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Strengthening, Restoration and Rehabilitation of the Greek Orthodox Church of Saint George - Old Cairo

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ABSTRACT: The Greek Orthodox church of Saint George is one of the most important archaeological sites in Egypt cultural heritage. This monument exists within the Fortress of Babylon, a Roman site which dates from 300 AD. Old Cairo has been identified as a core of activity by Muslims, Jewish, Coptic and Greek Orthodox religions.

Several studies have been previously developed before the elaboration of this restoration project. These studies were mainly to lower the water table which has been incradibly increased due to the rapid expansion of population within the vicinity. A dewatering system was developed and identified as contract 102. This process resulted in several cracks in the structure main elements especially for the upper recently built part of the church which is in a serious condition. The vertical cracks in its outer wall, together with the roof and the dome cracks are the main threaten to the structure overall stability. These cracks initiate a serious safety problem which may result in a local or even total failure especially if the building is subjected to unexpected load conditions (earthquakes, excessive vibrations as result of explosions or even under the effect of heavy traffic vibrations).

A quick intervention requires a deeper knowledge for each element of the structure and accurate investigation to develop an appropriate technique for repair and strengthening. The accurate investigation is a key element for successful intervention. The present study is based mainly on an accurate system of investigation, monitoring and data collection required for computer modeling. The computer modeling is the key element for applying a successful structural restoration intervention. The study will propose a method of analysis able to interpret and to forecast the observed damage and collapse modes.

1 INTRODUCTION

The Greek Orthodox church of Saint George is one of the most important archeological sites in Egypt cultural heritage. The present structure is a result of several extensions, modifications and demolitions since the construction of its oldest parts. The church is built on one of the three towers of the old Roman fortress.

Several studies have been previously developed before the elaboration of this restoration study. These studies were mainly to lower the water table as a main factor to preserve this monument. Another important study was implemented which is the documentation of architectural historical elements. The present study is particularly important to perform not only an accrued analysis of what is visible but also the hidden part which is underneath the church structure. Observation of areas where damage is concentrated as a result of high compression (zones of crushing) or high tensions (zones of cracking or the separation of elements) and the direction of the cracks, together with an investigation of soil conditions, may indicate the causes of this damage. This may be supplemented by information acquired by specific tests. The existent structure contains several cracks in its main elements especially for the upper recently built part of the church which is in a serious condition. The vertical cracks in its outer wall, together with the roof and the doom cracks are the main threaten to the structure overall stability. These cracks initiate a serious safety problem which may result in a local or even total failure especially if the building is subjected to unexpected load conditions (earthquakes, excessive vibrations as result of explosions or even under the effect of heavy traffic vibrations).

2 INVESTIGATION, MONITORING AND DATA COLLECTION

The accurate investigation is a key element for successful intervention. Despite the fact that the lowering of the water table for the building was important to preserve the monument, it affected the structure considerably due to the resulted settlement which increased the existed cracks. The main aspects to be investigated are the following:

2.1 Soil Investigation

The main goal from soil investigation is to provide a preliminary assessment of the physical state and the structural performance at site. It can be seen from the previous studies that the structure is founded on a “very loose to medium dense silty sand”. Since the newly made drainage system was installed below the base elevation of the foundations, the flow of water that is directed to the drains may carry with it these fine particles, forming underground channels, known as piping. The presence of such voids could lead to differential settlements. A settlement monitoring will not be effective but the cracks observation is key answer for this problem. The soil investigation measures showed that, it has a limited effect on the structure.

2.2. Material Investigation

The monument structures built in different ages with different materials. The aims of testing material samples are to characterize the material, to detect its origin, to know its composition and content in order to use compatible materials for the repair, and to measure its decay. Eleven samples from different locations are extracted to represent the different parts of the building. The assessment of the laboratory test results for the materials is as follows:

- The lower basement is composed of very thick walls of hard limes-tone blocks having a compressive strength of 410 kg/cm^2.
- The upper basement is composed of the limestone rocks and is weaker than the lower basement (134 kg/cm^2).
- The church inner columns are made of weak porous limestone with compressive strength of 91 kg/cm^2, while the outer walls of the church are made of strong limestone (306 kg/cm^2)

2.3 Structural Investigation

2.3.1 The Shape and Structural System

The building is made of different structural systems and even with different construction materials. The upper church comprises a double shelled rotunda with a middle inner colonnade consists of eight columns that supports an elevated concrete dome. The outer roof slab (Gothic Vaults) is supported on these columns and on the outer circular stone wall. The outer roof slab consisted of a light weight bricks supported on radial steel beams (Figure 1). The middle circular columns and the outer stone wall are supported on a continuous concrete slab constructed on top of the remains of the old Northern Roman Babylon Fortress. The slab is reinforced with steel beams. The Old Fortress walls are made of limestone blocks with layers of red bricks.

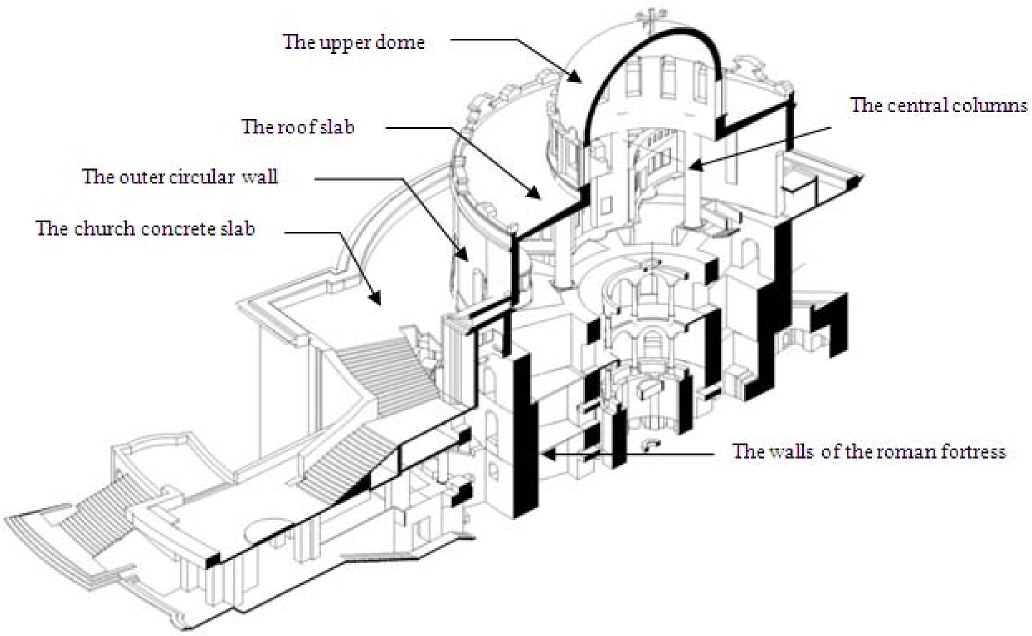

Figure 1. Half section in the building presenting the structural system.

2.3.2 Survey of the Structure Deterioration and Failure Signs

Full understanding of the structural behavior and material characteristics is essential for any conservation and restoration project. Before making a decision on structural intervention it is indispensable to first determine the causes of damage and deterioration, and then to evaluate the present level of structural safety. The factors that will lead to the speedy deterioration process are the bad quality of stone material, Porosity and inhomogeneous structure of the stone material, environmental pollution, influence of soluble salts, weathering effect and impact of biological growth. The analysis of the available data, and the full understanding of the structure behavior and material characteristics indicated that these factors have a limited effect.

2.4 Cracks Monitoring and Assessment

Several cracks have been noticed after the last erection of the upper church, this fact explains the use of the steel reinforcing system for the outer stone wall. This system was made to stop the deterioration of the wall lateral capacity and to decrease the cracks effect. These original cracks increased as a result of the surface pumping of the water at the beginning of the dewatering project in June 2000. The increase of cracks was found more pronounced along the building big openings (windows and doors). The cracks observed in the church doom and roof slab are another set of critical cracks. The plaster coating represents a very weak layer affected by the lateral deformation of the church outside wall. These damages made imperative to remove the plaster layer as it is of no archeological value. The cracks in the upper dome are less critical than the roof cracks and the dome itself contains valuable painting which makes it impossible to be destroyed. The dome cracks are mainly due to the corrosion of the steel beams used to reinforce the concrete of the dome. It can also be concluded that the vibrations as a result of the traffic especially the Underground Metro and the tourist buses were the main causes cracking on the west part of the church. It is clear that the outside walls are sensitive to vibration as they are loose as a result of the vertical cracks which extended up to the upper edge.

3 THE COMPUTER MODEL

The final aim of the design model would be the proposal of a method of analysis able to interpret and to forecast the observed damage and collapse modes and to critically consider the effectiveness of some techniques for repair and retrofitting when applied.

3.1 Modeling of the Structural Elements

A three dimensional finite element model is prepared with the aid of SAP2000 computing program. Figure 2, represents the geometry of the model. All the structural details were induced as they are shown in the structure photographs.

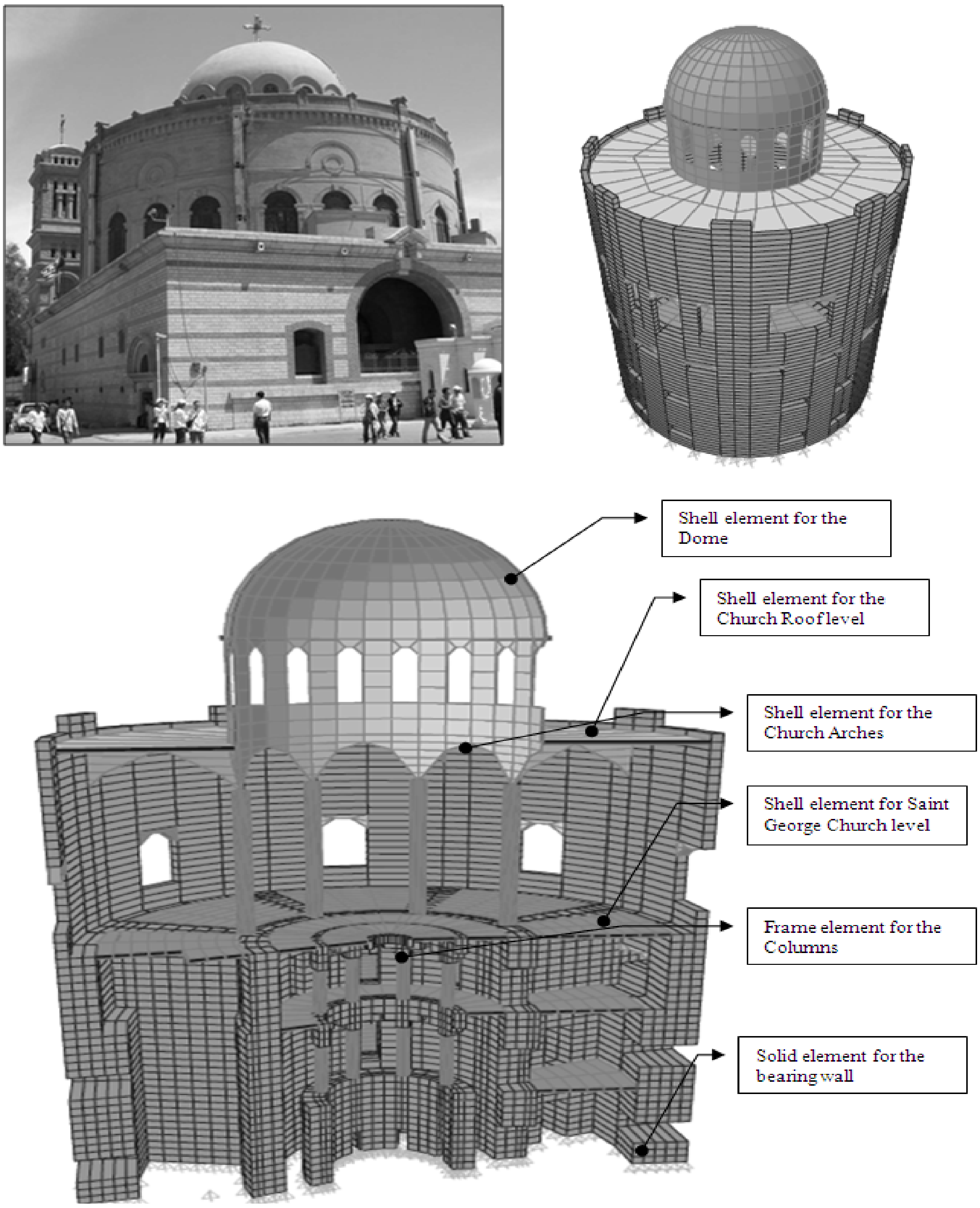

Figure 2.General Prospective of the Building and Representation of the structural elements.

3.2 Design Criteria

The materials used in the model are brick, stones and concrete.
The loads are considered according to the Egyptian Code of Practice 2008

3.3 Model Output and Stress Distribution

The structural characteristics of the building are analyzed on the basis of linear-elastic analysis. A comparative analysis of results obtained from the model and the presence of the major cracks can easily be predicted. The stress distribution represents the zones of the large tensile stresses. The cracks are assumed to occur when the tensile principle stresses exceed the tensile ultimate strength of the material. The direction of the crack is perpendicular to the direction of the tensile principal stress. The comparative analysis of the results presents a clear explanation for the position of the cracks, as shown on figure 3.

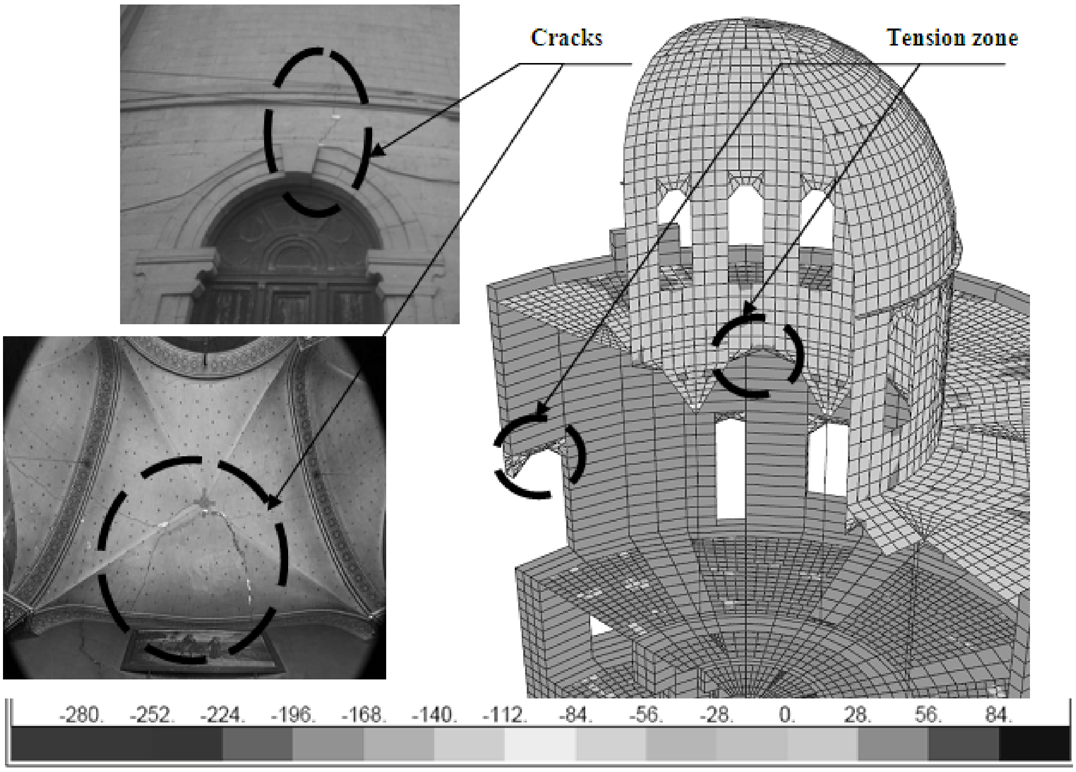

Figure 3.High Tension Stresses in the Arches and around the Openings

3.4 SAP2000-Dynamic characteristics

The Dynamic characteristics of the structure have been made based on the modal analysis. The analysis determines the un-damped free vibration mode shapes and frequencies of the system. Six modal analyses have been considered however the first mode shape is sufficient as it is the lowest-frequency mode (Longest period). Figure 4 shows the modal shape number 1.

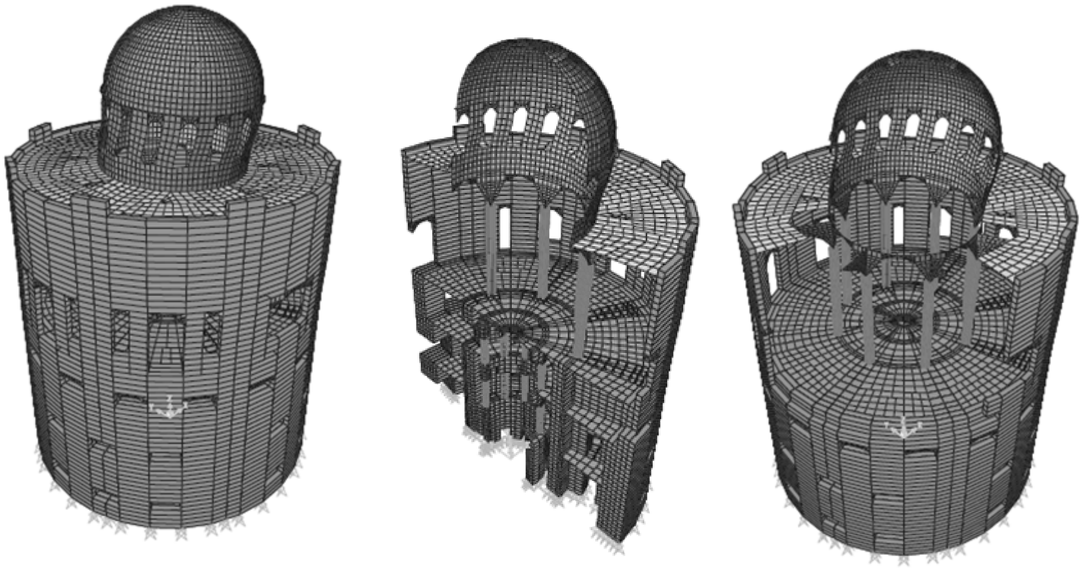

Figure 4.Mode Shape Number 1 Time period (0.46797 second)

4 DIAGNSIS AND SAFETY ASSESSMENT OF THE RESULTS

The submitted results from the site inspection, the monitoring of the structural elements and the computer analysis found the following deficiencies:
- The loss of integrity of the structural system due to the low tensile capacity of masonry, occurrence of cracks at each storey level and separation of the massive walls from the rigid parts of the structure. These cracks are concentrated around the openings (windows and doors) where the stresses from the model proved the presence of high tensile where the main cracks were found.
- Failure or damage to the secondary decorating elements (gypsum plaster for the inside of roof slab) due to amplified effects and low bearing capacity.
- The differential settlement widened the existed cracks and initiated new cracks.
- Shear failure of walls or the upper parts due to the poor quality of mortar and low shear force resistance.
- The dynamic analysis of modes of failure and the dynamic characteristics proved that the structure is sensitive towards the expected possible earthquakes.

These deficiencies indicate different signs of deterioration such as local damages, cracks and unaccepted deformations. These types of cracks may be represented in the lower part of the structure. On the other hand the signs of deterioration may be a warning that the structure is suffering and the internal stresses increases than the allowable bearing capacity of the materials. In that case a quick intervention is imperative or the stability of the structure will be in danger. This is clear and may be represented in the upper part of the structure.

The repair and rehabilitation works should not be limited to the signs of deterioration only but to the main causes of these deterioration signs. These main causes may be represented as follow:
- The design and structural system deficiency. Mainly the tension stresses on the top of the building openings.
- Insufficient lateral capacity to resist horizontal loads (mainly wind and earthquakes).
- The use of brittle non-homogenous material
- The differential settlement resulted from the dewatering and drainage system.

5. REPAIR AND STRENTHENING APPROACH

The main objectives of the repair and strengthening method are to repair all the signs of failure, to strengthen the structure by adding new structural elements that will be connected to the existing structure to increase its safety margin and to release the existing structure from part of the existing loads by transmitting these loads to the newly added structural elements.

5.1 The proposed repair method

The proposed repair method can be shown in the detailed drawing in figure 5.

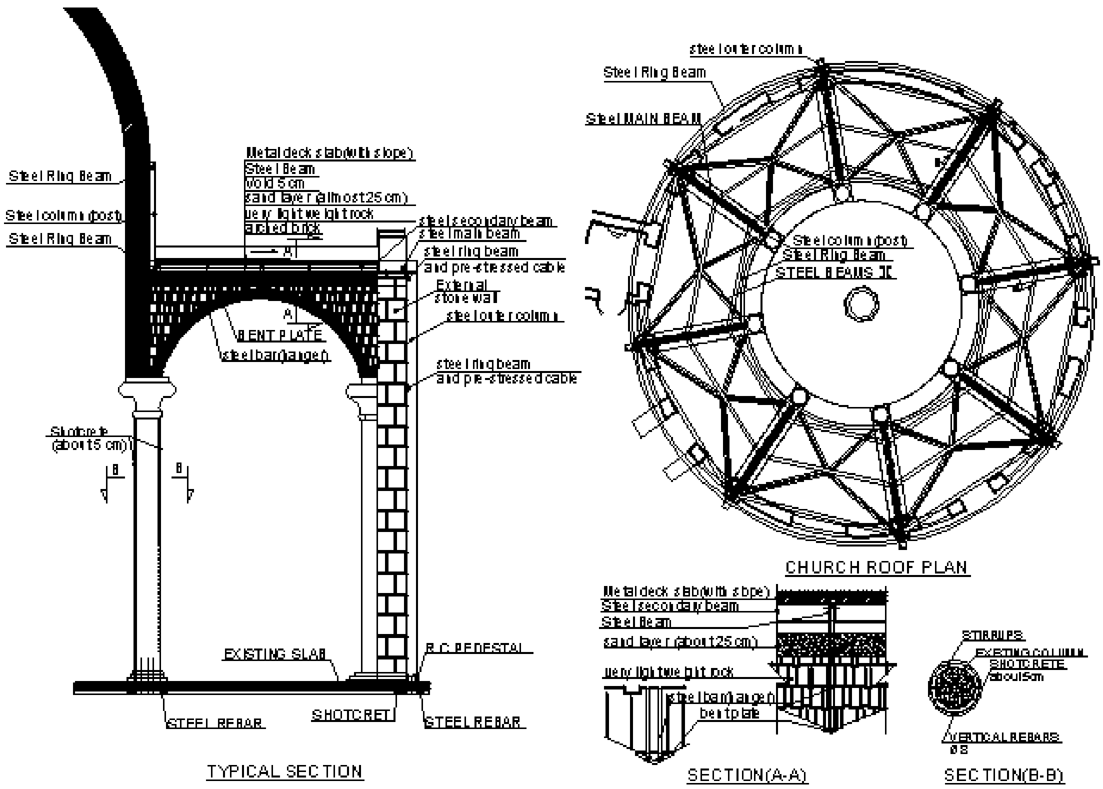

Figure 5 Strengthening Details.

The proposed repair method can be summarized in the following steps;
1- The injection and grouting of all the cracks with suitable grouting material. This procedure should be applied from the lower basement and go up to the higher levels.
2- The introduction of post tension steel cables at the proposed four locations:

- Base of the doom.
- Under the windows opening of the central dome.
- Top of the external wall.
- Over the windows of the external wall.

Due to the structure vulnerability it is suggested that the required pre-stressing forces for the post tension of the cables should be limited to counter act the reactions of the gravity loads only.

3- The strengthening of the church outer stone wall by adding 8 steel columns from outside of the church. The new added columns should be connected together with steel circular ring beams. The circular steel ring beams will be down near the church floor, on top of the windows and near the roof. The ring beams will connect the steel beams together and the pre-stressed cables will be directly connected to the stone wall.
4- The strengthening of the internal church middle columns by adding a steel cage made of steel rings and longitudinal plates and then a layer of concrete is added.
5- The strengthening of the upper central dome by adding some shear-connectors to the outer side of the dome and pouring additional layer of concrete.
6- The strengthening of the circular double vaulted roof block slab is achieved by introducing a new light weight concrete slab above the existed one. The new slab will be carried by a series of circular steel beams which will be supported mainly on the outer steel columns and the central church columns. The connection between the existed and the new roof slab will be realized by using stainless steel hangars to be drilled from inside of the church through the existing slab from a v-shaped steel plates to support the folded edges of each slab panel. The steel hangars will be limited to these edges. The hangars will be connected to the new added steel beams using the system of screw jacking to transmit the load. The procedure should be made carefully and on steps. Finally the new roof that located above the existing masonry brick roof should have an interlayer to insure the transmission of the loads and ventilation of the existed roof. In this way the old roof is hanged to the new one transmitting part of its load to the new roof. The new roof will also prevent the old one from the outside surrounding environment and can improve its isolation too.

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CONCLUSIONS

Old Cairo is a remarkable example of Egyptian heritage. The monuments within it are certainly worthy of any conservation effort that is undertaken to protect them.