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Investigation Techniques Carried out on the Qutb Minar, New Delhi, India

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ABSTRACT: In the framework of the Eu-India Economic Cross Cultural Programme "Improving the Seismic Resistance of Cultural Heritage Buildings", aimed at the preservation of ancient masonry structures with regard to the seismic risk, different NDT were applied to the Qutb Minar, New Delhi, India, in September 2005. The paper describes the different investigation techniques applied (Ambient Vibration and Pulse Sonic Velocity Tests), intended to define the dynamic response of the tower and to qualitatively define the masonry conditions. For the dynamic modal identification analysis different test equipments were used, in order to compare the data and to have more reliable results. The dynamic parameters resulted from the acquisition campaigns will be used to estimate the mechanical properties of the masonry walls and the boundary conditions of the structure, to be considered in successive seismic nonlinear analyses of the Qutb Minar, aimed at the assessment of the safety level of the construction.

1 INTRODUCTION

The Qutb Minar, is the highest monument of India and one of the tallest stone masonry towers in the world. Inside, a helical staircase with 379 steps communicates to five balconies, where the *Mu'adhdhin* (muezzin) called to prayer. The minaret has also a symbolic function, being a sign to glorify the victory of Islam against idolatry. The construction began during the reign of Qutb-ud-din around 1202, but the erection stopped at the first storey. The next ruler, Iltutmish, added the next three storeys. The tower was damaged by lightning in 1326 and again in 1368. In 1503 Sikandar Lodi carried out some restoration and enlargement of the upper storeys (Chandran 2005).

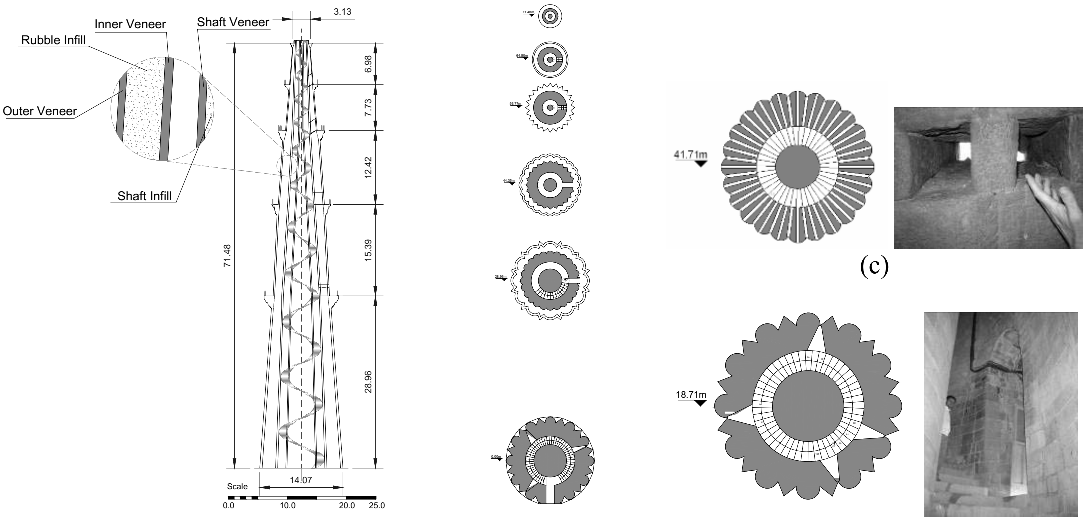
As a reference to the importance of the monument, the Qutb Minar has been inscribed in the world heritage monument list since 1993.

(a) (b)

Figure 1 : (a) General view of the Qutb Minar; (b) detail of the Koran's inscriptions carved in the stone.

2 STRUCTURAL AND DAMAGE SURVEY

The Qutb Minar directly rests on a 1.7 m deep square ashlar masonry platform with sides of approximately 16.5 m, which in turn overlies a 7.6 m deep lime mortar rubble masonry layer, also square, with sides of approximately 18.6 m. The bedrock is located around 50-65 m below the ground level. The Minar cross-section is circular/polilobed, being the base diameter equal to 14.07 m and tapering off to a diameter of 3.13 m at the top, over a height of 72.45 m. The tower is composed by an external shell corresponding to a three leaf masonry wall and a cylindrical central core (Figure 2a).



(c)

(a) (b) (d)

Figure 2 : Geometrical survey: (a) vertical section of the Qutb Minar; (b) cross sections at different levels; (c) small size ventilation openings; (d) tapered windows.

The core and the external shell are connected by a helical stairway and by 27 “bracings” composed by stone units with an average cross section of 0.40×0.40 m^2. The stairway is spiral, disposed around the central masonry shaft, and it is made of Delhi quartzite stone. Each storey has a balcony and the uppermost storey finishes with a platform.

The Minar is also provided with diffuse ventilation openings that can be divided into two groups: some smaller openings on three levels and larger openings (windows) respectively presented in Figure 2c and Figure 2d. In correspondence of the second and third levels of the smaller openings the cross section of the tower decreases almost to 50% of the total.

The Minar outer shell is composed by a three leaf masonry wall. In the first three storeys the external veneer is made of ashlars of red and buff coloured sandstone whereas the internal is composed by Delhi quartzite ashlars. In the two upper storeys the external veneer is made of white marble stones and the internal of red sandstone. The infill is composed by rubble stone masonry, mainly with stones taken from the destroyed temples during the Islamic dominion.

By direct visual inspection (September, 2005) it was possible to notice that the damage currently manifested by the tower is related to cracks and material decay, see Figure 3. The majority of cracks are positioned in the lower part of the Minar, in the inner veneer of the external shell and in the central shaft, from the base of the tower to the first level, covering approximately a height of 15 m. A wide damage pattern, indicated by vertical cracks, is localized on the West and South sides; some minor cracks were found on the North side. A difference in the crack morphology on the N-S and in the West quadrants was noticed. In fact the crack pattern detected in the North and South sides manifests with long vertical fissures, while in the West side diffuse vertical thin parallel cracks are present.

(a) (b) (c)

Figure 3 : Damage survey: (a) cracks in the outer shell veneer; (b) and (c) cracks in the inner shell veneer and central core, respectively.

3 DYNAMIC IDENTIFICATION ANALYSIS

Preliminary analyses, carried out by the Indian Institute of Technology, Madras, Chennai, India (Chandran 2005), were taken into account for the test planning definition. The natural frequencies of the Qutb Minar were estimated by two numerical models with different boundary conditions: 1) stiff and 2) flexible base restraints. In both cases the masonry was considered to be isotropic, with an elastic modulus of 1.0 GPa in the first model and 0.6 GPa in the second. Table 1 presents the first five natural frequency values related to the observed mode shapes.

According to these first numerical estimations the first five expected frequencies of the tower range between 0.6 and 8.1 Hz. The tower behaves as a cantilever beam with mainly bending mode shapes.

Table 1 : First five natural frequency values.

Mode shape	Stiffer end Hz	Flexible end Hz	Comment
1	1.06	0.58	1st Bending
2	3.26	1.70	2nd Bending
3	6.47	3.39	3rd Bending
4	7.69	4.04	Torsion
5	8.12	4.25	Axial

3.1 *First Identification Analysis*

An acquisition chain composed of 8 uniaxial piezoelectric accelerometers, with a bandwidth ranging from 0.15 to 1000 Hz , a dynamic range ±0.5 g and a sensitivity of 10 V/g, connected to a data acquisition system with 16 bit A/D converter, provided with anti-aliasing filters in the amplification cards was considered for the first modal identification, performed by the University of Minho. As the digital band was configured to digitalize between ±0.05 g the system resolution was equal to 8 µg (equal to the transducer resolution).

3.2 *Test Planning*

To measure the dynamic response of the Qutb Minar to ambient vibrations, 20 points on five levels of the structure were selected. The sensors were placed in correspondence of the five existing balconies of the tower. The measuring points and directions are presented in Figure 4. As the experimental tests were based on the measurement of ambient vibrations with sequential data sets, one point at the top of the Minar was selected to be the reference point in the *x* (E-W direction), *y* (N-S direction) and *z* (vertical) directions. On each balcony the transducers were positioned in four points, two in triaxial (*x, y, z*) configuration and two in the *y* direction. The four points were positioned in the same line along the *x* direction; two points were located in the external shell and the others two in the internal core. Such test layout was chosen in order to evaluate the degree of connection between the external shell and the central core, since the two structural parts could have manifested a different dynamic response. The ambient vibrations were measured in all of the 20 points with 9 sequential setups, with a sampling frequency of 100 Hz and a total sampling of 20 min, approximately 1000 times the minimal expected period.

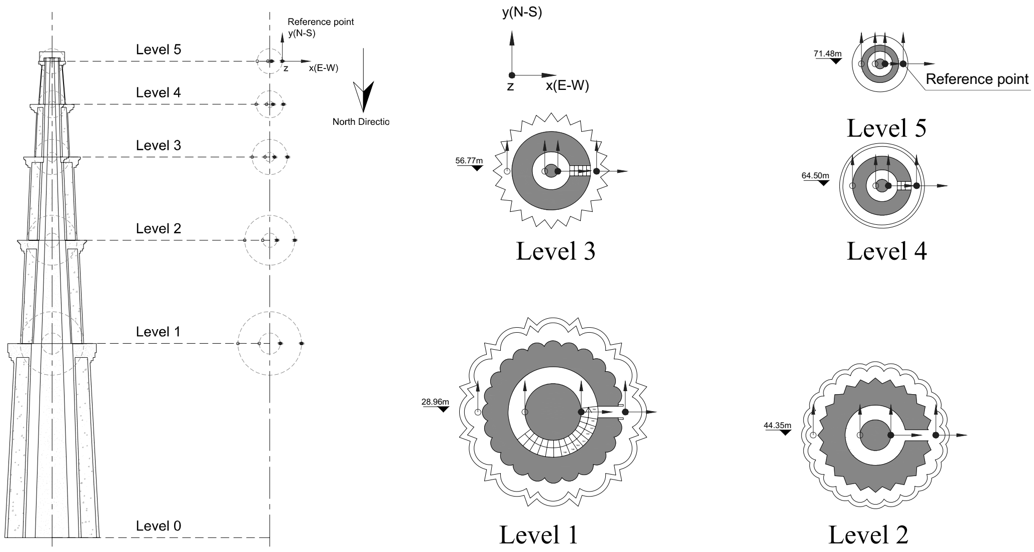


Figure 4 : Measuring points and directions.

3.2.1 Experimental Results

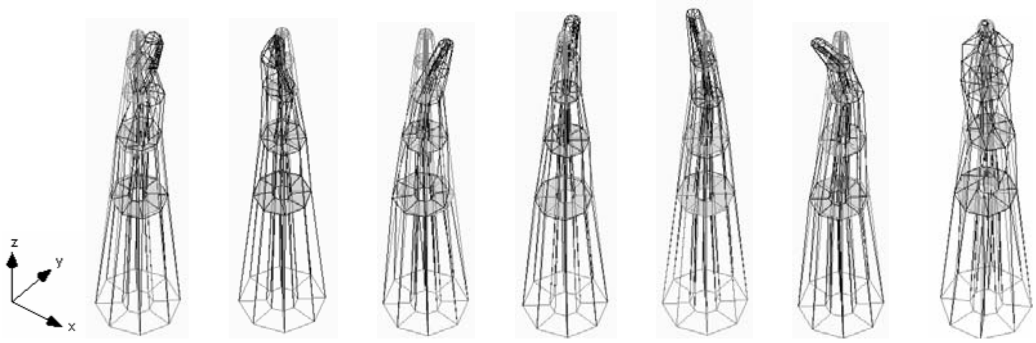
Output-only modal identifications techniques were used to estimate the modal parameters: resonant frequencies, mode shapes and damping coefficients. These techniques are based on the dynamic response measurements of a virtual system under natural (ambient or operational) conditions, and they are based on the assumption that the excitation is reasonably random in time and in the physical space of the structure (Ewins 2000, Brincker et al. 2000). In the case of the Minar, the ambient vibrations were mainly induced by the wind.

The software ARTeMIS Extractor Pro was used for the signal processing. Two different techniques were considered to estimate the dynamic parameters, in order to have more reliable results. Both of the techniques operate in the time domain and are based on the Stochastic Subspace Identification (SSI) method: Unweight Principal Component (UPC) and Principal Component (PC). These techniques were selected because they are robust and allow modal parameters estimation with high frequency resolution (Peeters 2001). In the different analyses, pairs of closely spaced frequencies were noticed, especially concerning the first two modes. This is due to the axisymmetric cross section of the structure, fact that generally leads to near pairs of bending mode shapes. For this reason SSI methods were selected for the modal identification, since they are between the most adequate in similar cases, given the difficulty to estimate closely spaced modes with frequency domain methods.

Table 2 : Dynamic results.

Mode shape	UPC Hz	PC Hz	Error %	MAC	Aver. Damping %	Comment
1	0.793	0.785	1.003	0.777	3.253	1st Bending
2	0.814	0.814	0.025	0.443	2.555	2nd Bending
3	1.955	1.953	0.079	0.988	1.126	3rd Bending
4	2.010	2.009	0.080	0.994	0.749	4th Bending
5	3.741	3.741	0.001	0.992	1.394	5th Bending
6	3.861	3.864	0.061	0.988	0.884	6th Bending
7	4.400	4.484	1.889	0.309	3.570	1st Torsion
8	6.006	5.966	0.671	0.743	1.653	7th Bending
9	6.146	6.073	1.186	0.832	1.347	8th Bending
10	6.282	6.261	0.330	0.907	1.270	Axial
11	6.977	6.968	0.137	0.865	0.972	2nd Torsion
12	8.090	8.174	1.033	0.690	2.131	Undefined
13	8.525	8.530	0.065	0.788	2.247	9th Bending
14	8.669	8.663	0.064	0.879	2.471	10th Bending

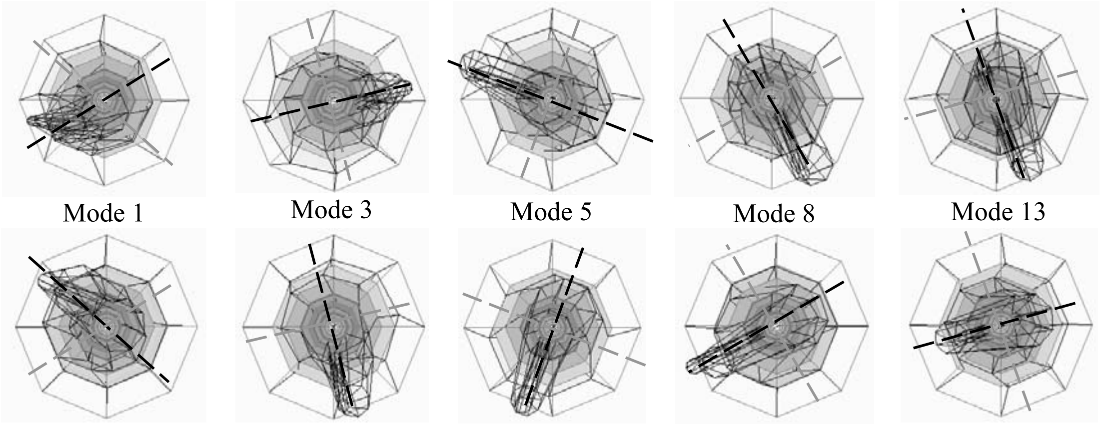
The maximum level of vibration measured on the top of the Minar was lower than 2.5 mg. The 9 data series acquired at 100 SPS (Samples Per Second) were then processed by a decimation of 5 (Nyquist frequency of 10 Hz), with segment length of 516 points and 66.67% window overlap, with 3 projection channels for the subspace identification. 20 structural modes and 30 noise modes were considered for the stochastic estimation of the models. Concerning the frequency results, Table 2 summarizes the experimental values for both of the analyses. The estimated corresponding frequencies, arising from the two methods, are very similar, with an error less than 2%. The closest frequencies are related to the first two modes, with values of 0.79 and 0.81 Hz. Figure 5 shows a perspective view of the defined mode shapes. Ten bending, two torsional, one axial and one undefined mode shapes were estimated. It is stressed that the two first bending modes were not clearly defined at the top, especially at the fourth balcony (Level 4).



Mode 1 Mode 2 Mode 3 Mode 4 Mode 5 Mode 6 Mode 7

Figure 5 : Perspectives of the first seven mode shapes (UPC method).

Figure 6 shows the estimated bending modes, from above. As it can be observed, the bending modes directions are almost perpendicular for the closely spaced pairs of frequencies. This is due to the axisymmetric cross section of the tower.


Mode 1 Mode 3 Mode 5 Mode 8 Mode 13

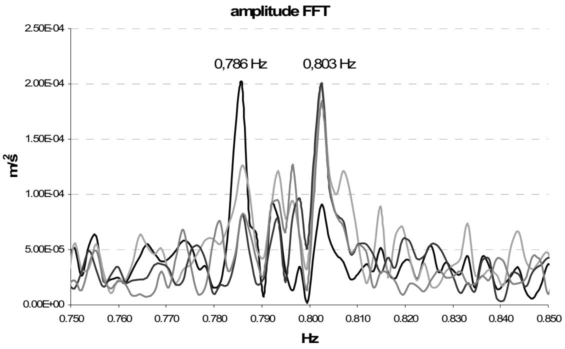
Mode 2 Mode 4 Mode 6 Mode 9 Mode 14

Figure 6 : Bending main directions for bending mode shapes (UPC method).

The Modal Assurance Criterion (Allemang and Brown 1983), the well known procedure to evaluate the correlation between two sets of mode shape vectors (the results vary from 0 to 1, i.e. from bad to good correlation), was used to compare the results emerged from the two modal identification procedures considered. Results are presented in Table 2. Only for the second and the seventh mode the MAC value is lower than 0.70, which means that, globally, the analysis can be considered accurate.

3.3 Second Identification Analysis

By using the sensors disposition reported in Figure 4 at the top (fifth) level of the Minar, Ambient Vibration Tests were also carried out by the University of Padua, by using a different acquisition system. Eight piezoelectric acceleration transducers with the same characteristics respect the first acquisitions were used, connected to a module provided with 24 bit A/D converter acquisition card. A sampling rate of 100 SPS was considered, with a total of 65,536 points acquired. In this case, a single amplitude peak FFT on the complete set of points was performed. The visualization of the FFT function in correspondence of the first resonant peaks and comparative results in the frequency domain respect the first 9 frequencies identified by University of Minho (PC method) are provided in Figure 7. A good match between the obtained frequencies can be noticed (maximum error equal to 2.7%).



Mode shape	FFT amp. peak Hz	PC Hz	Error %
1	0.786	0.785	0.127
2	0.803	0.814	1.351
3	1.950	1.953	0.154
4	2.008	2.009	0.050
5	3.755	3.741	0.373
6	3.866	3.864	0.052
7	---	4.484	---
8	5.992	5.966	2.600
9	6.046	6.073	2.700

Figure 7 : left: amplitude FFT, first resonant peaks, related to the two first mode shapes individuated; right: comparative frequencies results, different acquisition systems.

4 SONIC TESTS

4.1 Introduction

Sonic pulse velocity tests (RILEM Recommendation 1996) were carried out on the Qutb Minar by the University of Padua. Tests were aimed at the qualitative evaluation of the masonry composing the structure. As a first step, the sonic velocity in the external veneer red sandstone was defined. Subsequently, a semi-direct test was carried out on an external corner of the Minar, at the base level, on the outside.

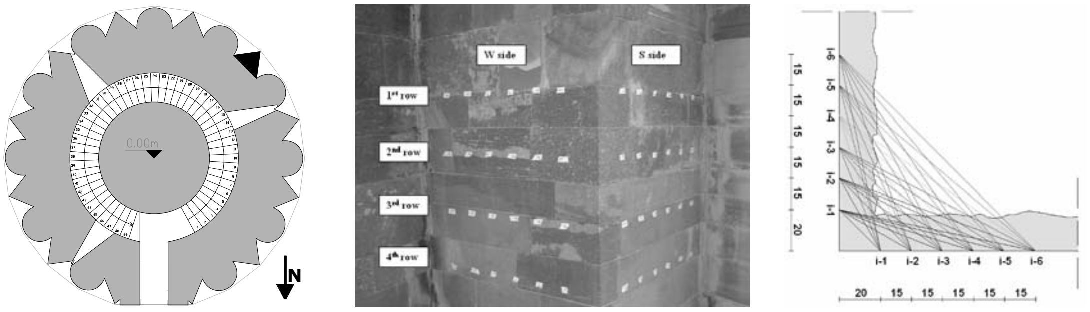
4.2 Stone characterization

A red sandstone specimen of the outer veneer was tested in order to characterize its sonic velocity. The approximate dimensions of the block were 0.40 (length) × 0.20 (height) × 0.20 m (thickness).The test was performed on the long side of the specimen, hitting one side with an instrumented hammer (1 kHz frequency range, 1.1 kg hammer mass) receiving the sonic waves on the other side by means of two piezoelectric acceleration transducers, the same used for the dynamic tests.

The results obtained from the tests were of difficult interpretation due to the high velocity encountered in the stone and to the reduced dimensions of the sample. Averaging on the two considered paths, the defined velocity was equal to 5383 m/s.

4.3 Semi-direct test on a corner, base level

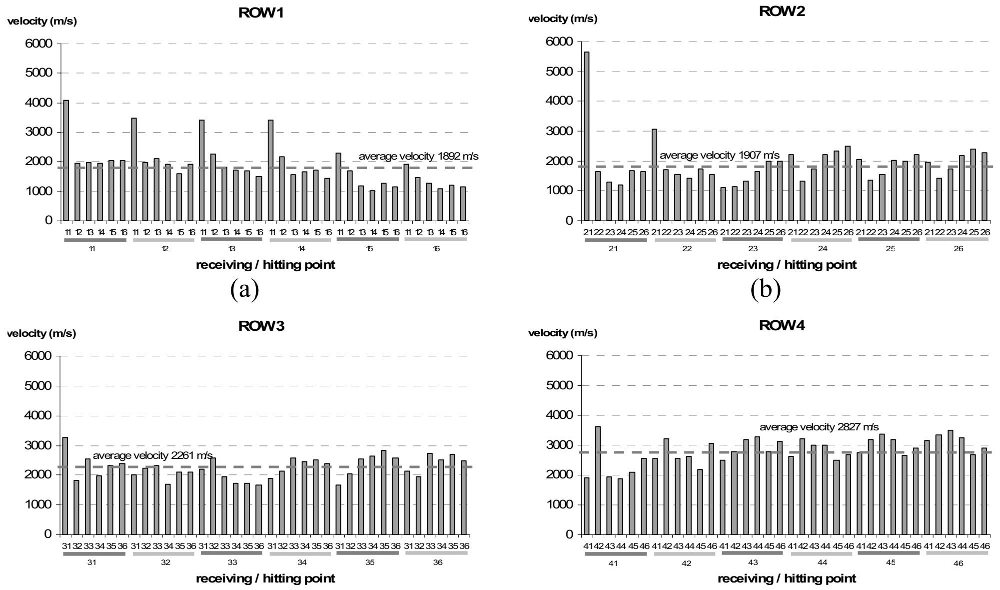
The complex geometry of the cross section of the Qutb Minar, did not allow a simple direct test on two opposite sides, hence it was decided to perform a semi-direct sonic test (transmitter and receiver positioned on two sides of a masonry structure, approximately with an angle of 90°) on one corner, at the base level (Figure 8a). The acquisition grid was rectangular, with six columns and four rows. The spacing between adjacent columns and rows was kept constant and equal, respectively, to 0.15 and 0.30 m. The distance of the first row from the ground corresponded to 0.56 m, and the distance of the first column from the corner, on both sides, was equal to 0.20 m (Figure 8b).



(a) (b) (c)

Figure 8 : (a) view of the base cross section of the Qutb Minar: in black the corner selected for the sonic test; (b) view of the testing grid; (c) test cross section, sonic paths on the i-th row – i =1 to 4.

Test consisted in hitting with the instrumented hammer one side of the corner (the West side). On the other side six acceleration transducers were placed simultaneously, recording only the paths relative to a given row. Hence, per each row (horizontal plane), thirty six paths were recorded (Figure 8c). The overall average velocity value corresponded to 2222 m/s, and the minimum velocity value found was 1017 m/s. Noticeable velocity variations were encountered on the paths supposedly crossing for a big part the internal rubble masonry infill respect the ones referable to the “corner” paths. In correspondence of the paths relative to the closest points to the corner (i1-i1, i = 1 to 4), at different heights, the highest velocity values were found, not too far from the velocity found in the red sandstone sample. Also, an increasing sonic waves velocity was noticed from the 1st to the 4th row, being the average row velocity values (from the 1st to the 4th) equal to 1892, 1907, 2261 and 2827 m/s respectively (Figs. 9a, b, c, d).



(c) (d)

Figure 9 : Velocity histogram, sonic paths, (a) 1st to (d) 4th row.

Considered the fair velocity values encountered, it seems reasonable to hypothesize that no remarkable size voids within the tested masonry or major detachments between the external veneer and the infill are present.

5 CONCLUSIONS

Concerning the preservation of cultural heritage historical buildings, the first step in the structural analysis is the attainment of a sound knowledge of the structure and of the composing materials, in order to proceed in the assessment of the building with “correct” bases. With this perspective and aiming at the seismic protection of the building, several NDT tests were carried out by different research groups on the structure of the Qutb Minar in Delhi, India, to evaluate its structural behavior.

Dynamic tests were carried out considering several test positions, at different heights, in order to proceed with the modal identification of the tower. To double-check the obtained results, different acquisition system were employed. Tests carried out by the University of Minho, Portugal, were aimed at the definition of the modal parameters (natural frequencies, mode shapes and damping coefficients) of the Minar, also to evaluate the degree of connection between the central shaft of the tower and the external shell.

The modal identification procedures considered gave satisfactory results. Several natural frequencies and corresponding modes were defined, with reduced errors in the frequency values and a general high correlation (MAC values) between the mode shapes defined with the two time domain methods used. The comparison with the results obtained by the University of Padua indicated a good match between the obtained frequencies, with reduced errors.

Difficulties in obtaining a clear definition of the two first mode shapes in the upper levels (the central shaft seemed to present higher displacements respect the external shell) can be possibly correlated to a decreased degree of connection between the external and the internal parts of the structure, at the top of the tower. To ascertain this observation, a more refined net of sensors would however be required.

Results emerged from sonic pulse velocity tests, carried out in semi-direct configuration on a corner at the base of the tower, qualitatively defined a masonry with fair compaction characteristics. In fact no major inconsistencies, depicting remarkable detachments between the leaves of the external shell masonry wall or medium/big size flaws, were detected.

The obtained data will be used for the validation of the preliminary numerical models considered for the definition of the dynamic test layout, in order to have reliable tools for the seismic assessment of the Qutb Minar.

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