RESTORATION OF THE HISTORIC CHURCH OF ST. GEORGE IN CAIRO AND THE ROMAN TOWER UNDERNEATH

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ABSTRACT

The Church of St. George is located in the old Cairo and more specifically at the Margirgis area and belongs to the Greek Orthodox Patriarchate of Alexandria and Whole Africa. It is an Unreinforced Masonry rotunda 27m diameter at the base, 13 dome diameter, 11m dome and drum height and total height 22m, built at the beginning of the 20th Century upon the ruins of a previous Church. The rotunda is based upon a three storey Roman Tower (Eastern Roman Empire-Byzantium) circular in plan, built around 1st CE A.D. The tower, 27m external diameter, consists of two perimeter rings of thick roman masonry walls (opus caementicium) interconnected with radial walls. The intervention concept is based upon the thesis that the Roman Tower is a significant historic monument including the several additions and modifications it has sustained during the 2000 years lifetime, while the Church of St. George (MARGIRGIS) is considered as a recent monument (listed).

INTRODUCTION

The Church of St. George is located in the old Cairo and more specifically at the Margirgis area (Margirgis is a paraphrase of the Greek Aigiorgis meaning St George) and belongs to the Greek Orthodox Patriarchate of Alexandria and Whole Africa. It is an Unreinforced Masonry rotunda 27m diameter at the base, 13 dome diameter, 11m dome and drum height and total height 22m, built at the beginning of the 20th Century upon the ruins of a previous Church. The wall paintings have been drawn by the famous Greek painter Parthenis.

Figure 1. External view of the Church and Tower (left) and interior of the Tower (right)

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The rotunda is based upon a three storey Roman Tower (Eastern Roman Empire-Byzantium) circular in plan, built around 1st CE A.D. The tower, 27m external diameter, consists of two perimeter rings of thick roman masonry walls (opus caementicium) interconnected with radial walls (fig. 1 & fig. 2). At the end of 19th CE A.D. the small church of St. George, that existed upon the tower, was ruined by fire as well as the wooden floors of the Tower. At the beginning of the 20th CE A.D. the Roman Tower was restored from the fire with the addition of R/C floors and then the imposing Rotunda was erected above the restored Tower.
HISTORICAL CONTEXT

The whole complex, today partially being the St. George Convent, is located at the place of the Babylon Fortress (fig.3), on the Nile bank, as fully described initially by Strabo at 26 B.C. The Babylon fortress had been built upon a previous installation of the Ptolemies, which was used a harbor entrance for the canal linking the Nile to the Red Sea (246-46 B.C.), a canal first attempted, unsuccessfully, by the Pharaohs of the twenty sixth dynasty (610-595 B.C.), and first achieved by Darius I (521-486 B.C.). This canal was in use in the Trajan era (107 B.C.) who was probably the one that commissioned the two Towers designating the entrance to the port, while Diocletian significantly expanded the fortress installation (298-302 B.C.). The church of St. George and the Tower is one of the two Towers of the harbour entrance.

![Exterior view](image)

![Interior view](image)

Figure 4. Elaboration of Rotunda walls with significant cracks

Figure 5. Tower (left) and Church dome and groin vaults (right) significant cracks

PATHOLOGY

(a) Roman Tower

The Roman Tower had been flooded in its lower level up to 2002, when a massive program of underground tunnels and well-points for dewatering parts of Old Cairo was completed. The rise of the
water table may be attributed to the construction of the metro line (Margirgis Station) passing the old Nile bed, creating a diaphragm.

The Roman Tower sustained serious damage in the surface of the stone walls of lower level due to the long term flooding, fully penetrating cracks at the walls resulting mainly from old settlements and only partially due to the dewatering while corner stones had been removed at specific locations (fig.5). The cracks at the Tower were stable after the dewatering as was evident from the glass markers installed. One very significant source of surface damage resulted from the fesses of bats that inhabited the Tower in thousands.

![Figure 6. F.E. analysis of Church (elastic)](image)

(b) St. George Church

The rotunda presented serious structural issues as the weight of the Dome created outward thrust forces on the external perimeter wall via the groin vaults, an action that lead to evolving (glass markers) vertical tensile cracks on the perimeter URM wall as well as tensile cracks at the bottom of the groin vaults as the perimeter wall was moving outwards. Additionally a part of the Church outer floor was founded beyond the Roman Tower, on soft river deposits, that lead to differential settlements (fig 4 and fig 5). Finally the eight internal circular brick masonry columns, suffered extensive cracking at their bottom (spalling-off of plaster)

![Figure 7. F.E. analysis of existing Church (nonlinear) for 1.60 the dead loads](image)
INSITU AND LABORATORY INVESTIGATIONS

During the first stages of the design (mainly) and during construction the following in-situ and laboratory works were executed:

- Complete architectural survey of the monument
- Chemical and Mechanical analysis of stones, bricks and mortars
- Recording of all cracks
- Survey of all doors and windows
- Documentation of all valuable historic wooden doors of the Tower (Roman or Islamic Style)
- Investigation sections at the columns of the Church, the groin vaults and the dome.
- Carbon dating of wooden doors and wooden ties
- Investigation of the wall painting (moisture, temperature, UC cameras, Thermic Cameras)

These investigations resulted in the following material properties:

a) Stone masonry
- Design compressive strength of masonry : $f_{cd} = f_{ck}/\gamma_M = 5.30/2.50 = 2.20\text{MPa}$
- Modulus of elasticity: $E=1000f_{cd}= 3.0\text{ GPa}$
- Poisson ratio: $\mu=0.20$
- Shear strength: $V_{rd} = f_{vko}+0.40\sigma_d = 0.30+0.40\sigma_d$

b) Brick masonry
- Design compressive strength of masonry : $f_{cd} = f_{ck}/\gamma_M = 2.30/2.50 = 0.92\text{MPa}$
- Tensile strength parallel to the bedjoints: $f_{wtd}=2.0*0.9*f_{cd}/10 = 0.18\text{Mpa}$
- Tensile strength perpendicular to the bedjoints: $f_{vtd}=0.9*f_{cd}/10 = 0.09\text{Mpa}$
- Shear strength: $V_{rd} = f_{vko}+0.40\sigma_d = 0.30+0.40\sigma_d$
- Modulus of elasticity: $E=1000f_{cd}= 2.0\text{ GPa}$
- Poisson ratio: $\mu=0.20$
ANALYSIS

The church was analysed for the existing condition. For that an accurate FE model was developed in Etabs 9.70 which included all the geometrical aspects of the monument. The initial approach was elastic spectral dynamic analysis using the Egyptian code. Using this approach it was indeed verified that the pathology (crack pattern) of the church corresponded with areas of high tensile stresses (fig.5). Additionally a NL static analysis was implemented using the methodology presented by Penelis et al (2010), which is a step-by-step non-iterative procedure using the SAP2000 API and external commands (fig.6). This nonlinear analysis verified that the church has inherent structural form problems that eliminate the capacity for applied dead loads unless a strengthening approach is applied. The same analyses were also implemented (elastic and nonlinear) for the selected strengthening scheme, and verified that the capacity of the structure for vertical loads combined with lateral excitation is significantly improved and fullfills the code requirements with minimum cracking (in case of design earthquake)

RESTORATION

The intervention concept is based upon the thesis that the Roman Tower is a significant historic monument including the several additions and modifications it has sustained during the 2000 years lifetime, while the Church of St. George (MARGIRGIS) is considered as a recent monument (listed).

a) Roman Tower

The Tower is a robust and stiff structure consisting of thick stone masonry walls with intermediate solid brick masonry layers (opus caementicium). The principle of the intervention was the restoration of the bearing capacity of the structure without and addition or strengthening, given that the almost 2000 years of existence are proof of its sufficiency.

As already mentioned, the Tower presented fully penetrating cracks that were restored. The works executed are the following:

Structural restoration works
- crack restoration using pouzolanic grouts
- crack stitching,
- stone stitching

Architectural restoration works
- sandblasting of all wall surfaces
- repointing of all surfaces and removal of previous interventions with cement paste.
- antidust coating of the brick masonry layers for emphasis
- coating of all R/C floor surfaces (constructed after the fire in the restoration of 1909) with hand made coarse grain plaster
- restoration of valuable wooden doors of the Tower (Roman-Byzantine and Islamic type)
- restoration (supplements) of stone floors
- new architectural lighting

MEP works
- fire alarm system
- hi and low voltage cabling
b) Church of St. George

The rotunda is a newer monument that has significant structural issues that result from its structural form which transfers the weight of the dome as trusting horizontal forces, via the groin vaults, to the external perimeter wall, pushing it outwards.

The principle of the intervention is the structural restoration and strengthening of the rotunda so that it can adequately receive all static loads as well as to have acceptable performance under a significant earthquake.

To determine the intervention scheme, an elastic dynamic analysis of the rotunda was performed so that the critical areas could be determined. This analysis, that completely verified the observed crack pattern, the following three intervention options were discussed:

- Strengthening of the external perimeter wall and the eight internal columns with shotcrete
- Placing of tension rods at the groin vaults and between the columns and strengthening of the eight internal columns with shotcrete or FRPs.
- Introducing external post tensioning with tension rods at four levels externally, and strengthening of the eight internal columns with FRPs.

During the co-operation of all disciplines, the third solution was selected, given that the first was deemed inappropriate while the created structural problems during an earthquake (thrust of the rod on the columns) and also altered the architectural features of the church.

It should be noted that the selected solution is an evolution of an intervention during 1950 that introduced 8 external steel columns and steel cables to counterbalance the thrusting outward forces, an intervention that did not work due to the absence of post tensioning.

The required post-tensioning force, as well as all the other interventions at the internal columns, the groin vaults and the dome windows, were designed using elastic dynamic analysis and verified using static nonlinear analysis.

The works executed in the rotunda are the following:

Structural intervention works
- Crack restoration using pouzolanic grouts
- Crack stitching,
- Stone stitching
- External posttensioning at four levels
- Steel casing of all the dome window openings

Architectural restoration works
- Wall paintings restoration
- Icons restoration
- Marble floor removal and restoration
- Wooden windows and doors restoration
- Wooden furniture restoration
- New interior and exterior lighting
- Restoration and repointing of the decorative painting of the church
- Restoration and retouching of the decorative painting of the groin vaults
- Restoration of external stone cornices
Figure 12. F.E. analysis of strengthened Church (nonlinear) for 1.60 the dead loads

Figure 13. F.E. analysis of strengthened Church (nonlinear) for 0.30g lateral loads (1.1% drift)

MEP works
- installation of air conditioning system
- installation of sound system
- fire alarm and fire detection system
- fire-fighting system
- hi and low voltage cabling
- generator
- electrical substation
- fire pumps and tank

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