Preservation Provisions for the Environmental Protection of Egyptian Monuments subject to Structural Vibrations

Ottavia Corbi, Abdel Hamid Zaghw, Adel Elattar, Ahmed Saleh

***Abstract*—**The Egyptian area is characterized by a number of outstanding historical minarets, which represent a significant part of the monumental and architectural heritage of the country. Such structures usually are rather vulnerable as regards to environmental vibrations due to earthquakes, strong winds or even traffic vibrations, and proper protection strategies are required. In the paper some possible control devices are considered based on passive or semi-active control strategies, also making recourse to the adoption of smart materials.

***Keywords*—** Historical constructions, Egypt, Environmental vibrations, Dynamic structural control, Control devices, Shape Memory Alloys.

I. Introduction

THE protection of ancient historical buildings requires the set up of strategies that are able to couple effectiveness, reliability and low invasiveness, in order to preserve the monumental apparatus of the construction with respect, for example, to environmental vibrations due to traffic, earthquakes or strong winds.

As regards seismic protection, advanced technologies may be conceived according to the special characters of the many structural typologies of historical monuments interesting the Mediterranean area.

These may be founded on structural control strategies aimed at the reduction of dynamic vibrations, both base on more classical passive systems or semi-active control systems adopting new materials such as Shape Memory Alloys.

Control systems based on smart strategies couple have been demonstrated to be able to couple high potential effectiveness with robustness and low operative costs, thus offering some clear advantages both with comparison to passive or active control systems.

The Egyptian area is characterized by many minaret constructions, with Cairo city used to be named the city of one thousand minarets [1], because of 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 build during the Mamluk period were among the most severely hit. Irregular mass and stiffness distribution along their heights with large displayed stalactite carving made them more vulnerable to damage during earthquakes compared to other minaret styles [2].

In the current research, the dynamic characteristics of an outstanding Mamluk-Style minaret are investigated and possible applications of classical or smart base isolation techniques are considered.

II. The Qusun Mynaret

The minaret is the Qusun minaret (1337 A.D, 736 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.

Field investigations were conducted to obtain: (a) geometrical description of the minaret, (b) material properties of the minaret stones, and (c) soil conditions at the minaret location. Ambient vibration tests were performed to determine the modal parameters of the minaret such as natural frequencies and mode shapes.

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 minaret.

Examining the refined finite element model under different seismic excitations indicated the vulnerability of such structure to earthquakes with medium to high a/v ratio (Usually masonry structures are, anyway, affected by high seismic vulnerability [3], [4]).

Possible application of classical or smart base isolation

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techniques is investigated.

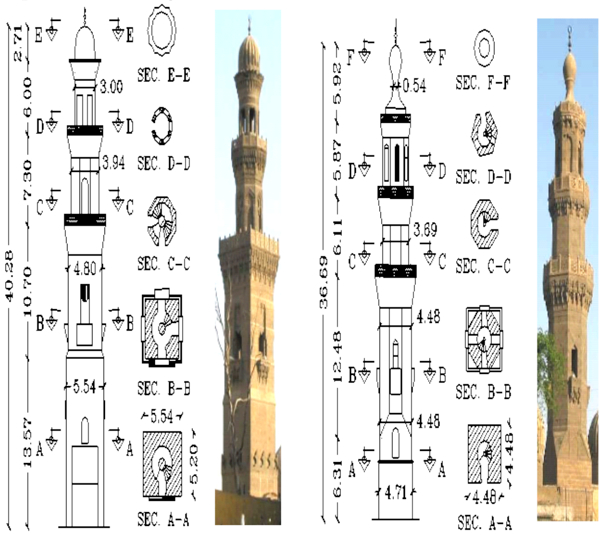

Fig. 1 Qusun Minaret.

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.

These parameters were extracted from laboratory tests carried out on samples taken from the minaret bodies.

Tab. 1 Minaret Material Properties

Property	Limestone	Fill
Elastic modulus (MPa)	3625	50
Spec. gravity (KN/m3)	20.9	20.0
Poisson's ratio	0.20	0.20
Compr. strength (MPa)	14.69	-----
Tensile strength (MPa)	1.34	-----

III. VIBRATION ENVIRONMENTAL TESTS AND NUMERICAL MODEL

The ambient vibration response of the minaret was 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 as shown in Figure 2 [5]. The accelerometers were connected through dedicated cables to a 16-channel 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.

Data were then analyzed to obtain natural frequencies, mode shapes and damping ratios, as usual in ambient vibration tests [6], [7].

The first four modes are bending modes; the fifth is a torsional mode and the sixth and seventh are again bending modes.

As regards the analytical model, a FEM model was built up based on eight-nodded solid elements 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 a realistic model that is as close as possible to the real structure.

A linear elastic dynamic analysis was performed, with a damping ratio of 5% assigned to the first twenty modes.

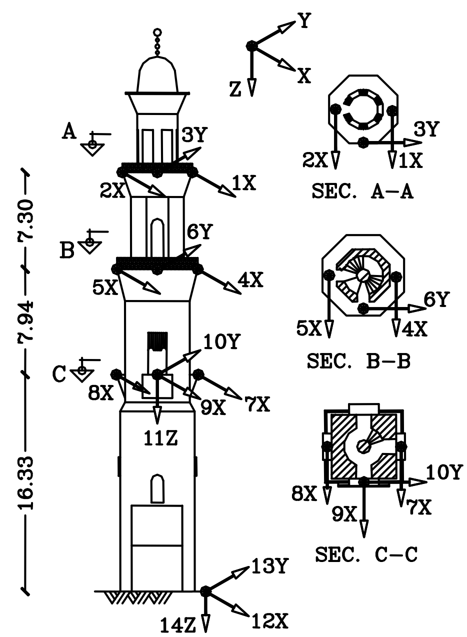

Fig. 2 Accelerometer Location on Qusun Minaret.

Tab.2 Vertical Stresses Due to Different Seismic Excitations with and without BI.

	Comp. (MPa)		**Ten. (MPa)**	
	No-BI	BI	No-BI	BI
El-Centro	8.10	0.85	5.5*	0.04
Mexico	0.97	0.48	0.0	0.00
Park-field	7.10	0.65	6.2*	0.00

* Stresses exceeding strength limits

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 mortar layers, it was decided at this stage that linear elastic analyses were sufficient to provide the qualitative distribution of stresses within minarets bodies and to obtain the basic dynamic characteristics.

Figure 3 shows mode shapes number 1, 3, 5 and 7 of Qusun minaret. The mode shapes obtained from the linear elastic finite element model were reasonably close to those measured experimentally.

As the preliminary finite element runs indicated some differences between the measured and the calculated frequencies, the finite element model was refined to match the first four fundamental frequencies of the minaret. This was done by slightly adjusting the soil modulus of sub-grade reaction and the stone modulus of elasticity.

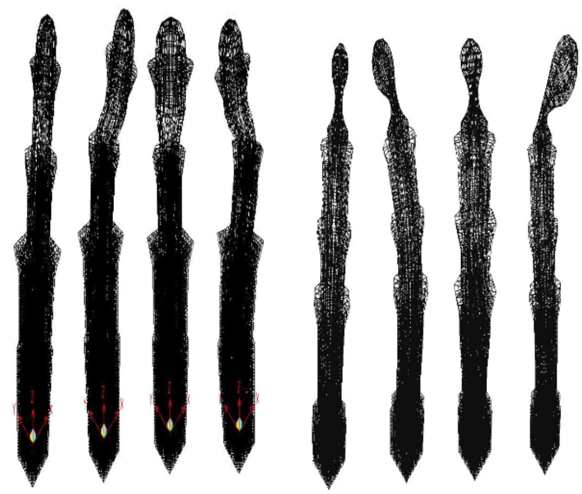

Fig. 3 Refined FE: 1st, 3rd, 5th, 7th Mode Shapes.

IV. Seismic response and BI system

The refined minaret model was then analyzed for three different earthquake records..

The selected 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.

It can be seen from Table 2 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).

To increase [8] both the flexibility and damping characteristics of this structure, the use of high density rubber bearings as base isolators was investigated.

In the proposed system, the Qusun minaret total weight of the structure (14600 KN) is to be transferred to the base through a system of twenty one 1000 KN capacity HDR bearings.

The bearings were designed according to [9]-[11] and arranged as shown in Figure 4.

Bearing properties used in the analysis were (Young's modulus E = 2000 MPa, and modulus of rigidity G = 7.0 MPa).

In order to avoid the possibility of overturning mode of failure, four 50 mm diameter vertical steel tie rods were used to link the minaret top part to its base as shown in Figure 4.

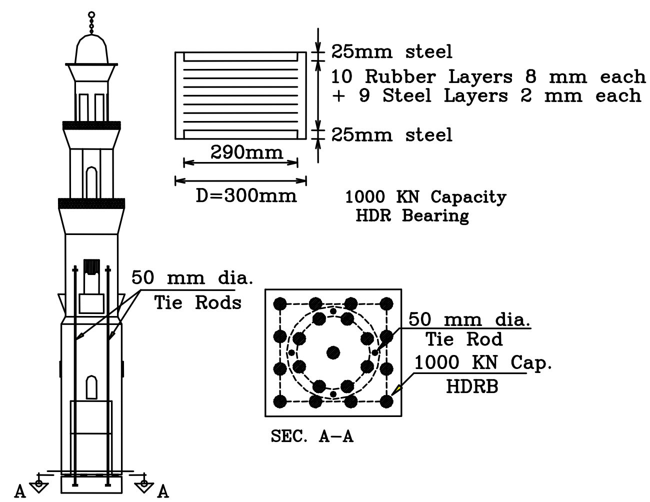

Fig. 4 The proposed BI system.

The first four bending frequencies were reduced by about 56%, resulting in a significant reduction of the minaret stresses (Table 2). However, tensile stresses at the second balcony columns were still higher than the limestone tensile strength (Table 1).

V. Model discussion and planning of control strategies

After the dynamic analyses performed on the minaret under the action of different seismic excitations by making recourse to both site investigations and field tests in order to develop the relevant finite element model, one may conceive alternative strategies of protection as regards to possible seismic events.

These may be based on the exploitation of self-adjusting skill of smart materials such as Shape Memory Alloys, especially useful in the absence of reliable forecasts on the excitation details [12], [13].

To this regard one should figure out some basic issues regarding the results from numerical analyses and possible approaches for the design of appropriate devices for the structural control [14]-[20] of vibrations of the minaret.

First of all, one should emphasize that the proposed FEM model adopts an elastic assumption for the material composing the minaret body.

Such an assumption allows to use commercial software for numerical investigations, drastically reducing the computational effort in the numerical analyses with respect to the more appropriate and realistic assumption which would refer to the non-linear model of the masonry, that is, for example, the No-Tension model [21]-[33] (some applications may be thought for soils [34]- [36]), or any mechanical model exhibiting some fragile behavior under tensile stresses with some well-contained tensile strength and the development of fractures allowed according to a kind of plastic-flow low, of the type illustrated in Figures 5 and 6, as regards the stress-strain mono-axial behaviour.

Actually the minaret walls are composed of two layers of flat-faced limestone blocks, namely external and internal with each layer composed of blocks of different dimensions connected together by mortar.

Although the masonry material usually locally is unable of supporting any, or very low, tensile regime, some overall skill of absorbing contained levels of tensile stresses, and therefore some low tensile strength of the masonry structure, is exhibited.

On one side, this allows the adoption, at the first stage of the analysis, of the simplified elastic model where the structure is pushed to comply with the mechanical parameters of the masonry material.

On the other side, the results from elastic analysis may expedite the qualitative evaluation of the behavior of the structure, but do not achieve results that are quantitatively such reliable.

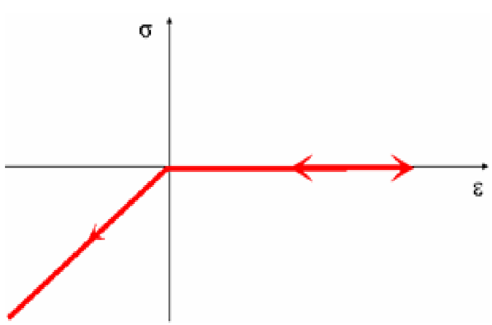

Fig. 5 No-Tension (NT) behaviour.

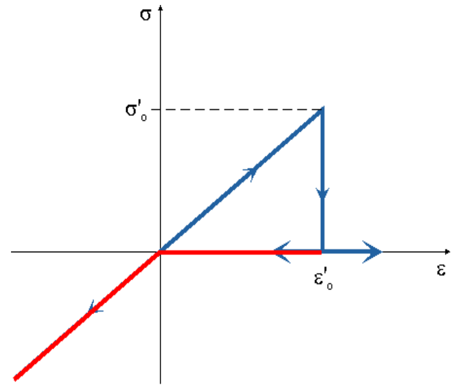

Fig. 6 Elastic-Brittle Low Tension (LT) behaviour.

Actually, these results may differ significantly from data coming out from investigations developed under the NT (Figure 5) or Elastic Brittle Low Tension (Figure 6) assumption, as regards the real intensities of stress regimes activated within the body of the structure.

Anyway, especially with reference to dynamic analyses where the application of more complex models is still under course of development and it is certainly much heavier as regards the computation effort, FEM models based on the elastic assumption may be referred to for understanding and individuating the dynamic modal shapes and, hence, the qualitative overall response of the structure.

This also allows to recognize and allocating the weak points of the structure, and, thus, giving some useful indications as regards the possible positioning of reinforcements or provisions, and the typologies of interventions to be preferred for the specific case.

This, of course, represents a necessary premise for planning any intervention strategy and making it effective.

An additional consideration can be drawn as regards the particular investigated structural typology: Mamluk style minarets are basically rigid structures with irregular distribution of mass and stiffness.

This would push towards studies also analyzing the rigid body motion of the structure, which could easily exhibit some purely rocking modes under dynamic ground excitation .

These feature is not at all trivial, since the rocking mode has been demonstrated to have highly complex dynamics, that are affected by very high levels of uncertainty [37].

Moreover this type of investigation is of primary interest, since the rocking type mode is often recorded during earthquakes in towers or tower-like structures, or structures that may be modeled by some rigid bodies assembly.

To this end worst scenario approaches might be set up as well, for stabilizing the forecast about the rocking response of rigid bodies or rigid bodies assemblies [38].

Such approaches may also be applied for inferring evaluations about the response of the structure after introducing the reinforcement or the control device, and, therefore, for making comparisons between the responses of the unprotected and protected structure.

Finally, one may observe that, according to the executed investigations, the minaret typology is susceptible to significant damage during relatively strong earthquakes having medium to high a/v ratio.

This would require some kind of intervention, that for example, may be aimed at the dissipation of the incoming energy from the ground soil and to the shifting of the frequencies of the main structure and the soil, of the type of the base isolation system presented in the above, or, also, to the insertion of special dissipation devices at suitably identified positions.

Techniques such as reinforcements by means of composites might be adopted with the purpose of making the behavior of the structure more rigid [39]-[41].

Actually the same base isolation system and the dissipating devices may be conceived in such a way to embed some special materials of the type of Shape Memory Alloys (SMAs) [42]-[56], which offer the advantage to make the structure self-adjusting with respect the incoming excitation, realizing a semi-active device with improved response with respect to the passive strategies.

VI Smart strategies of protection by means of Shape Memory Alloys

Based on the discussion reported in the previous section, some semi-active control of the Qusun minaret may be designed by using Shape Memory Alloys.

The first device may be referred to the realization of a base isolation system embedding some SMA tendons of the type illustrated in Figure 7, where it is denoted by a(t) the horizontal ground acceleration at the bottom of the BI piles, by w=m·g the vertical load burdening on the BI system corresponding to the weight of the upper structures, by m the mass of the upper structure, by u the horizontal displacement at the foot of the structure, that is at the top of the BI piles, with respect to the base of the BI columns, and by ϕ the BI piles' average rotation.

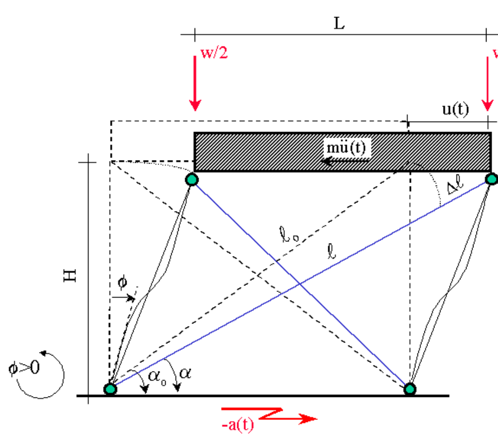

Fig. 7 The BI device based on a SMA tendons system, supporting the Qusun minaret.

With comparison to the classical base isolation, the SMA control system has an improved performance with high re-centering capacity, thus containing the absolute displacements of the structure, besides the dissipating capacity proper of the BI system, thus improving its performance.

Moreover, since the critical regions in the investigated Qusun minaret bodies were identified as the columns supporting the top cap "Mabkharah" , one possible strategy would consist of making such columns some SMA columns, that is to say some structural elements embedding for example some SMA hinges; in this case the model would be the one shown in Figure 8, and the hinges may be designed as shown, as junctions with the upper part without damaging the ancient structure.

In those SMA hinges: the central massive wedge is designed in order to equilibrate the normal and shear forces, while the peripheral SMA plates accomplish the task to react to the bending moment.

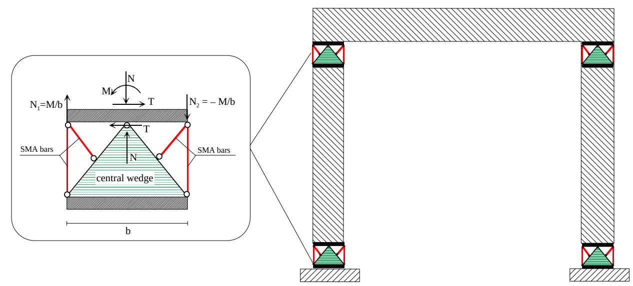

Fig. 8 Two columns connecting the lower part of the Qusun minaret with the top cap "Mabkharah", embedding some SMA hinges.

In this case, in the Figure 8, the bottom of the columns is connected with the lower part of the structure, whilst they are connected, at their top, to the "Mabkharah" cap, with u denoting the horizontal displacement of the upper cap part with respect to the base of the columns.

Referring to the single degree of freedom mechanism, and denoting by k_s the stiffness of the piles with SMA inclusions instead and being $T = k_s \cdot u$, by adopting a one-dimensional SMA constitutive relation based on modified plasticity models able to develop inner hysteretic cycles and applying the isothermal stress-strain rate relation to the frame, one can write

$$\dot{T} = k_s \left\{ \dot{u} - |\dot{u}| \left| \frac{T-\Theta}{T_c} \right|^{n-1} \left[\frac{T-\Theta}{T_c} \right] \right\}, \qquad (1)$$

$$\Theta = k_s \gamma \left\{ \hat{u} - \frac{T}{k_s} + 2\frac{\psi}{\pi} |u|^p \tan^{-1}\left[(\xi \cdot u)^3 \cdot |\xi \cdot u|^q \right] \right\} \qquad (2)$$

$$\hat{u} = u, \ \gamma = \frac{T_o - T_c}{k_s \psi - T_o}, \ \psi = c_\psi \frac{T_c}{k_s} \tag{3}$$

where Θ is the evolutionary one-dimensional *back-shear*, q<1, all other symbols represents material constants and T_o and T_c are the *limit* and *critical* shear stress values

$$T_o = \begin{cases} T'_o & \text{if } T > 0 \\ T''_o & \text{if } T < 0 \end{cases}; \quad T_c = \begin{cases} \nu T'_o & \text{if } T > 0 \\ \nu T''_o & \text{if } T < 0 \end{cases}. \tag{4}$$

where ν is a prefixed percentage. By assuming in the back-shear expression $\hat{u}$ =0, the hardening is driven to zero.

From the above relations the restoring force may be calculated by simultaneous integration of Eq.(1) and the controlled dynamic motion equation of the structure.

VII. CONCLUSION

In the paper one focuses on the protection of historical and monumental buildings in the Mediterranean area.

Strategies devoted to the preservation of architectural heritage should be conceived in such a way to couple effectiveness, robustness and low invasiveness in order to comply with low impact requirements and to be realized in the maximum respect of the original apparatus, whilst mitigating the effects of incoming dynamic actions.

Besides passive strategies, semi-active dynamic control systems have been demonstrated to exhibit a big potential, when properly designed for the structure under examination.

Excellent results are shown by semi-active devices exploiting special properties of smart materials that undergo phase transition processes, such as Shape Memory Alloys.

In this case two main problems arise concerning, on one hand, the proper modeling of the mechanical behavior of the alloys and, on the other hand, the proper design of the control device.

To this regard, the model should couple the skill of capturing the main features of the alloy, which usually exhibit thermo-mechanical coupling with manageability for engineering applications, and the design should be aimed at making the alloy based device to exhibit the special pseudo-elastic behavior.

In details, in the paper one refers to the structural typology of the Egyptian minaret, and to the set up and design of control strategies for the protection of such historical constructions.

Preliminary analyses developed with reference to the Qusun minaret, constructed during the Mamluk era (14^{th} century) in the Cairo city, confirm the vulnerability of this type of structures with regards to earthquakes

Base isolation using HDR bearings significantly reduces the stresses in the minaret bodies. However, more research is required to explore other possible and more efficient techniques.

A possibility in this sense is represented by the design of provisions embedding SMA members, both realizing a semi-active BI system coupling re-centring skill to dissipative properties of ordinary BI devices, and designing SMA hinges to be inserted at specific points, for example, at the connections of the column floor with the top cap of the minaret, where a weak point is individuated during the numerical investigation.

ACKNOWLEDGMENT

The authors acknowledge the financial contribution of European Commission through the project WIND-CHIM.

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