EVALUATION OF THE STRUCTURAL INTEGRITY OF HISTORICAL STONE MINARETS

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ABSTRACT :

Minarets are tall, slender structures that define the skyline of old Cairo and the historical ones stand as a testimony to the ingenuity of the engineer at that time. This research investigates the dynamic parameters for two identical stone minarets using ambient vibration testing technique and utilizing test results to update their structural models. The procedure is advantageous in the assessment of historical structures due to the fact that it is non-destructive. It is capable of extracting unique characteristics of the structure and may be used for health monitoring as well as fine-tuning of theoretical models.

KEYWORDS: Minarets, monuments, ambient vibration, finite element modeling, modal analysis.

1. INTRODUCTION

Minarets have always fascinated people living in Cairo as well as visitors. Some of them are dated as far as 600 A.D., the tall, slender structures are visible all over the old Cairo area and stand as a testimony to the ingenuity of the engineer at that time. However, the inventory of historical minarets is decreasing due to extreme loading (mainly due to earthquakes) as well as the degradation of the construction material due to aging process and environmental conditions. This paper documents the procedure used for the assessment of two stone minarets, which included both ambient vibration testing as well as numerical modeling. The need for understanding the dynamic behavior of historical minarets and for achieving a structural model capable of simulating the actual response as close as possible has prompted researchers to try ambient vibration testing. The procedure is non-destructive, and the dynamic characteristics obtained by processing the measured data may be used to tune a finite element model and thus increase the confidence in the theoretical model. The measured dynamic characteristics may be repeated after a certain period of time, to be used for condition monitoring of the structure. The concept has been adopted for modern as well as historical structures (Binda et al., 2001, and Zaki et al., 2006). However, each historical structure is unique and poses new challenges.

2. THE MINARET

The subjects of this research are two identical minarets, constructed on two adjacent structures – the mosque and khankah (boarding house for a religious sect) of Prince Shaykoun (Fig.1). Constructed around 1350 AD, the two minarets are 20 meters high and are supported on the mosque and khankah entrance vaults. The minarets have a square base with side dimensions 4.3 meters, and the minaret section is transformed from the square into a circle via a transition octagonal section. At the top of each minaret is an onion-shaped ornament. Figure 2 shows a schematic drawing for the minarets, which was utilized for developing the finite element models. The minarets are particularly interesting due to the fact that the ornament at the top of one of the minarets fell down during the October 12, 1992 Dahshour Earthquake (Mourad and Osman, 1994). The minaret was later restored and the ornament returned to the top of the minaret (Fig. 3).

Figure 1 The two minarets of Prince Shaykhou.

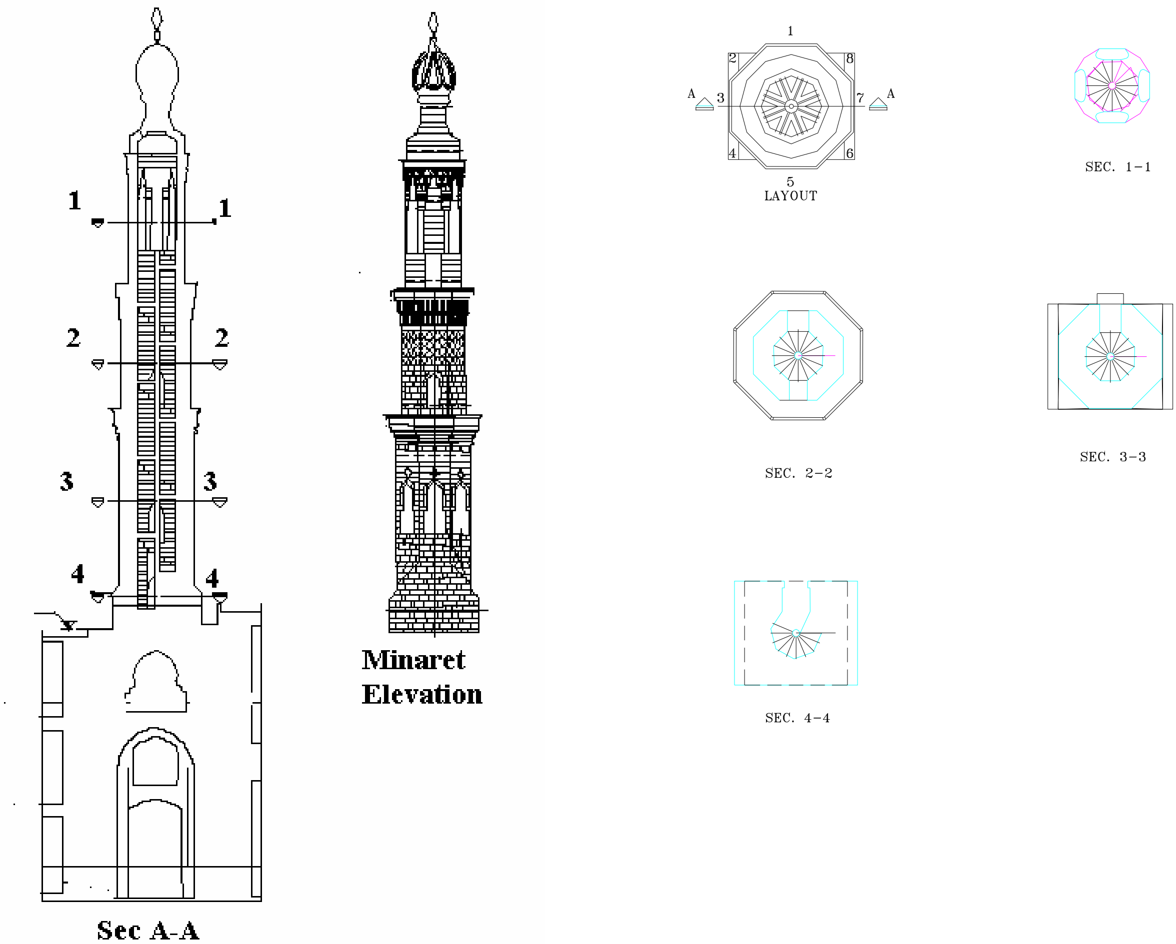


Figure 2 Schematic drawings for the minarets of Prince Shaykhou.

Figure 3 Pictures of minarets of Prince Shaykhou during restoration after the October 12, 1992 earthquake.

3. EXPERIMENTAL STUDY

To evaluate experimentally the dynamic characteristics of the minarets (natural periods and mode shapes), the minarets were instrumented by an array of accelerometers. The ambient excitations resulted from both wind and heavy traffic moving loads exists along adjacent road. Two types of accelerometers were used in the measurements, the PCB 393B04, and the BK2867. Both accelerometers have very low frequency response, high resolution as low as 3×10^{-6}g, and lightweight. The accelerometers were arranged as shown on Fig.4 diagonally on both sides of the minaret shaft to be able to capture any torsional modes and measurement were taken in uni-direction assuming that modes are symmetrical due to minaret geometrical and stiffness symmetry. All sensors were then connected to a data acquisition system using low noise shielded cables as shown on Fig. 5a. The data acquisition system included the conditioner module which provided power to the sensors, eliminated high frequency components, and amplified the low amplified signal. The A/D conversion card used was a 16 channel 16 bits high speed card with simultaneous sampling and A/D conversion characteristics. Analogue anti-aliasing filters were included in the signal conditioner module. The system was attached to a dedicated laptop in which all the measurements were controlled and recorded.
The accelerometers were firmly attached to the stone walls using special devises that was specially designed to facilitate installation and to ensure that all vibrations are fully reproduced into the sensor in the required frequency range (Fig.5b). A 100 samples per second rate was used to sample the measured response and the signals were recorded for durations of 600 seconds. Figure 6 shows a sample for the recorded time histories.
The collected response data due to ambient excitation were then analyzed to obtain the modal characteristics of the minaret. Fortunately the ambient excitations were strong enough to produce satisfactory amplitudes for more reliable modal analysis. All signals simultaneously recorded from the shown locations were subjected to signal processing. The signals were de-trended, applied by low pass filtering for eliminating frequencies higher than that in the range of interest (1-20 Hz) and applied by Hanning windows to confirm periodicity of the signals and each selected part of it. The processed records were then examined for frequency peaks after conversion into the time domain. Cross spectral analysis expressed more the structural peaks since any other arbitrary peaks from the ambient noise would diminish when using cross spectrums (Fig.7). To construct the cross spectral matrix The constitutive data blocks were examined one by one for acceptance or rejection.
The examination of the data block was done in both the time domain and frequency domain. Typically rejected data blocks were those with unresolved sudden or sever changes in the time history or those where the signal to

noise ratio was remarkably low or those when the repetitive spectral peaks are concealed by noise resonances. After the suitable cross spectral matrix has been obtained, two methods for modal identification were used, the Frequency Domain Decomposition (FDD) (Brincker et al., 2000) and the Eigen Realization Algorithm (ERA) (Huang, 1999).

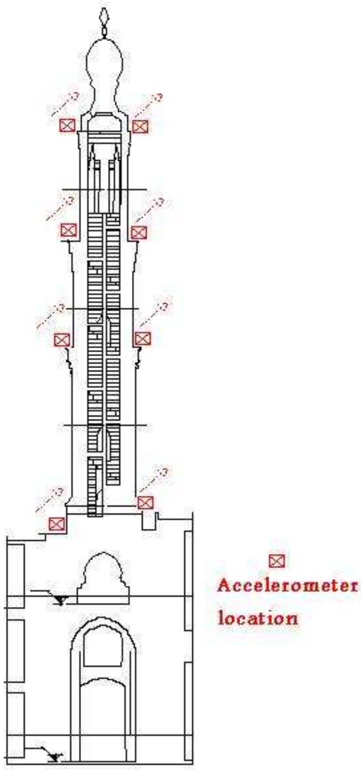


Figure 4 Locations of the accelerometers along the minaret height

(a-Data acquisition system) (b- accelerometer with fixing devices)

Figure 5 Photos of the used instruments

The software MODAL (Brownjohn et al., 2001) specially developed for modal identification was used to implement the methods. It was possible to obtain the modal characteristics, the frequencies and the mode shapes. The results are shown on Fig.8.

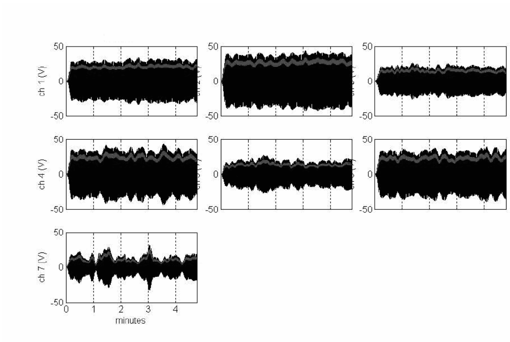


Figure 6 Time History Records

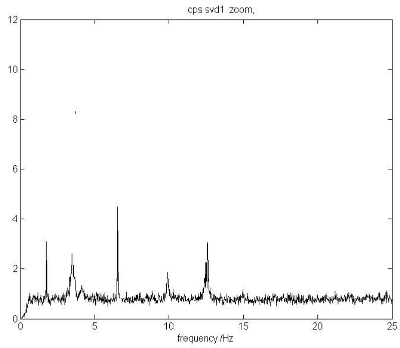
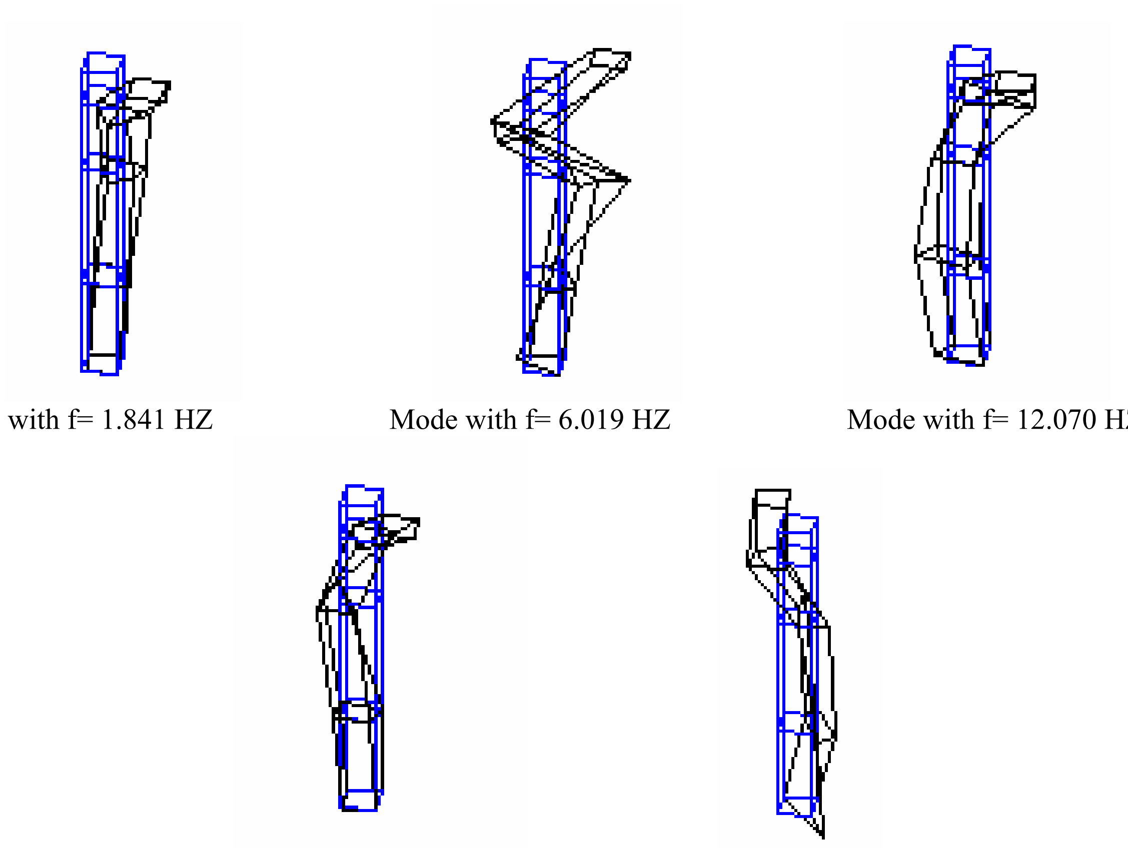


Figure 7 Sample Spectrum of the signals



Mode with f= 1.841 HZ

Mode with f= 6.019 HZ

Mode with f= 12.070 HZ

Mode with f= 16.620 HZ

Mode with f= 25.420 HZ

Figure 8 Sample measured Mode Shapes with their frequencies

4. ANALYTICAL STUDY

Following the experimental measurements, an analytical study was performed. Within this study, the minaret body which consists of the minaret shaft supported on a vault was modeled using the finite element technique. For such purpose, the linear elastic finite element computer program SAP2000 was utilized (SAP2000 (2007)). Eight nodes solid element were used to simulate the minaret and mosque walls. Shell elements were used to simulate the helical stairs inside the minaret shaft and the onion ornament as shown on Fig.9. In preparing such model all fine details such as openings, recesses in the walls, and changes in wall cross-sections were accurately simulated as much as possible to create a realistic model that is as close as possible to the reality. However, due to complexity of minaret configuration, many of the features were approximated. Results indicated that the first ten modes were associated mainly with the shaft response, and due to high stiffness of the mosque walls supporting the minaret shaft, these walls did not contribute to the minaret behavior as shown on Fig.10 which shows sample of the recorded mode shapes

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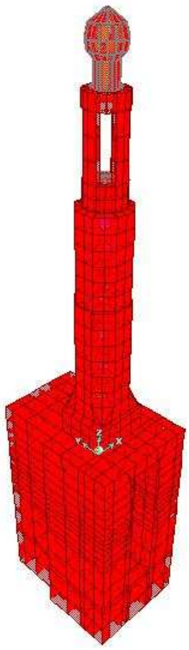
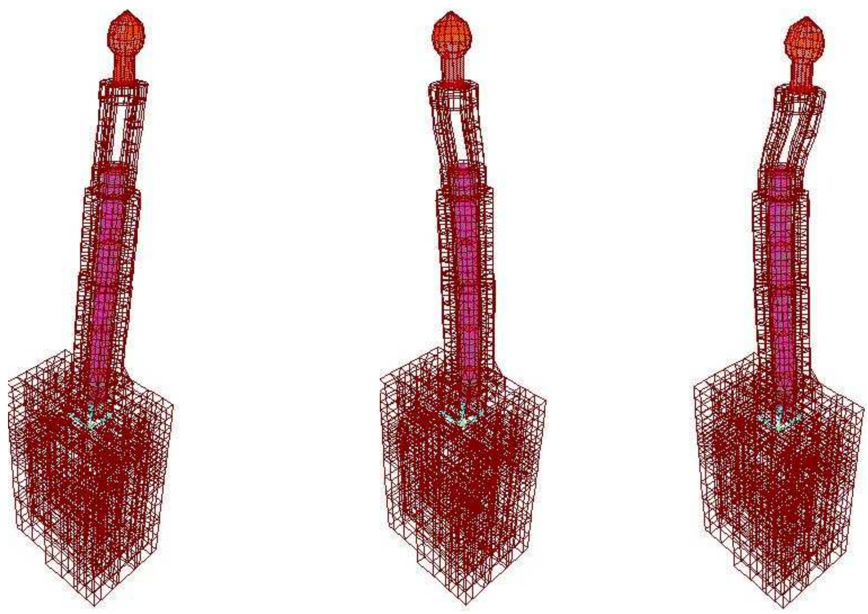


Figure 9 Minaret configuration



Mode 1 Mode 3 Mode 6

Figure 10 Sample of estimated Mode shapes

Since the mosque body was not contributing to the minaret dynamic characteristics, it was decided to focus the study on examining the response of the minaret shaft. For such purpose, the more sophisticated multi-purposed finite element program, COSMOS/M was utilized. This program allows for importing the model geometry from the three-dimensional drawing files giving more detailed and accurate presentation. The three dimensional tetrahedral element available in the program was used to model the minaret shaft as shown on Fig.

11 (COSMOS/M, 1997). As can be noted the model resemble to a great extent the real structure.
It is worth mentioning that the finite element model utilized assumed that the construction material is homogeneous, isotropic and continuous, i.e. lumping filling, mortar and stones together. Although this assumption is not matching the reality, previous research studies and experimental tests conducted in this regard showed that assuming average mechanical properties for the wall assemblages based on the values of mechanical properties for the material forming it can give a reasonable estimate of the real behavior (El Attar and Osman, 2004). For such purpose, the mechanical properties for elements forming the wall and the towers were assumed to have an average specific gravity of 20000 N/m^3, a Poisson's ratio of 0.2, and an initial elastic modulus of 80 MPa.
To study the dynamic behavior of the minaret, a frequency analysis was conducted by COSMOS/M program. The analysis provided the mode shapes and the natural periods for the minaret as listed in Table 1, whereas Fig.12 shows a sample of the computed mode shapes.

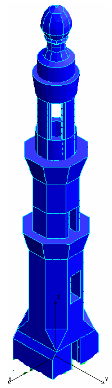


Figure 11 Finite element model for the minaret shaft

5. CORRELATION BETWEEN ANALYTICAL AND EXPERIMENTAL RESULTS

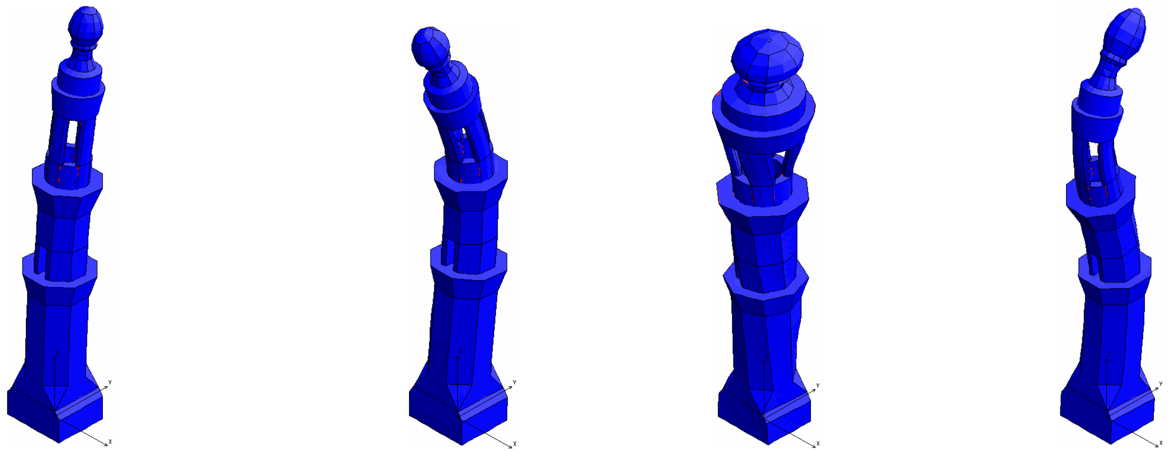
Comparing the periods indicated in Table 1 and Fig. 8 showed that the natural periods for the analyzed model is lower than that recorded from the experiment. This indicates that the model is more rigid compared to the real structure due to softening of the material or possible flexibility of the roof supporting the minaret. Consequently, it was decided that the analytical model need to be soften through reducing the elastic modulus to 50 MPa instead of 80 MPa.
The model was re-analyzed and the mode shapes and their natural periods were recorded. Table 1 lists the natural period of the estimated modes with that of the measured modes. Comparison showed that they closely resemble each other and follows the same pattern. Such finding gave an indication that the developed finite element model is accurate and can simulate the minaret response. On the other hands, correlation between the measured and calculated periods were found to have a maximum error estimated in calculating the natural period in about 5.45%

Table 1: Comparison between measured, and calculated natural periods

Mode Number	Preliminary Calculated Period (sec.)	Measured Period (sec.)	Updated Calculated Period (sec.)	Percent. Difference (measured vs. updated)
1	0.452784	0.5431	0.5727	5.450%
2	0.420108	0.5431	0.5314	2.154%
3	0.131682	0.1661	0.1665	-0.240%
4	0.128587	0.1661	0.1626	2.107%

CONCLUSIONS

The dynamic behavior of the historical minarets of Shaykoun was evaluated using ambient vibration testing. The minarets natural periods and mode shapes were experimentally identified and measured using will placed instruments. A three dimensional Finite Element model was constructed based on the actual geometry of the minarets as surveyed from the site. The model was then updated using the results of the experimental measurements. Good correlation was noted between the dynamic characteristics estimated using the updated model and the results obtained from the ambient vibration tests. Consequently, this updated model can be used with high confidence in the future to predict the minaret response to earthquake loads.



Mode 1 Mode 3 Mode 5 Mode 6

Figure 12 Sample of mode shapes for the minaret

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