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Earthquake structural problems and urgent measures undertaken to support the Katholikon of Dafni Monastery in Athens, Greece

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Abstract

The Byzantine monastery of Dafni, already inscribed in the world heritage list of UNESCO, is one of the most important monuments of middle Byzantine period, famous worldwide for the excellent mosaics of the Katholikon. Being in a highly seismic area, the monastery suffered throughout its history a large number of earthquakes that caused many structural problems and damages to its mosaics.
This presentation focuses on the emergency measures undertaken by the Greek Ministry of Culture after the earthquake of September 7th 1999 in Athens, in order to avoid local collapses and further damages from aftershocks, and ensure safe working conditions for the personnel. The basic philosophy of the urgent interventions and the different temporary shoring and strutting measures, that have finally been realized, are briefly presented.

1 Introduction

Immediately after the struck of the 7-9-1999 earthquake, an interdisciplinary working group of scientific personnel (engineers, architects, archaeologists and conservators) was assigned by the Ministry of Culture in order to make the necessary inspections and assess the nature and the significance of the damage provoked to this major monument [1]. In the same time a Scientific Committee,

composed by high-level experts, namely, Prof. Ch. Bouras, Prof. T. Tassios and Prof. H. Mariolakos, was created to collaborate with the competent authorities, offer guidance and follow up all the relative projects.

Bearing in mind the risk of aftershocks, special tissues were immediately installed at various heights near the mosaics to collect the mosaics' tesserea, which could fall down, while telltales were installed in all the accessible severe cracks. A crane was used for inspections all around the dome area and the exonarthex, while parts of dislocated masonry were removed to the ground.

According to these first inspections, the monument was characterized as severely damaged, concerning both the structure and its mosaics. The Ministry of Culture decided to undertake urgent temporary measures to support the damaged buildings and protect them from further deterioration [2]. The project was designed and undertaken by the Directorate for Restoration of Byzantine and Post–byzantine Monuments, in collaboration with the 1st Ephoreia of Byzantine Antiquities and the Directorate for the Conservation of Antiquities.

2 Brief description of Katholikon

The Byzantine monastery of Dafni comprises various buildings laid out in a square plan, dated from the 11th century and afterwards [3]. In the present situation (Fig.1) most of the buildings are in ruins, except of the Katholikon, part of the internal range of cells, kinsterna and the northern fortification walls. The Katholikon belongs to the octagonal type, preserves an extensive part of mural mosaics (Fig. 3,4,6) and comprises (Fig 1,2) the main church, the sanctuary, the narthex and four chapels, which complete its orthogonal plan. In the western part, only the perimetric walls of the exonarthex and the bell tower have survived.

The central part of the main church is cross-shaped in plan. Over the center, rises the dome (Fig 2,3) carried on eight pendentives, four semicircular arches, and four squinches in the corners, achieving in this way the transition from circle to square. Thus, twelve piers, laid out in a square plan, provide support to the dome together with the groin vaulted arms of the cross, situated in a higher level. The hemispherical dome is carried on an almost cylindrical drum with 16 piers and 16 vaulted windows. Its diameter is 8,2m and its height is 16,4m. All the other parts of the church are groin vaulted.

3 Historical pathology

The Monastery is situated in a neogene tectonic graben between the mountains Eagaleo and Korydallos at the west side of the basin of Athens, 150m away from the E-W trending marginal fault between the alpine Mesozoic limestone and the post-alpine deposits [4]. Located in a tectonically active area, many intensive earthquakes damaged Dafni's Monastery throughout the centuries. Partial collapses and extended damages were provoked to the load bearing structure and the valuable mural mosaics, which led in great scale interventions [5].

The exonarthex does not preserve today its groin vaulted cover. Thanks to extended restoration works realized in the middle of 20th century, its perimetric

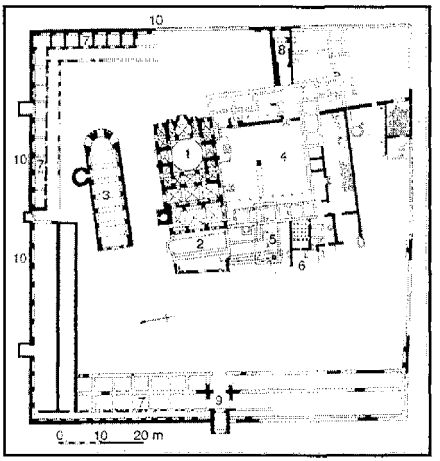


Figure 1: Byzantine Monastery of Dafni.

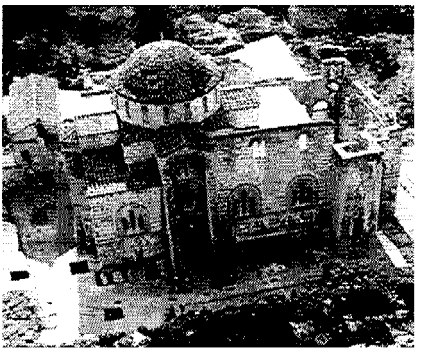


Figure 2: NE view of Katholikon.

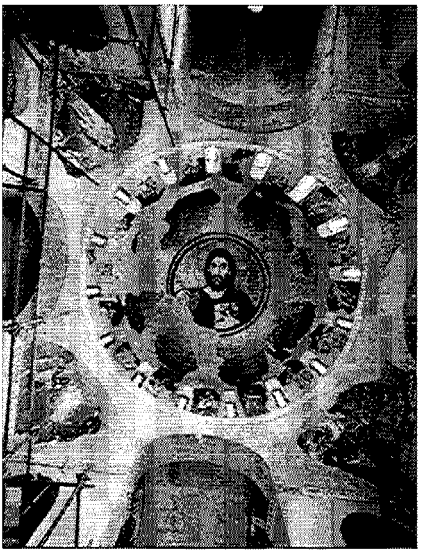


Figure 3: View from below of the central part of the Katholikon.

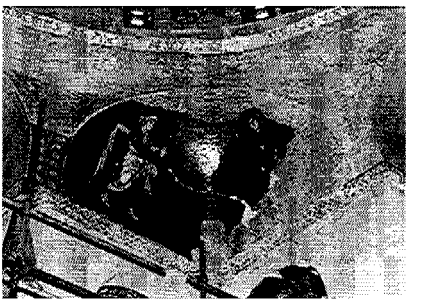


Figure 4: NE squinch heavily damaged.

walls are still standing free [6]. The dome and its drum were demolished and re-erected in 1891. The groin vaulted cover of the narthex and important parts of the walls were re-erected after severe damages and local collapses (1894) [7]. Two stone masonry buttresses were added in the external northern arm of the cross to support the central piers, while in the southern arm steel straps were installed, in three different levels all around the central piers, anchored by special steel constructions placed in the southern façade of the monument (1907).

An important part of the mosaics, especially in the re-erected areas, was removed and replaced after the accomplishment of the structural interventions

with the collaboration of Italian mosaic conservators (1890-1897) [5,7].

The upper part of the southeastern corner of Katholikon was re-erected and the extrados of all the vaulted structures were repaired. Retiling of the roof and local repointing of the masonry crumbling mortar joints took place [6]. Moreover, a steel tie was installed to the external upper part of the drum, encircling the hemispherical shell of the dome near the springing level.

4 Damages caused by the 7-9-1999 earthquake

After the earthquake, an extensive network of shear and bending cracks appeared on the vertical walls and piers and on the arches and groin vaults, affecting both the structural safety of the building and the mural mosaics (Fig. 5). The damages are more extensive in the higher parts, especially on the piers of the drum of the dome, the squinches, the arms of the cross and the sanctuary (Fig. 3, 4, 5, 6). The most defective parts of the lower levels comprise the structural dislocation and outwards split of the external walls of the NE corner, and the appearance of vertical cracks in the corner piers of the free standing walls of exonarthex. On the external walls of the bell tower, older cracks were enlarged and new ones appeared. The last remains of the internal staircase collapsed.

The structural condition of the dome's area, concerning the drum itself and the load bearing structures underneath, was assessed as extremely critical [8]. In fact, the drum's piers situated perpendicular to the direction of the earthquake present horizontal bending cracks on the top and the bottom, whereas those situated parallel to it present diagonal shear cracks. In all cases the cracks are running through the thickness of the piers, thus creating very often an inclined slide plan and local dislocations of masonry's parts. The crack pattern revealed that the drum could not any more behave as a whole. Fortunately, the existence of the external upper metal tie-rod encircling the dome near the springing level averted severe cracking of the hemispherical shell. Moreover, all the arches are also cracked near the crown or the haunches, while the NE and NW arches under the squinches present severe dislocation near their crown, with consequently out of plane deformations of the squinches themselves.

Taking into account the above pathology, it was assessed that, in a case of a severe aftershock, the possibility of a complete collapse of the two already dislocated squinches, which support the dome, and the activation of a dome's collapse mechanism could not be excluded. This assessment was supported not only by the historical pathology of the Dafni's Katholikon itself, but also by the fact that a lot of well known octagonal Byzantine churches do not preserve any more their initial dome in our days, probably due to similar damages.

5 Basic concept of the emergency intervention

Taking into account the severe damages of the structure, as well as the danger of eventual aftershocks, temporary measures had to be undertaken urgently. The aim was on one hand to reduce the danger of further worsening of the damages and, on the other, to ensure accessibility and safe-working conditions for the

scientists, conservators, workers, as well as to enable the emergency works on the mural mosaics. Besides, these measures were necessary for the realization of all the adequate surveys and investigations, in order to design, as quickly as possible, the suitable schemes for final structural restoration works.

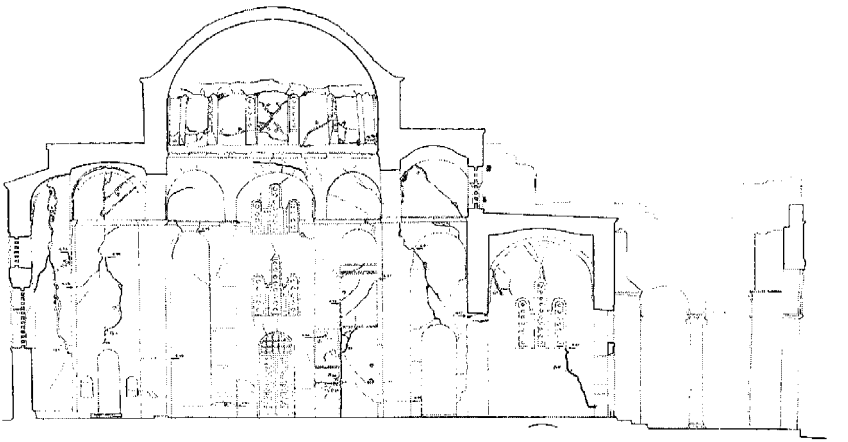


Figure 5: E-W longitudinal section - Crack pattern on the southern elevation.

Figure 6: View from below of the piers of the southern part of the dome's drum.

All the emergency interventions had to be designed taking into account specific demands deriving from the importance of the monument and the necessity for implementation of future restoration works. They had also to be reversible, easily assembled and gradually disassembled in the interior; moreover they had to be adjustable to the deformed geometry of damaged elements, and versatile against possible new findings. Their implementation had to avoid any contact with the vulnerable mural mosaics, as well as any excavations.

Two basic categories of interventions have been undertaken. The first concerned the installation of various types of scaffoldings in the interior and exterior, as well as the water isolation of the vaulted roof. The second one concerned the strutting and shoring the various parts of the monument.

6 Presentation of the emergency interventions

Rigid metallic scaffoldings with steel and wooden platforms at different levels were constructed in the interior of the monument (Fig. 8). The number of these platforms depended on the total height of the various areas and the needs of the conservators for the urgent interventions to the mosaics.

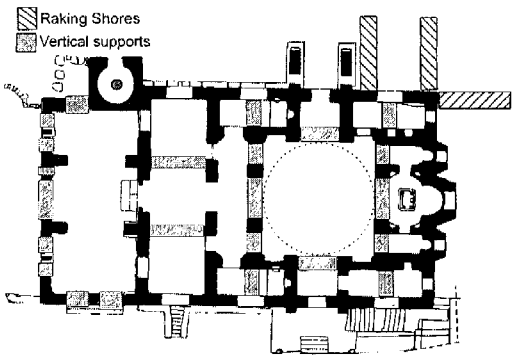


Figure 7: Areas where raking shores and vertical supports were placed.

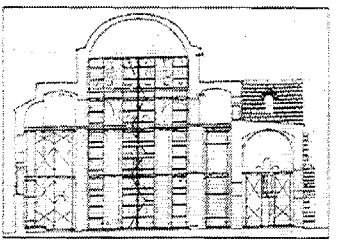


Figure 8: Internal rigid scaffolding and working platforms.

In the central area the whole scaffolding was designed in order to offer safe working surfaces for the personnel and carry all the weight that could derive from a possible total or partial collapse of the dome.

Externally, a more common scaffolding was installed to provide accessibility to the higher levels of the walls and the roof, while temporary water isolation has been realized just below the byzantine tiles, to protect the cracked vaulted structures and the mural mosaics decorations from leaking water. All scaffoldings were completely independent from the entire building and consisted of tubular galvanized steel elements.

In order to improve temporarily structural stability and to avert the danger of collapse, especially in the central part of the building in case of possible aftershocks, alternative possibilities had to be considered. The best measure to reduce the movements at the springers of the four main arches would be the installation of a system of ties. This was postponed to be part of the final restoration project, since the realization of the adequate anchorages of such ties necessitated long drilling through the width of the already cracked and dislocated squinches, with consequences to the mural mosaics.

The use of traditional shoring procedures, with the props resting on the ground outside the building in order to undertake seismic forces, was rejected. In fact, given the important mass of the monument, the calculations made to

estimate the approximate dimensions of such steel props have indicated that the new structures and especially the surface foundations to anchor them on the ground had to be of substantial dimensions. On the other hand anchoring the props in the ground by piles was excluded due to the existence of archaeological substrata. Furthermore, there was a general hesitation for the implementation of such massive constructions that may act in some cases as battering rams causing local destruction of the elements they are supposed to support. Therefore, such structures were installed only in the NE corner of the building, where a pronounced tilting of the external walls has been noticed. In this area, the telltales installed just after the earthquake, indicated further opening of cracks, i.e. a tendency of the corner to detach.

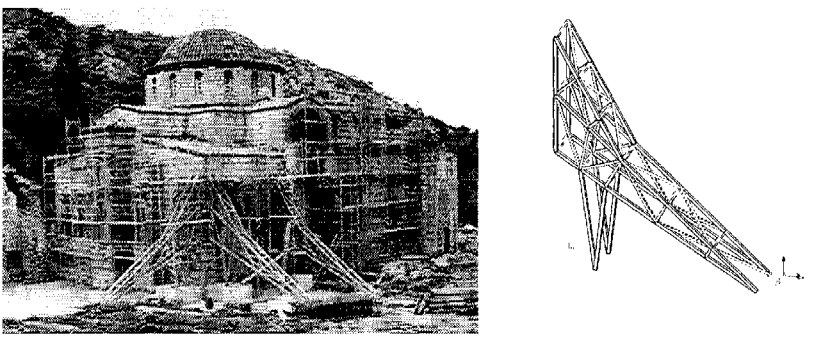


Figure 9: Northeastern view of Katholikon with metal raking shores.

Thus, a system of three interconnected double-framed metallic raking shores was constructed (Fig 7, 9). The raking shores were designed to act as distinct independent new elements and not as integral parts of the structure. They behave as cantilever beams and are able to carry horizontal seismic forces to the specially designed reinforced concrete foundation elements.

The metal framework was constructed using simple rectangular hollow steel beams, protected against rust. Each framework was founded on two concrete "feet", laid out partly under the ground surface in especially excavated pits, after carrying out all the necessary archaeological investigations. The front connection of the framework was anchored with special devices in the bottom of the feet, to take the best profit of their mass since it acts as a kind of counterweight, while the back foot was articulated. Between the metal framework and masonry walls, a 12cm full layer of wooden beams and wedges (together with a 3mm soft packing) were inserted, to provide better contact with the masonry while allowing relative movement, unless the corner did start to move outwards.

In the interior, vertical props were built up beneath the main arches in order to provide vertical support to their cracked structure and relieve the disrupted piers from the heavy loads of the dome. These steel props were designed to act as distinct independent new elements and not as integral parts of the structure; they have no firm contact with the piers in their sides (Fig. 10). That is why they were not anchored in the ground by means of foundation elements. This solution was chosen in order to avoid excavations and destruction of the marble floor.

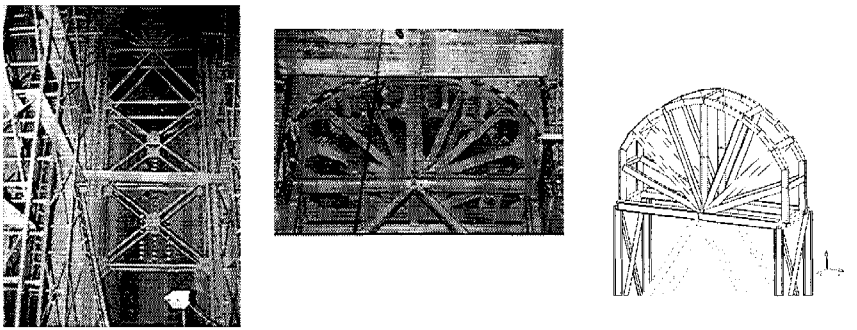


Figure 10: Steel vertical props to support the arches.

The use of steel shapes, suitably protected against rust, instead of timber, was adopted in order to reduce the dimensions, provide better fire resistance and avoid dimensional changes due to moisture variations and creep effects [9]. The steel elements were executed based on in situ measurements and moulds to fit the deformed geometry of the arches. Smaller pieces were connected by means of electrical welding in a worksite outside the monument, whereas larger elements were constructed and carefully transported in the interior, where the final structure was assembled by screwing the joints. Especially the vaulted upper parts of wide arches were set up in two parts (Fig. 10) with screwing joints in order to provide easy transport and partial disassembling. The smooth contact between the masonry and the steel beams was achieved by inserting a very dense layer of wooden beams and wedges, together with 3mm soft packing. The whole system permitted to follow the relief of the masonry without harming the surfaces, while allowing relative movement.

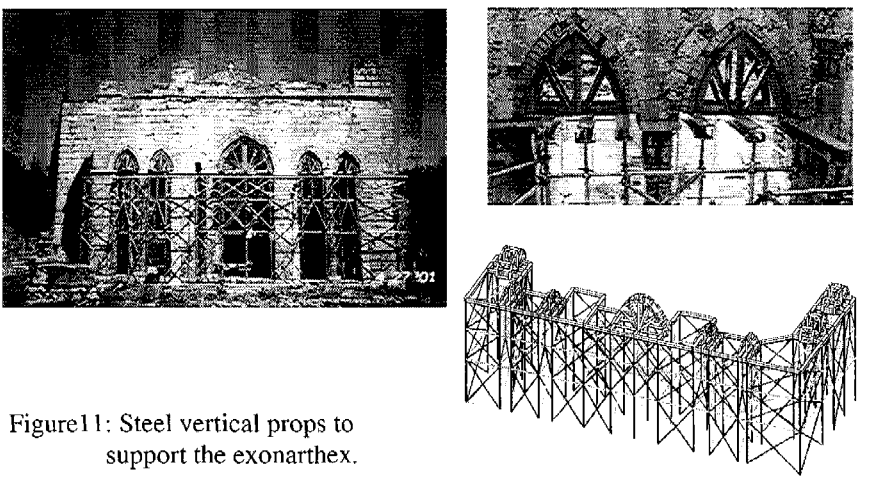
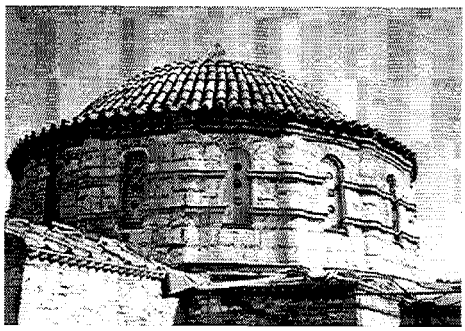


Figure11: Steel vertical props to support the exonarthex.

The same procedure was followed for the lower vaults of the central area situated under the squinches after local detachment of the mural mosaics and repairs of the area of the dislocated crowns. This procedure was also used for the arches of each of the chapels in the four corners of the main church, the crypt, the

exonarthex and the major arches of narthex (Fig. 7). In the case of exonarthex, only the upper parts were constructed, using steel normal profiles (Fig.11).

Regarding the drum of the dome, specific measures of strapping the piers in two levels and bracing its openings were decided, by means of specially designed steel elements (Fig. 12,13). The final geometry and form was based on in situ measurements for each deformed pier and opening, while special care was taken to assure the assemblage of all these structures without harming the mural mosaics. Only in the south pier the mosaics were partially removed.



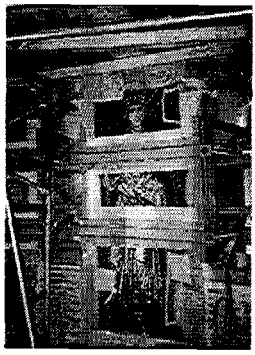
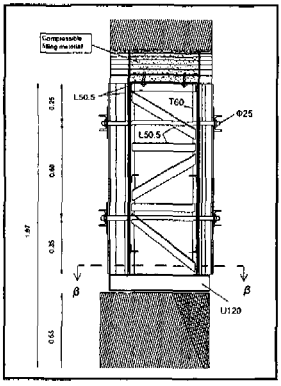


Figure 12: External and internal view of the dome after the interventions.



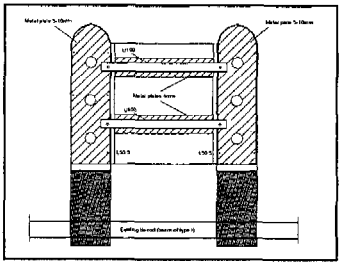
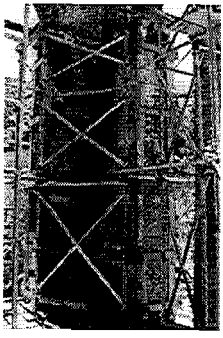


Figure 13: Internal view of the interventions of the dome. Drawings of the metal structure.

Strapping techniques were also applied in the two corner piers of the exonarthex and the bell-tower, as shown in fig 14.



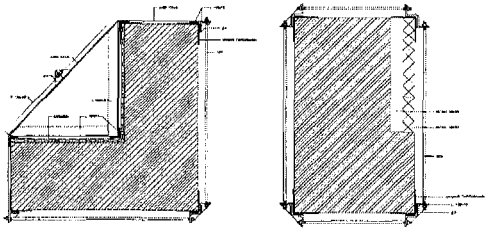


Figure14: Steel straps to support the exonarthex corners.

7 Conclusions and Acknowledgements

The afore mentioned immediate measures have permitted the implementation of the necessary emergency works on the mural mosaics and the achievement of detailed surveys and investigations indispensable for the design of the final restoration works.

Regarding the final redesign of the monument, several research programs were initiated on specific matters, concerning accurate survey of geometry, construction materials and types, monitoring of the evolution of the damages and structural analysis, in collaboration with the National Technical University of Athens (Prof. A. Georgopoulos, Assoc. Prof. E. Vintzileou) and the Polytechnic School of Aristotle University of Thessaloniki (Prof. I. Papagianni).

The fulfillment of the whole project had the constant support and guidance of all the members of the scientific Committee, as well as of M. Fountoukou, Director, A. Christofidou, Head of the Section for the restoration works, N. Charkiolakis, Head of the Section for the studies on Byzantine monuments of the Directorate for Restoration of Byzantine and Post–byzantine Monuments, and E. Tsofopoulou, Director of the 1st Ephoreia of Byzantine Antiquities.

The execution of the project was carried out by the specialized construction company STEM, under the direction of A. Froussos.

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