first floor appears less damaged than that at the ground floor.

AVMs were accomplished on 23 October 2016. The measurements on the south basement were accomplished on 29 October 2016. The locations of the velocimeter are shown in Figure 2. The record duration was 16 min for the south basement, 6 min at the north side of first floor and 10 min for the remaining records. The sampling frequency was 128 Hz. The Fourier amplitude spectra of velocity are shown in Figure 3.

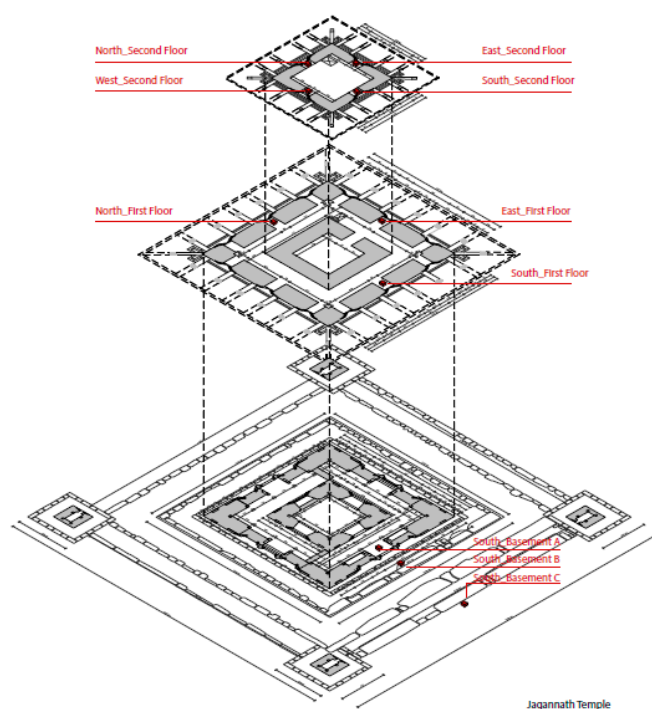


Figure 2. Locations of the velocimeter, Jagannath Temple.

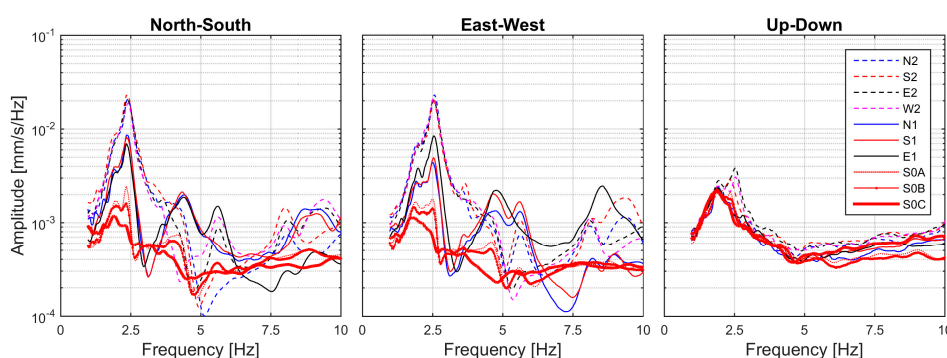


Figure 3. Fourier amplitude spectra of velocity, Jagannath Temple.

The first two frequencies correspond to the fundamental modes along the NS ($f_1 = 2.3$ Hz) and EW ($f_2 = 2.5$ Hz) directions, respectively. Similarly, the third and fourth frequencies correspond to the second modes along the NS ($f_3 = 4.3$ Hz) and EW ($f_4 = 4.7$ Hz) directions, respectively. The fifth frequency ($f_5 = 5.6$ Hz) corresponds to the first torsional mode around the vertical axis, as the N and S walls move along the EW direction, and the E and W wall along the NS direction. Two frequencies follow ($f_6 = 8.1$ Hz, $f_7 = 8.6$ Hz) without clear indications about their modal shape. The eighth frequency ($f_8 = 9.1$ Hz) correspond to the third mode along the NS direction. Finally, the ninth frequency ($f_9 = 9.4$ Hz) corresponds to the second torsional mode around the vertical axis. The measures at the second floor show the typical coupling between the horizontal and the vertical components due to the global bending response of the building. No significant peak was detected at the basement, south side, outside the temple, showing the absence of local amplification effects.

2.2. The Case of Krishna Temple in Bhaktapur Durbar Square

In the case of Krishna Temple (Figure 4), STs, of direct and indirect type, have been applied at the base of the masonry bearing parts, as indicated in Tables 2 and 3.



Figure 4. Krishna Temple, Bhaktapur.

Table 2. Indirect STs, Krishna Temple.

Wall	Vert. Vel. 1 (450 mm; m/s)	Vert. Vel. 2 (900 mm; m/s)	Vert. Vel. 3 (1350 mm; m/s)	Vert. Vel. Mean V. (m/s)	Horiz. Vel. (250 mm) Mean V. (m/s)
East wall	328	2497	1574	1466	1397
South wall	412	1597	2345	1452	898
North wall	/	1127	831	979	1139
West wall	/	1062	929	1299	873

According to well established relations between sonic wave velocity and masonry compactness, Table 2 confirms that the latter is low along both the horizontal and the vertical directions. This is probably due to internal damage and low level of maintenance. Moreover, the very low values of the sonic waves along the vertical direction over short distance (450 mm) highlight the poor mechanical performance of mud mortar joints.

Table 3. Direct STs, Krishna Temple.

Point	Vel. Ext. Zone (m/s)	Vel. Int. Zone (m/s)	Mean Velocity (m/s)
S-E corner	832	1389	1110
N-W corner	1376	1706	1541

AVMs were accomplished on 24 October 2016. The locations of the velocimeter are shown in Figure 5. The arrows show the instrumental N direction. The duration of each record was 16 min and the sampling frequency 128 Hz. The Fourier amplitude spectra of velocity are shown in Figure 6.

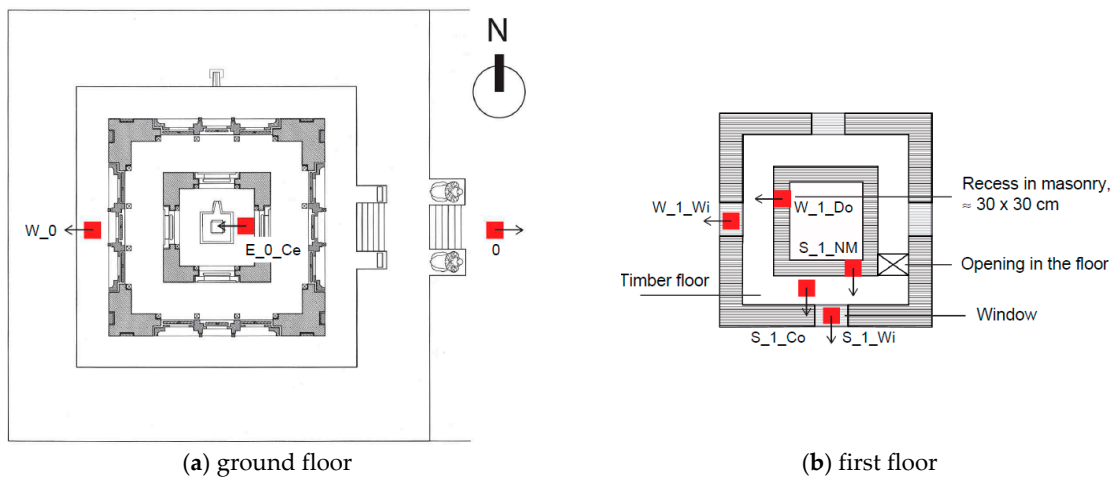


Figure 5. Locations and orientations of the velocimeter, Krishna Temple.

The first two frequencies ($f_1 = 2.3$ Hz, $f_2 = 2.4$ Hz) have mixed components, along the NS and EW directions, possibly with torsion. The third frequency ($f_3 = 3.3$ Hz) corresponds to the first torsional mode around the vertical axis (the S wall moves along the EW direction and the W wall along the NS direction). The fourth frequency ($f_4 = 5.6$ Hz) has mixed components along the NS and EW directions. The fifth frequency ($f_5 = 6.1$ Hz) corresponds to the free-field and the basement, showing local amplification effects. Finally, the last three frequencies ($f_6 = 6.5$ Hz, $f_7 = 9.4$ Hz, $f_8 = 9.8$ Hz) have again mixed components along the NS and EW directions. Coupling between the horizontal and the vertical components can be found at the first floor.

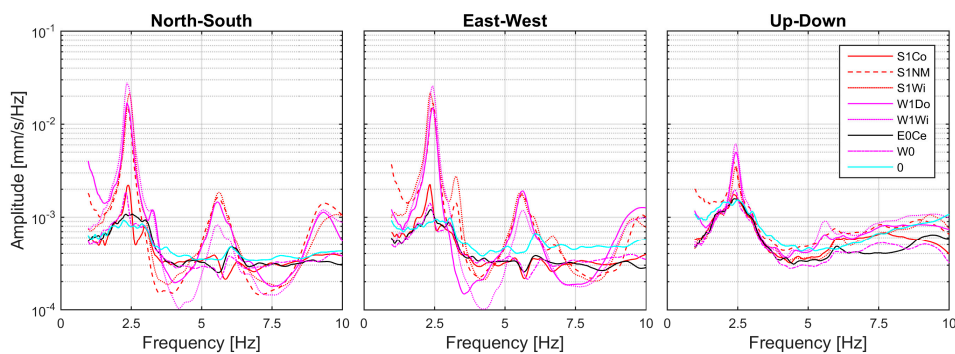


Figure 6. Fourier amplitude spectra of velocity, Krishna Temple.

3. Potential Interaction between STs and AVMs

The frequency values reported in Section 2.1 with reference to Jagannath Temple evidenced a well-known and recognizable structural behaviour consisting of modes along the principal directions of the building and torsional modes. Horizontal and vertical components are coupled according to global flexural behaviour. The frequency values are in agreement with the level of wave velocity across the thickness of masonry, ranging between 850 and 1700 m/s, with reasonable level of homogeneity and low scatter. However, if we consider that the tests have been carried out on a damaged structure, both STs and AVMs seem to indicate that the dissipation capacity of the monument under seismic actions has been efficient and performing.

Regarding Krishna Temple, both STs and AVMs show a less effective structural performance, which is consistent with higher level of observed damage. More specifically, a potential field of research is the integration of information from dynamic identification by means of AVMs—i.e., natural frequencies and modal shapes for each direction—and those from sonic wave velocity distribution in the walls along the same direction.

4. Preliminary Conclusions

On the basis of the presented investigation, the following conclusions can be drawn:

- Usually, in ND in situ investigations, there is the habit to consider separately the results coming from different techniques. Nevertheless, in the case of historic constructions or monuments, this approach does not take full advantage of surveyed information. Indeed, especially after earthquakes or in any case of observed significant damage, combined interpretation can be of interest. This is the case of STs and AVMs.
- Generally, potential integration of these two tests could be difficult because STs provide local results whereas AVMs global results. In addition, the former are based on hammer induced vibrations, whereas the latter use natural and anthropic vibrations.
- Nevertheless, a potential common point of these techniques is damage identification. More specifically, the natural frequencies and mode shapes along a principal direction, provided by AVMs, can be put in relation with the sonic wave velocity across damaged and non damaged parts of the walls along the same direction.

- When evaluating masonry through STs, as general consensus, a 2000-2500 m/s velocity indicates a good level of compactness. Similarly, for the constructions under consideration, a frequency greater than 2.0 Hz indicates a good level of stiffness. Nevertheless, the proposed investigation is more complex because it aims at accounting together for local (STs) and global (AVMs) measures, even though both are related to vibrations.
- STs and AVMs resulted in good agreement and consistent with the observed structural damage.

Acknowledgments: The support of UNESCO Kathmandu office to IUAV's damage survey activity in 2017 and 2018, and IUAV's funding of an international in situ workshop in 2016 are gratefully acknowledged.

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