DOI: http://dx.doi.org/10.12989/sss.2008.4.2.221

The use of SMA wire dampers to enhance the seismic performance of two historical Islamic minarets

Adel El-Attar*, Ahmed Saleh, Islam El-Habbal, Abdel Hamid Zaghw and Ashraf Osman

Cairo University, Giza, Egypt

(Received September 29, 2007, Accepted November 22, 2007)

Abstract. This paper represents the final results of a research program sponsored by the European Commission through project **WIND-CHIME** (**W**ide Range Non-**IN**trusive **D**evices toward **C**onservation of **HI**storical Monuments in the **ME**diterranean Area), in which the possibility of using advanced seismic protection technologies to preserve historical monuments in the Mediterranean area is investigated. In the current research, the dynamic characteristics of two outstanding Mamluk-Style minarets, which similar minarets were reported to experience extensive damage during Dahshur 1992 earthquake, are investigated. The first minaret is the Qusun minaret (1337 A.D, 736 Hijri Date (H.D)) located in El-Suyuti cemetery on the southern side of the Salah El-Din citadel. The minaret is currently separated from the surrounding building and is directly resting on the ground (no vaults underneath). The total height of the minaret is 40.28 meters with a base rectangular shaft of about 5.42 × 5.20 m. The second minaret is the southern minaret of Al-Sultaniya (1340 A.D, 739 H.D). It is located about 30.0 meters from Qusun minaret, and it is now standing alone but it seems that it used to be attached to a huge unidentified structure. The style of the minaret and its size attribute it to the first half of the fourteenth century. The minaret total height is 36.69 meters and has a 4.48 × 4.48 m rectangular base. Field investigations were conducted to obtain: (a) geometrical description of the minarets, (b) material properties of the minarets' stones, and (c) soil conditions at the minarets' location. Ambient vibration tests were performed to determine the modal parameters of the minarets such as natural frequencies and mode shapes. A 1/16th scale model of Qusun minaret was constructed at Cairo University Concrete Research Laboratory and tested under free vibration with and without SMA wire dampers. The contribution of SMA wire dampers to the structural damping coefficient was evaluated under different vertical loads and vibration amplitudes. Experimental results were used along with the field investigation data to develop a realistic 3-D finite element model that can be used for seismic risk evaluation of the minarets. Examining the updated finite element models under different seismic excitations indicated the vulnerability of such structures to earthquakes with medium to high *a*/*v* ratio. The use of SMA wire dampers was found feasible for reducing the seismic risk for this type of structures.

Keywords: shape-memory alloy; seismic mitigation, SMA dampers; historical monuments.

1. Introduction

Historically, Cairo city used to be named the city of one thousand minarets (Abouseif 1987). It possesses a large inventory of historical Islamic minarets that date back to the early Islamic period (641 A.D). Following the 1992 Dahshur earthquake, large numbers of these minarets were recorded to experience different levels of damage. Examining damage records indicated that minarets built during the Mamluk period were among the most severely hit. Irregular mass and stiffness distribution along

*Corresponding Author, E-mail: adelattar291258@link.net

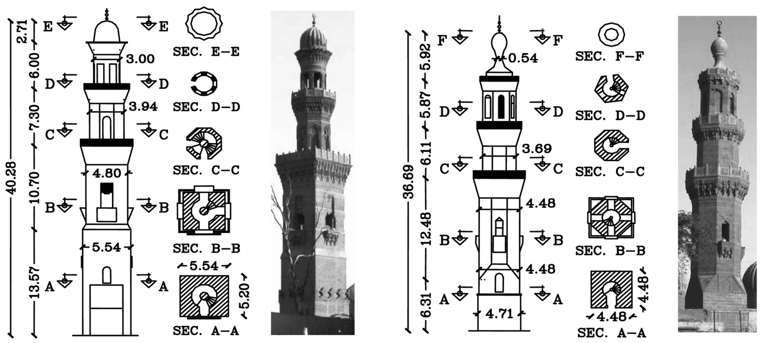
their heights with large displayed stalactite carving made them more vulnerable to damage during earthquakes compared to other minaret styles (Aly 1996).

In 2003, a scientific research program co-sponsored by the European Commission (WIND-CHIME) was initiated with the objectives of finding innovative techniques and appropriate seismic protection systems for preserving endangered monuments similar to Mamluk minarets. This paper summarizes the results of an experimental and analytical study that was conducted to assess the seismic response and dynamic behavior of two minarets belonging to this era, namely, Qusun minaret constructed in 1337 A.D (736 H.D) and Al-Sultaniya minaret (known also as the southern minaret of Qusun) constructed in the 1340 A.D (739 H.D).

2. Historical and geometrical description

The minaret of Qusun is located in the Al-Suyuti cemetery on the southern side of the Citadel and shown in Fig. 1(a). It has an impressive rectangular stone shaft carrying an octagonal second story with a stone Mabkharah on top. From the first glance, it seems that the minaret is free standing structure. However, a closer look indicates that it was constructed by the prince Seif Eldin Qusun Al-Saki as a part of his monastery (Khanqa) for teaching Islamic rules. This is clear from the crenellation at the rectangular section. Furthermore, the entrance to the minaret shaft, which is above this crenellation, shows the level of the roof, which must have been reached by the staircase outside the minaret shaft. After the destruction of the adjacent monastery, the minaret is currently separated and directly resting on the ground. The total height of the minaret is 40.28 meters with the first balcony at 16.80 meters from the ground level, the second balcony at 24.40 meters and the third one at 31.85 meters. The base rectangular shaft is about 5.20 × 5.54 meters and it extends to the first balcony. On 1888, severe deep cracks within the minaret lower body were observed. In response, the Arabic Committee Restoring Islamic Heritage restored this part of the minaret by using four steel rods installed to tie the minaret four side walls together. In addition, the committee installed stone parapets to the balconies and repaired the damaged part from the top cap “Mabkharah”.

The minaret of Al-Sultaniya was built in the 1340 A.D (739 H.D). It has an extraordinary construction displaying ambitious proportions and magnificent treatment of stone. The minaret now stands alone and not connected to any buildings but it seems that it used to be attached to a huge unidentified structure (its staircase starts from a level believed to be the roof of the surrounding



(a) Qusun Minaret (b) Al-Sultaniya Minaret

Fig. 1 Qusun and Al-Sultaniya minarets

building). The minaret has three balconies and its total height is 36.69 meters as shown on Fig. 1(b).

3. Construction materials

Examining the minarets walls, and available records, indicated that the minaret bodies were constructed in two layers of flat-faced limestone blocks, namely external and internal with each layer composed of blocks of different dimensions connected together by mortar. Between the external and the internal layers, a filling material consisting of cohesive and cohesionless materials highly chaotic with limestone was placed. For the top parts (typically from second balcony), a single layer of limestone blocks was used for construction. Material properties of the minaret limestone and the fill are given in Table 1.

3.1. Local soil conditions

The soil stratification at the site was assumed based on boreholes obtained from close by projects (El-Attar 2004). Local soil was found to be consisting of a fill layer followed by sandy layers over which the minarets are founded. The sand layer extends down to the rock level. In the current study, soil sub-grade reaction was taken equal to 7.5 N/mm^3.

3.2. Ambient vibration tests

Ambient vibration responses of the two minarets were measured using eight-uniaxial and two-triaxial force balanced accelerometers produced by Kinemetrics with +/- 0.25g range (type Episensor FBA ES-U, and Episensor FBA ES-T). The accelerometers were placed at various locations on the minarets as shown in Fig. 2 (Bongiovanni, 1998). The accelerometers were connected through dedicated cables to a 16channel signal conditioning unit type Kinemetrics VSS-3000, which in turn was connected to a Laptop computer equipped with a high speed “I/O Tech” data acquisition card. Due to the expected high stiffness of the minarets, data were sampled at 100 samples per second, resulting in a nyquist frequency of 50 Hz.

Vibration readings were recorded for at least five minutes. Each test was repeated 5 times to examine the repeatability of the results. Data were then analyzed to obtain natural frequencies, mode shapes and damping ratios. Fig. 3(a) shows a sample of the linear power spectra of the X-direction data for accelerometers number 1, 4, and 7. The phase angle records of each waveform are shown in Fig. 3(b). It can be seen that there is a fundamental mode at frequency 1.17 Hertz in the X-direction, and that all three accelerometers were moving in the same direction. The mode shape at this frequency is obtained

Table 1 Minaret material properties

Property	Limestone	Fill
Elastic modulus (MPa)	3625	50
Specific gravity (KN/m^3)	20.9	20.0
Poisson’s ratio	0.20	0.20
Compressive strength (MPa)	14.69	
Tensile strength (MPa)	1.34	

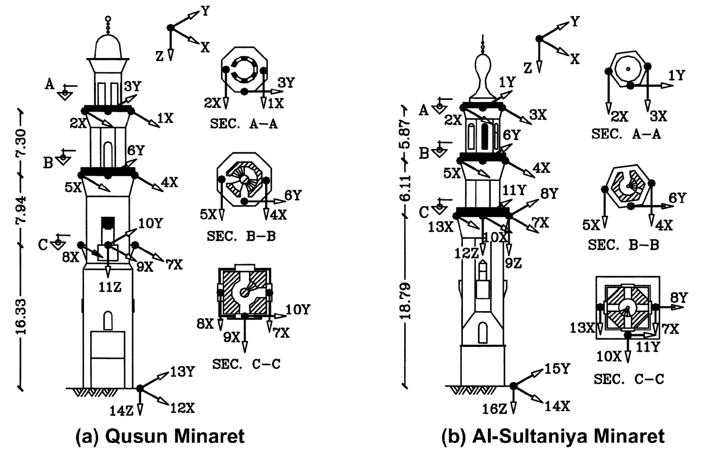


Fig. 2 Accelerometer locations on Qusun and Al-Sultaniya minarets

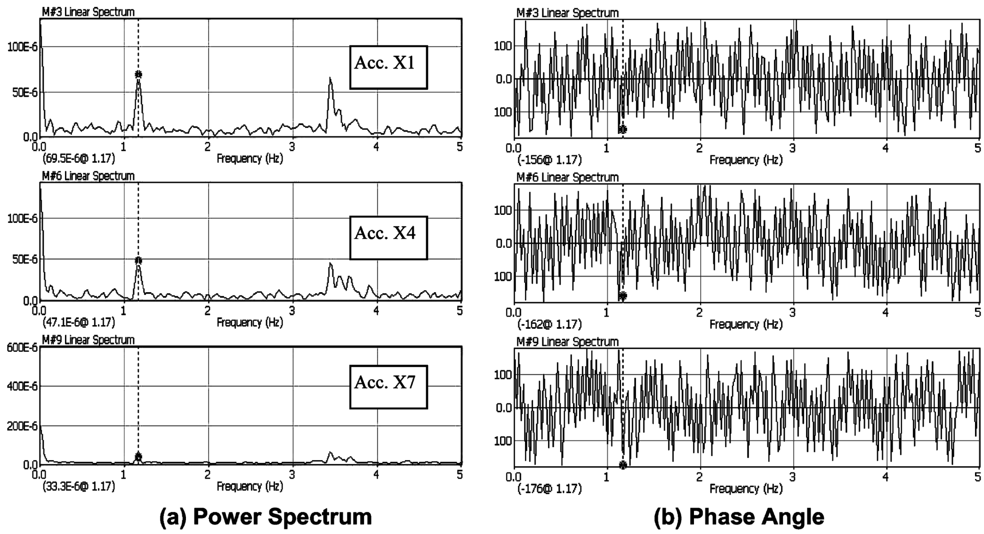


Fig. 3 Sample of the ambient vibration test results obtained for qusun minaret (Second Mode at 1.17 Hz)

by plotting the linear power spectrum amplitude at each level. Fig. 4(a) shows the mode shapes of Qusun minaret corresponding to the first two fundamental frequencies in the X-direction. The first two mode shapes in the Y-direction are also given in Fig. 4(b). Similar plots were obtained for Al-Sultaniya minaret.

Table 4 gives the measured fundamental frequencies and modes of vibration of both Qusun and Al-Sultaniya minarets for the first eleven modes. It can be seen from this table that, despite the different shapes of the two minarets, their modes of vibration are identical, where the first four modes are bending modes; the fifth is a torsional mode and the sixth and seventh are again bending modes.

3.3. 1/6th scale model test

The tested model was assumed to represent a 1/16th scale of the actual Qusun minaret. The complicated

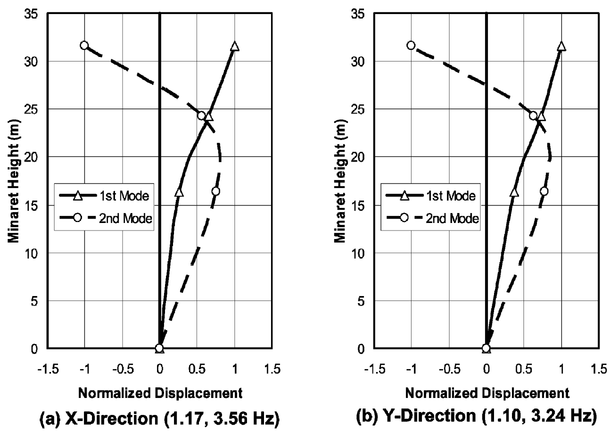


Fig. 4 Measured first two mode shapes of Qusun minaret

shape of the real minaret was simplified into a cantilever type model that faithfully reflects the main aspects of the minaret conditions regarding; (a) geometry, (b) stress level, and (C) dynamic response. The similitude requirements listed in Table 2 were implemented.

The same limestone and mortar used in the actual minaret was implemented in the small-scale model. The test specimen had a clear height of 2.0 meters and a hollow cross-section of 40×40 cm and a 20×20 cm void. The model was built using 20×10×10 stones. Laboratory tests were carried out to determine the mechanical properties of the used limestone, material properties of the model limestone are given in Table 1 above.

3.4. Test set-up

Fig. 5 shows the load set-up used for the free vibration test of the model minaret. A 1.5×1.5×0.5

Table 2 Similitude requirements for the $1/16^{th}$ scale model

Scaling Parameter	Symbol	True Replica Model	$1/16^{th}$ Scale Model
Length	S_l	S_l	16
Time	S_l	$S_l^{1/2}$	4
Frequency	S_ω	$1/S_l^{1/2}$	0.25
Velocity	S_v	$S_l^{1/2}$	0.625
Gravity Acceleration	S_g	S_v	Neglected
Acceleration	S_a	1.0	1.0
Mass Density	S_R	S_E / S_l	256
Strain	S_ε	1.0	1.0
Stress	S_σ	S_E	1.0
Young's Modulus	S_E	S_E	1.0
Specific Stiffness	S_E / S_ρ	S_l	1.0
Force	S_F	$S_E\, S_l^2$	256
Displacement	S_d	S_l	16
Energy	S_{En}	$S_E\, S_l^3$	4096

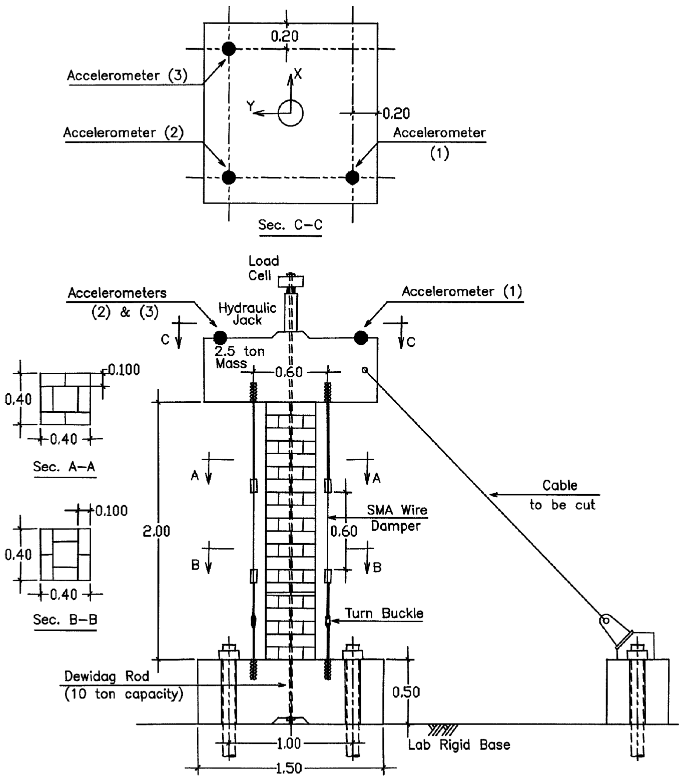


Fig. 5 Load set-up of the 1/16th scale model minaret

meters reinforced concrete base was used to connect the model to the laboratory rigid base. The model minaret was embedded for 10.0 cm into the reinforced concrete base to simulate a base fixation. The reinforced concrete base was then connected to the laboratory rigid base through four 10cm diameter steel bolts. A 1.0×1.0×1.0 reinforced concrete mass (25 KN) was placed on top of the model. A 10.0 cm socket was again used to attach the top mass to the model minaret.

As the cross-sectional area of the tested model was equal to 1200 cm^2, the 25 KN mass produced a vertical stress on the shaft (model) equal to 0.21 MPa, which is less than the 0.50 MPa typically obtained for the lower stone layers in the actual minaret. For this reason, and in order to produce a state of stress similar to that typically developed in the real structure, a prestressing rod with diameter 25mm was used to apply vertical compression to the model. The vertical force was then applied through a hollow hydraulic jack attached to the top mass and was monitored through a dedicated load cell (Fig. 4). Using this technique, the vertical stresses on the model stones could be raised to a realistic level without adding extra mass on top, which minimized the hazard during the free vibration test (Fig. 6).

The model was instrumented by three tri-axial force balanced accelerometers produced by Kinemetrics with +/-0.25 g range (type Episensor FBA ES-T). The accelerometers were placed on top of the 25 KN mass as shown in Fig. 5. The same data acquisition system used for the ambient vibration test was used for the free vibration one. Due to the expected high stiffness of the model, data were sampled at 200 samples per second, resulting in a nyquist frequency of 100 Hz. The tests on the model minaret were carried out without SMA wire dampers and with SMA wire dampers.

The SMA wire dampers consisted of 3.5 mm diameter, 600 mm long wires. Four of these wires were

Fig. 6 The 1/16th scale model minaret tested at the concrete research laboratory, Cairo university

attached to the top concrete cap and the bottom reinforced concrete base using strong steel cables and a turnbuckle. The turn buckle was used to stress the SMA wires to a strain level of 0.01 (10000 μe). This strain level was found to be the optimum working strain for the SMA wire dampers from previous test results.

3.5. Test procedure

Several free vibration tests were carried out on the model minaret. The test parameters were (a) the axial compressive stresses, and (b) the cable pull-out displacement. To examine the effect of the compressive stress level at the minaret base on its dynamic response, three levels of axial load were tested; that is 25 KN, 75 KN and 125 KN corresponding to vertical stresses of 0.21 MPa, 0.625 MPa and 1.04 MPa respectively. For each of these stress levels, the model was tested under lateral displacements of 1, 2, 3, 4, and 5 mm in both X and Y directions resulting in $3\times5\times2 = 30$ test runs. Each test run was repeated 3 times to examine the repeatability of the test results. These 30 runs were carried out without any SMA wire dampers and with SMA wire dampers.

The inclined cable shown in Fig. 5 was pulled using a turnbuckle. The model displacement during the cable tensioning was monitored using a 0.01 mm accuracy dial gage. When the required displacement was reached, the cable was suddenly cut using an electric saw. The model acceleration response was recorded using the previously described data acquisition system.

3.6. Test results

Figs. 7 through 10 are examples of the recorded time-acceleration records during the free vibration tests with their associated power spectrum. All data were low passed at a 6 Hz frequency to eliminate all noise and response from other modes. The logarithmic decrement technique (equation 1) was used to obtain the damping ratio associated with the first mode of vibration.

$$\ddot{X}(t) = \ddot{X}(t_0) \times e^{-\omega\xi t} \tag{1}$$

Where;

$\ddot{X}(t)$ = acceleration at time (t)

$\ddot{X}(t_0)$ = acceleration at time (t_0)

ω = circular frequency

ξ = damping ratio (as related to critical damping)

Test results are summarized in Table 3 for both X & Y directions, with and without SMA application.

Inspection of the test results in Table 3 indicates that, the presence of SMA dampers increases the damping ratio in both X and Y directions. The slight increase is attributed to the small size of the SMA wires as compared to the large size of the test specimen. Fig. 11 shows the effect of the presence of SMA on the measured damping ratio. It can be seen from this figure that there is always an increase in the damping ratio, but the effect of the SMA was more significant at lower axial force.

4. Analytical models

The two minarets were modeled using the finite element technique. Eight-noded solid elements were used to simulate the external, internal, and fill regions. Shell elements were used to simulate the helical stairs. All fine details including, openings, recesses in the walls, and changes in the minaret cross-sections were faithfully replicated to create realistic models that are as close as possible to the real structures.

Material properties adopted in the finite element models of both minarets are listed in Table 1. These parameters were extracted from laboratory tests carried out on samples taken from the minarets bodies.

A linear elastic dynamic analysis was performed. The used damping ratio according to the small-scale model test was equal to 2%. This ratio is expected to increase to 3% when properly designed SMA wire dampers are used. The analytical study was performed using both damping ratios. Although, the behavior of the construction materials under severe loading conditions is expected to be nonlinear-inelastic, in addition to the inherent heterogeneous nature of stone walls interconnected through weaker

Table 3 Summary of free-vibration test results

SMA	P (KN)	Frequency (Hz)	Circular Frequency ω (rad/sec.)	Damping Ratio ξ (% of Critical Damping)	Test Direction
Without SMA	25	4.1	25.76	2.91	
	75	4.49	28.21	1.24	ξ
	125	4.69	29.47	1.09	
	25	3.71	23.31	1.93	
	75	3.91	24.57	1.56	Y
	125	4.3	27.02	1.48	
With SMA	30	4.1	25.76	3.19	
	80	4.49	28.21	1.24	X
	130	4.69	29.47	1.17	
	30	3.71	23.31	2.14	
	80	3.9	24.50	1.55	Y
	130	4.3	27.02	1.48	

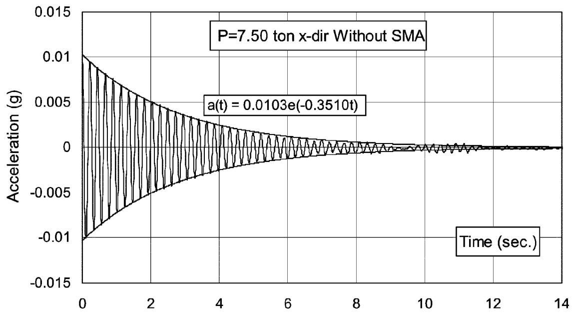


Fig. 7 Free vibration acceleration record in X-direction under 75 KN vertical compression (Without SMA Application)

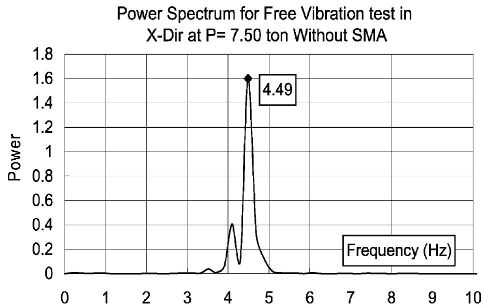


Fig. 8 Power spectrum of the acceleration record in X-direction under 75 KN vertical compression (Without SMA Application)

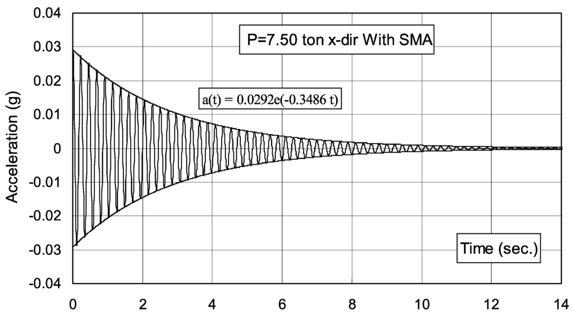


Fig. 9 Free vibration acceleration record in X-direction under 75 KN vertical compression (With SMA Application)

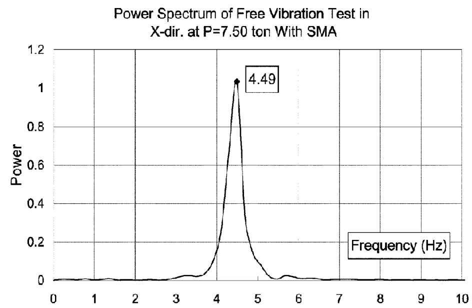


Fig. 10 Power spectrum of the acceleration record in X-direction under 75 KN vertical compression (With SMA Application)

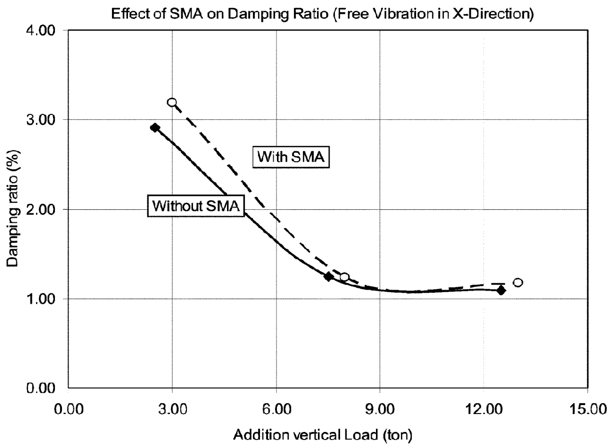


Fig. 11 Effect of SMA on damping ratio in X-direction

mortar layers, it was decided at this stage that linear elastic analyses will be sufficient to provide the distribution of stresses within minarets bodies and to obtain the basic dynamic characteristics. Fig. 12 shows mode shapes number 1, 3, 5 and 7 of both Qusun and Al-Sultaniya minarets.

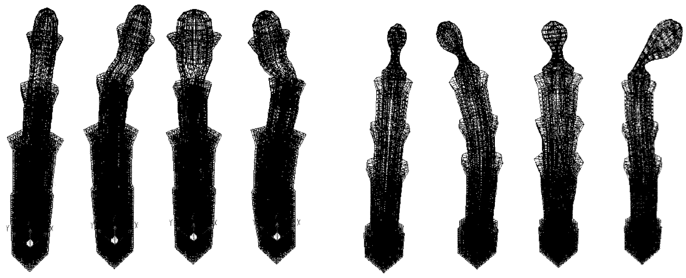


Fig. 12 Mode shapes obtained from the refined finite element models

Table 4 Minarets fundamental frequencies and modes of vibration

Mode	Qusun minaret			Al-Sultaniya minaret		
	Measured	F.E. Model	Mode description	Measured	F.E. Model	Mode description
1	1.10	1.10	1st bending Y-dir	1.03	0.99	1st bending X-dir
2	1.17	1.15	1st bending X-dir	1.10	1.00	1st bending Y-dir
3	3.47	3.24	2nd bending Y dir	3.54	3.77	2nd bending X-dir
4	3.56	3.32	2nd bending X-dir	3.59	3.86	2nd bending Y-dir
5	5.62	5.32	1st torsional	4.39	5.33	1st torsional
6	6.79	6.57	3rd bending X-dir	5.54	6.76	3rd bending X-dir
7	6.84	6.78	3rd bending Y-dir	5.54	6.79	3rd bending Y-dir
8	-----	7.27	2nd torsional	8.72	9.57	4th bending Y-dir
9	-----	9.31	Axial vertical	9.30	9.71	4th bending Y-dir
10	11.65	10.06	4th bending Y-dir		10.27	Axial vertical
11	12.0		4tth bending Y-dir	12.50	12.06	2nd torsional

As the preliminary finite element runs indicated some differences between the measured and the calculated frequencies, the finite element models were refined to match the first four fundamental frequencies of each minaret. This was done by slightly adjusting the soil modulus of sub-grade reaction and the stone modulus of elasticity. The updated finite element model results for the first eleven modes are given in Table 4 for both Qusun and Al-Sultaniya minarets. It is interesting to observe that the mode shapes obtained from the linear elastic finite element model were reasonably close to those measured experimentally. Although, in the current case, the presence of SMA wire dampers did not significantly change either the fundamental frequencies or the mode shapes, it has pronounced effect on the minarets damping ratio. It is expected that, if larger wire sizes were used, the compressive force due to wire prestressing will increase, which in turn may result in increasing the minaret stiffness and consequently its stiffness.

5. Seismic response of the minarets

The refined minaret models were then analyzed for three different earthquake records. In selecting these earthquake records, two main aspects were considered, namely, the frequency content of the record and the peak ground acceleration to peak ground velocity ratio (*a*/*v*). As such, the selected

Table 5 Vertical stresses within the minarets body due to different seismic excitations

Maximum Stresses	Qusun Minaret				Stress Location
	Compression (MPa)		Tension (MPa)		
	2% Damping	3% Damping	2% Damping	3% Damping	
El-Centro	8.07	7.32	7.05*	6.20*	
Mexico	0.78	0.78	6.20*	----	2nd Balcony columns
Park-field	3.77	3.77	2.83*	2.83*	2nd Balcony columns
	Al-Sultaniya Minaret				
El-Centro	2.33	2.03	1.99*	1.65*	2nd Balcony columns
Mexico	0.36	0.30	0.02	----	2nd Balcony columns
Park-field	2.66	2.24	2.63*	1.91*	2nd Balcony columns

*Stresses exceeding strength limits

records were picked to cover a wide spectrum of frequencies and a/v ratios. The three records selected were: (a) the N-S component of 1940 Imperial valley earthquake recorded at El-Centro site with high a/v ratio (a/v >1.2); (b) the N-S component of 1966 Parkfield earthquake recorded at Temblor site with intermediate a/v ratio (1.2> a/v >0.8; and (c) the N-S component of 1985 Mexico earthquake recorded at Zihuatenejo with low a/v ratio (a/v <0.8).

All three records were scaled down to a peak ground acceleration of 0.15g that corresponds to the maximum expected earthquake acceleration within Cairo city for a return period of 475 years (Egyptian Code 2001).

Each earthquake record was applied in the X & Y directions of each minaret. It can be seen from Table 5 that high vertical compressive and tensile stresses were recorded within the minaret body due to different earthquakes, and in many cases these stresses exceeded the limestone tensile strength (Table 1).

6. Conclusions

This paper provides a general overview on the seismic response of Islamic minarets constructed during the Mamluk era (14th century) under the action of different seismic excitations. Site investigations along with field tests were used to develop a refined finite element model that resembles as close as possible the actual dynamic behavior of this type of structures. Through the findings of this research the following conclusions were drawn;

· Mamluk style minarets are rigid structures with irregular distribution of mass and stiffness. The fundamental frequencies of the investigated minarets were 1.10 Hz and 1.03 Hz for Qusun and Al-Sultaniya minarets respectively.
· The studied minarets will be susceptible to significant damage during relatively strong earthquakes having medium to high a/v ratio.
· The critical regions in the investigated minaret bodies were identified as the columns supporting the top cap “Mabkharah” for Qusun minaret and the narrow neck of the top bulb in Al-Sultaniya minaret.
· Shape Memory Alloy wire dampers can significantly increase the minaret damping ratio, which in turn can reduce the seismic forces acting on the minaret during an earthquake. However, more

research is required to establish a proper design of such dampers for each building case.

Acknowledgements

The authors acknowledge the financial contribution of European Commission through the project **WIND-CHIM** (**W**ide Range **N**on-**IN**trusive **D**evices toward **C**onservation of **HI**storical Monuments in the **ME**diterranean Area).

References

Abouseif, D. B. (1987), *The Minarets of Cairo,* The American University in Cairo Press.

Aly, A. S., Kordi, E. and Elwan, S. (1996), "Seismic response of Al-Gharry minaret", *Proceedings of the 7th Int. Colloquium on Structural And Geotechnical Engineering*, Ain Shams University, Cairo, Egypt.

Bongiovanni, G., Buffarini, G. and Clemente, P. (1998), "Dynamic characteristics of two earthquake damaged bell towers", *11th European Conference on Earthquake Engineering*, Balkema, Rotterdam, ISBN 90 5410982 3.

Egyptian Code for Calculating Loads and Forces in Structural and Building Works, Ministry of Housing, Infrastructure and Urban Communities, 2001.

Uniform Building Code, Vol. 2, *International Conference of Building*, Whittier, CA, 2002.

El-Attar, A. G., Saleh, A. M. and Zaghw, A. H. (2004), "conservation of a slender historical mamluk style minaret by passive control techniques", *J. Struct. Control Health Monitoring*, August 2004.

FC