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SEISMIC RESTORATION OF HISTORICAL ISLAMIC MONUMENTS

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ABSTRACT

This paper outlines the different methodologies and techniques followed for seismically restoring many of the Islamic monuments in Egypt during the past decade. Initially, it describes the different structural modes of failure exhibited by these monuments during earthquakes. Then, it discusses the methodology that should be followed to decide whether intervention is needed or not. Finally, it lists the restoration techniques utilized for repairing and strengthening these seismically endangered monuments.

Introduction

For structural engineers, seismic restoration of historical buildings represents a real challenge. The need for preserving the aesthetics, historical values and originality of the monuments, with limitations to the use of new available construction techniques and materials creates a strict frame of action to restorer when compared to the case of restoring ordinary buildings.

Within Egypt there are many Islamic monuments that need to be seismically restored. Aging process, dreadful environmental conditions, poor maintenance, misuse from inhabitants, in addition, to inherited structural weakness represented in the use of defected construction materials and fragile structural systems, made these monuments prone to damage in even moderate earthquakes. This paper discusses in details the modes of failure observed to Islamic monuments during past earthquakes; the methodology followed for assessing the monument safety and the experience gained during the past decade for restoring these monuments to be seismically proof.

Modes of Failure

Principal architectural Islamic monuments located within Egyptian territory can be categorized into; Mosques, Mausoleum, Citadels and Palace. From these four types, the vocabulary of Islamic architecture is derived and used for buildings of lesser important structures, such as public baths, fountains and domestic architecture. Examining these monuments indicated that they are characterized by the existence of main architectural features such as tall minarets, large span domes, wide arches and huge thick multi-leaf bearing walls as shown on Fig.1.

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Reviewing the observed damage reported during past moderate earthquakes indicated that they included; 1) Collapse to top part of the minarets as shown on Figs.2 and 3, especially the minarets belonging to Mamluk era. These minarets are characterized by having irregular mass and stiffness distribution along their heights which made them structurally vulnerable to damage during earthquakes compared to other minaret styles such as Ottoman ones which have uniform cylindrical shafts; 2) deep through cracks as shown on Fig.4 due to wall out-of-plan movement; 3) Bulging of the external leaves of the multi-leaf walls due to loss of contact between wall layers as shown on Fig.5; 4) cracking to large diameter domes similar to that shown on Fig.6; 5) deep corner cracks between perpendicular thick walls not physically connected as shown on Fig.7 due to their relative movement; and 6) Collapse of wooden roofs due to movement of supporting walls.

Figure 1. General view to old Cairo showing the main architectural features for Islamic monuments

Figure 2. Damage to the top part of North Shaykho Minaret (Bassala) during 1992 Cairo earthquake, with this part reassembled again on the ground during the repair process.

Figure 3. Falling of Al-Ssuity Mosque Bassala During Cairo 1992 earthquake

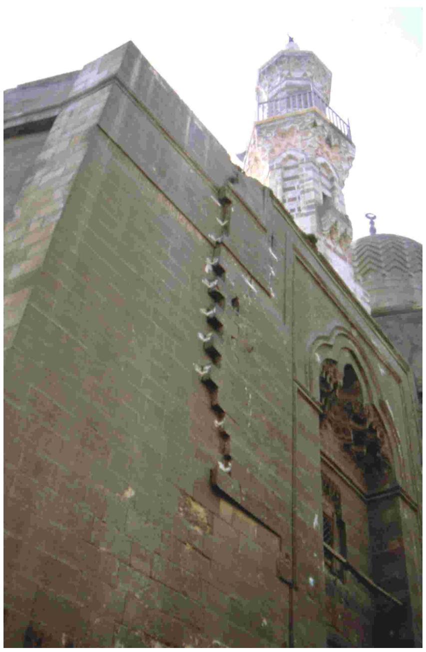


Figure 4. Deep through Cracks along the walls of Sarghitmish mosque

Figure 5. Bulging of external layer of mosque walls Shaykho

Figure 6. Cracking to domes of Bab El Azab

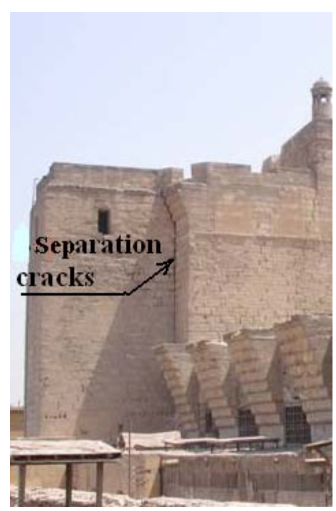


Figure 7. Deep separation cracks

Evaluating the Monument for Structural Safety

For evaluating the structural safety of monuments and deciding whether intervention is needed or not, experience proved that a methodology involves performing in-situ investigation, laboratory tests and conducting rigorous analytical analyses should be followed and strictly adhered to (Hassan, et al. 2004). The in-situ investigations usually include carrying out geometrical and constructional surveys to the monument, visual inspection to structural elements, excavating open pits and drilling boreholes for exploring foundation and sub-soil conditions, monitoring cracks and conducting, if possible, ambient vibration tests to assess the monuments dynamic properties. On the other hand, the laboratory tests include determining chemical and physical properties for both construction materials and founding soil. Finally, by using finite element techniques, the monument can be mathematically modeled and analyzed for both static and dynamic possible loading conditions to evaluate the levels of stresses within the monument body. In case, ambient vibration tests are conducted, the accuracy of the mathematical model can be verified.

In Situ Investigation

Geometrical and Constructional Survey

Initially, all information available on the monument in the literature should be collected. Then geometrical survey is performed. The outcome of this survey is full architectural plans, elevations and sections for the concerned monument. Also, deterioration maps showing all observed cracks, deteriorated stones and areas showing signs of plaster spalling or dampness should be prepared. Then, a constructional survey is performed to identify the construction material for each structural element and to show if the monument is constructed in the same era or on stages.

Visual Inspection and Structural Diagnosis

Visual inspection to the monument by the restorer is considered a very important step in the restoration process. During the inspection visits, the restorer should identify the critical elements/locations from the structural prospective. Care should be given to identifying all observed cracks and pattern of damage associated with them. Deep through cracks along corners as shown on Fig.8 can be taken as an indication to absence of physical connection between perpendicular walls. Consequently, during earthquake these walls can move independently and not as a box. Diagonal cracks through wall, can be also an indication to previous damage due to non-uniform settlement or earthquake. Restorer should observe and record all the stones or bricks decayed or deteriorated similar to those shown on Fig.9, since these signs indicate a weakness in the walls. Locations of bulging in the walls as shown on Fig.10 are an indication to loss of connection between wall multi-leaf layers due to decaying of binding mortar joining walls layers together.

Soil investigation

Close to monument walls, usually open pits are excavated to identify the foundation level and to evaluate the foundation structural conditions. In addition, boreholes are drilled to determine the soil stratification and the ground water table

Monitoring

Usually along observed cracks transducers (LVDT's or gauges meters) are placed to monitor their movements. Measurements to verticality of structural elements such as minarets are recorded on time intervals. Clinometers can be used to measure rotation of structural elements.

Figure 8. Deep through cracks at corner connection between perpendicular walls (Bab El Azab)

Figure 9. Decay to stones constituting the wall

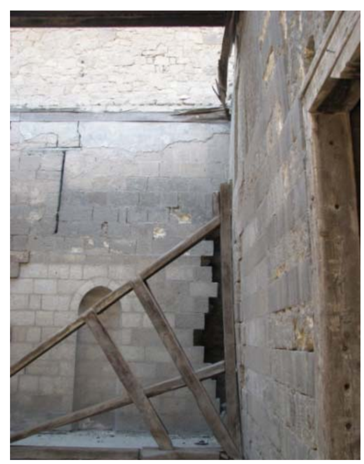


Figure 10. Bulging to wall

Nondestructive tests

Nondestructive tests can be classified into two categories, tests related to construction materials and other related to the structure itself. The tests related to materials include the use of endoscope to explore the walls composition, the use of mortar penetration device for determining the mortar strength and the sonic tests to check the presence of cavities within the walls bodies. With regard to the structure itself, ambient vibration tests are utilized to determine the natural periods, shape and damping associated with each mode. During the past decade and within the context of three scientific research projects (El Attar, et al. 2001, El Attar and Osman, 2004 and Zaki, et al. 2008), full scale ambient vibration tests were conducted on five minarets, and the northern wall of Cairo city. The studied minarets are Manjaq Al Yusufi, Qusun, Al-sultaniya and north and south Shaykha minarets. Views to these minarets are shown on Fig. 11. As can be noted all these minarets belonging to Mamluk era. The conducted tests provided data on the natural periods of the minarets, mode shapes and damping values. Figure 12 shows, as a sample, the arrangement of the accelerometers along shaykho minaret height, the utilized data acquisition system and the spectrum of the signals. Similarly, ambient vibration test was conducted to measure the dynamic characteristics of northern Cairo wall as shown on Fig.13. Again, mode shapes, damping and associated frequencies were collected to be used later in verifying the finite element models. Ambient vibration tests showed that the frequencies for the first bending two modes for these cantilever Mamluk minarets are ranging from 1.1Hz up to 2.0 Hz as listed in Table 1.

Figure 11. Studied minarets, from left to right, Manjaq Al Yusufi, Qusun, Al-sultaniya and Shaykha

Laboratory Tests

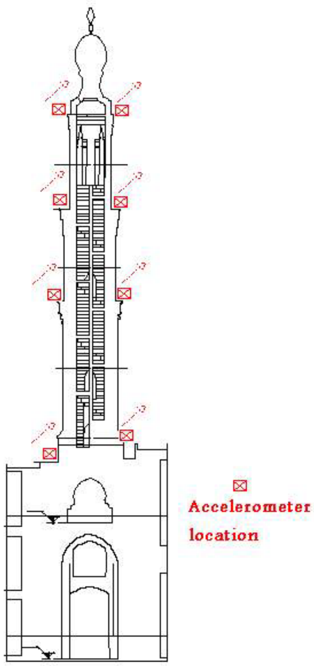
Many stone cores are extracted from the building walls and tested to determine the chemical and mechanical properties of the construction material. Also, samples extracted from the soil taken out of the borehole and analyzed to determine the soil properties.

Structural Analyses

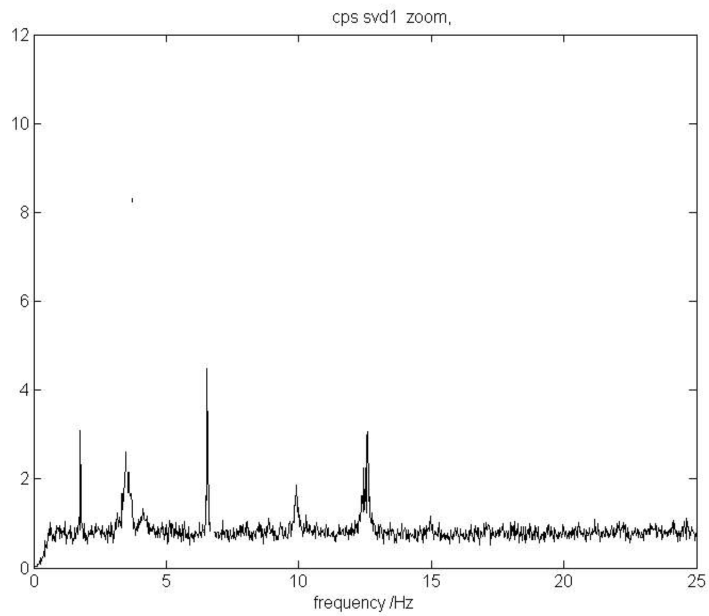
Using the finite element technique, the monument can be accurately modeled in order to evaluate the actual level of stress within the building elements under various loading conditions.

(Data acquisition system)

(Accelerometer with fixing devices)



Locations of the accelerometers



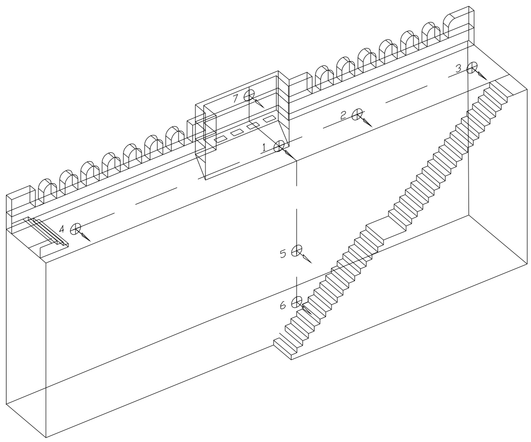
Sample Spectrum of the signals

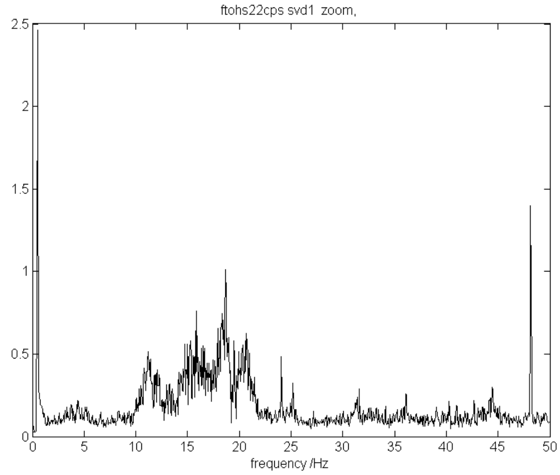
Figure 12. Sample ambient vibration test to shaykho minaret

Models can be global models similar to that shown on Fig.14 for the shrine of Hala Sultan Tekke at Cyprus or local model for part of the structure similar to that shown on Fig.15 and represents the minaret of Umm Sultan Shaaban in Cairo. The models are usually verified using the results obtained from ambient vibration test through running a free vibration analysis and comparing the frequencies obtained from the model, with those obtained from the tests.

Table 1. Measured Frequencies for Tested Minarets

Minaret	**Manjaq Al-Yusufi**		**Qusun**		**Al-Sultaniya**		**shaykho**	
Freq. (Hz)	**1.95**	**2.00**	**1.17**	**1.10**	**1.10**	**1.03**	**1.84**	**1.75**





Accelerometer Locations on the wall

Cross spectral Density Function

Figure 13. Ambient vibration test to Northern Cairo wall

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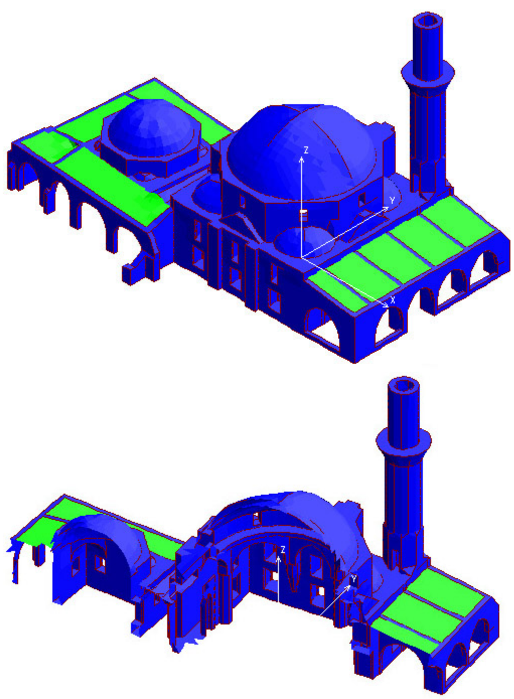

Figure 14. Global model for Hala Sultan Tekke

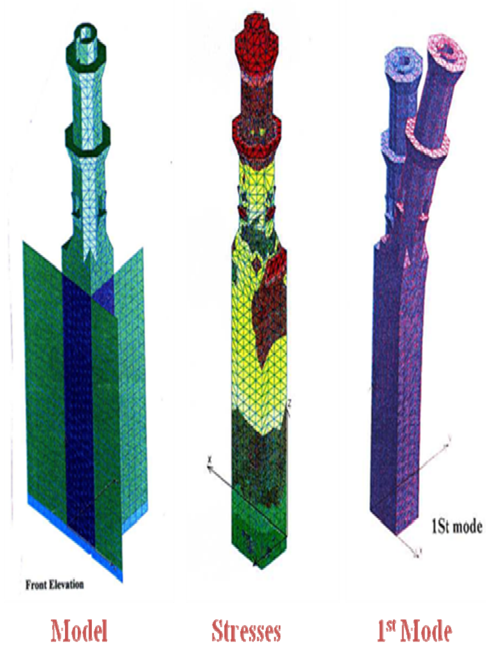

Figure 15. Local model to a Minaret

Once stresses within the monument body under the action of applied forces (dead, live, wind, earthquake…etc) are obtained, they can be compared with the allowable stresses and strengths of construction materials obtained from laboratory tests and the need for intervention or not decided. Experience indicated that for Islamic monuments in Egypt constructed from stones, the allowable compressive stress can be taken as 1.4 MPa, while the allowable tensile stresses can be taken in the range of 0.14 MPa. Also, conducted analyses indicated that most of these structures are sensitive to earthquakes having a/v (acceleration to velocity ratio) larger than 1.2.

Remedial Measures

Different strengthening techniques are utilized for seismic strengthening of monuments. It started by strengthening the monument walls. If the wall is bulged from one side, this indicates separation of wall leaves due to loss or decay of mortar binding the wall leaves together. In this case the bulged layer is taken out and rebuilt straight with injection to remaining part of the wall with compatible mortar (lime mortar), were the use of cement mortar is not acceptable. If the whole wall is tilted or bulged out-of-plane, it has to be taken out and rebuilt as shown on Fig.16. If any wide cracks observed through the wall, it stitched using either wood or stainless rods (no black steel should be used) or the wide crack injected. Then, the walls are checked for slenderness. Usually for such buildings, L/t should be limited to 20, where L is the wall height or the distance between perpendicular walls, which is shorter, and t is the wall thickness. In case these limits exceeded, it is preferable to provide a diaphragm in the form of open wooden truss at required levels parallel to roof, or buttresses perpendicular to walls. After that, connections among perpendicular walls are checked for the existence of physical bond. If this bond is missing, stainless ties or wood corners are used to connect these walls to ensure that they will work together as box under the action of lateral loads (Fig.17). Then, the roof, which is usually a wooden one, is repaired and strongly connected to walls to ensure that the roof will work as rigid diaphragm with the walls. If foundation needs to be strengthen due to soil problems, either shallow foundation system similar to that shown on Fig.18 can be adapted to relief the exerted bearing stress on the soil by widening the foundation, or micro-piles is utilized as shown on Fig.19. For retrofitting domes and minarets, existing cracks can be stitched or injected and FRP can be used to enhance the tension capacity of these elements as shown on Figs.20 and 21.

Figure 16. Rebuilding severely damaged walls

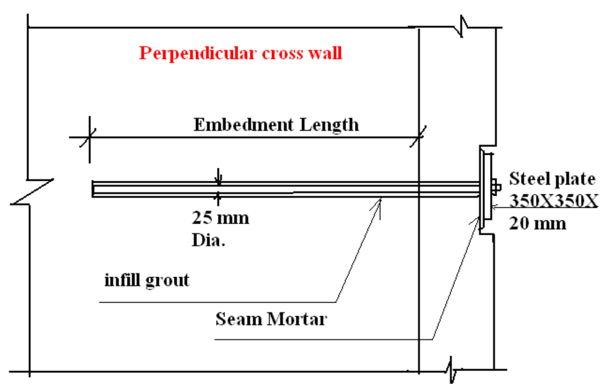

Figure 17. Connection between walls

Conclusions

The paper presented the strategy that should be followed for seismic retrofitting of endangered Islamic monuments in countries with moderate seismicity and have monuments constructed in similar style. Emphasis is placed on utilizing new non-destructive tests and technique such as ambient vibration to determine monuments dynamic properties and verify the mathematical models that will be utilized for assessing the levels of stresses within the monument. Finally, the paper summarized the different restoration schemes currently used.

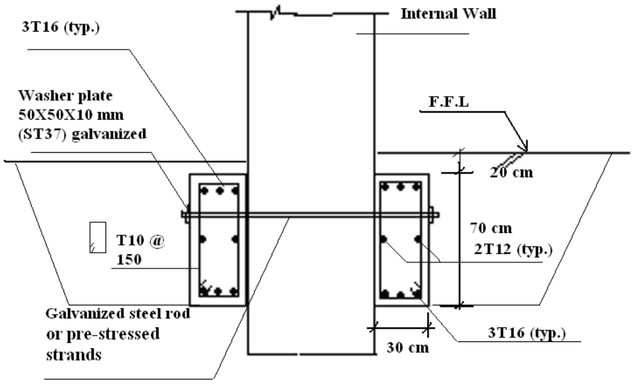

Figure 18. Shallow strengthening to foundation

Figure 19. The use of Micro-piles

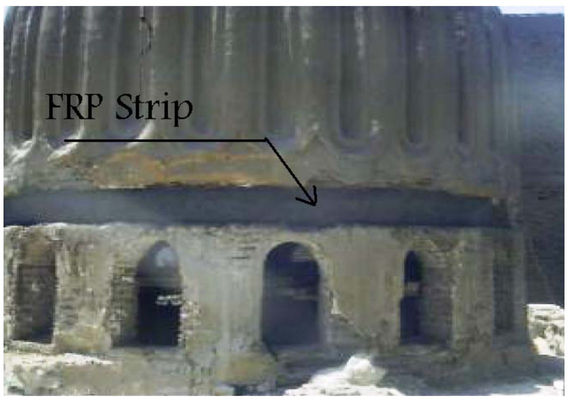

Figure 20. Repair of Saudon ring beam

Figure 21. Repair of Al-Aini Dome with FRP

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