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A multidisciplinary approach for the structural restoration of the Katholikon of Dafni Monastery in Attica Greece

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ABSTRACT: The Katholikon of the Byzantine monastery of Dafni (world heritage list of UNESCO), is one of the most important monuments of middle Byzantine period, famous worldwide for its mural mosaics. Being constructed in a seismic area, the Katholikon was affected throughout its history by a large number of earthquakes that caused structural problems and damages to its mosaics. This paper focuses first on the historical and recent pathology studies of the monument and the emergency measures undertaken by the Hellenic Ministry of Culture after the earthquake of 1999 in Athens. Then, a synthesis of the results of research programs, investigations and structural restoration studies is presented. Furthermore, a brief presentation is made of the first phase of interventions executed for the consolidation of the masonry and the control of their efficiency using novel methodologies, non destructive techniques and monitoring systems.

1 INTRODUCTION

Dafni Monastery, situated at approximately 10 km from Athens on the way to Eleusis, is one of the major Byzantine monuments in Greece (Millet 1899, Stikas 1962, Bouras 1998, Delinikolas et al. 2003). The Katholikon (main Church) of the Monastery (Figures 1 and 3) has suffered severe damages during the 7th September 1999 earthquake that affected the region of Attica.

Immediately after the earthquake, a multidisciplinary working group (Delinikolas et al. 1999) was formed by the Hellenic Ministry of Culture (HMC) with the assignment to do the necessary inspections, assess the nature and the significance of damages and elaborate, together with a Scientific Committee set to this purpose (composed by Professors Ch. Bouras, T. P. Tassios, E. Mariolakos and N. Zias) and all competent authorities of the Ministry, a strategic plan for the protection, conservation and restoration of the monument, its mosaics included.

Due to the severe damages of the structure and the danger of eventual aftershocks, the decision was taken for the application of emergency measures (Miltiadou-Fezans et al. 2003a). The aim of those measures was (a) to reduce the danger of further deterioration of structural damage and (b) to ensure accessibility and safe working conditions for all the scientific and technical personnel, thus enabling the execution of all the surveys and investigations, necessary for the design and implementation of the most adequate structural restoration interventions.

Figure 1. N-W view of the Katholikon of Dafni Monastery.

In parallel with the design and implementation of emergency measures, a first series of research programs were initiated, in order to record the state of the monument immediately after the earthquake. These programs were aiming at: (i) accurate survey of geometry (Georgopoulos et al. 2003), (ii) preliminary survey of damages, assessment of mechanical properties of construction materials, monitoring of the width evolution of main cracks, and preparation of a first detailed computer model of the monument used for preliminary structural analyses (Vintzileou, 2002) and (iii) assessment of the physicochemical characteristics of the construction and pointing mortars (Papagianni 2002).

The above research works were carried out in close collaboration with the responsible multidisciplinary team nominated by the competent authorities of the HMC. On the basis of a synthesis of the obtained results, adequately completed with detailed in situ observations and archive researches, the multidisciplinary group of the HMC has elaborated the structural restoration study (Delinikolas et al., 2003, Miltiadou-Fezans et al. 2003b). Following the proposals of this study, approved by the Scientific Committee and the Central Archaeological Council, it was decided to implement the structural restoration design and interventions in two phases.

Given the importance of the monument, a step by step multidisciplinary approach was adopted, both concerning the design and the implementation of the structural restoration interventions. Such an approach gives the possibility to start the execution of a series of interventions, and in the same time to perform the in situ and laboratory investigations that are necessary for the design of the next step. Furthermore, the assessment of the effect of the first step interventions to the structural behaviour of the monument can be carried out and taken into account for the design of the works of the second step. The first phase of interventions (that is completed) comprises measures taken to repair and strengthen masonry elements. The interventions of the second phase aim to improve the overall behaviour of the entire structure; their design is still in progress.

Moreover, within the HMC, it was judged as absolutely necessary to support the two phases of works with further research and investigations, comprising the design of adequate mortars and grouts, the experimental estimation of mechanical characteristics of masonry before and after grouting, the seismic monitoring of the structure, the application of NDT's for investigating invisible parts of the monument and controlling the grouting effect and efficiency.

In this paper, a brief synthesis of all the aforementioned investigations, studies, emergency and structural restoration works will be presented.

2 BRIEF DESCRIPTION OF THE KATHOLIKON OF DAFNI MONASTERY

The Byzantine monastery of Dafni comprises various buildings (laid out in a square plan), constructed over a long period of time, starting on the 11th century AD (Delinikolas et al. 2003). Currently, most of the buildings are in ruins, with the exception of the Katholikon, part of the internal range of cells, the cistern and the northern fortification walls.

The Katholikon belongs to the octagonal type and preserves large part of the original mural mosaics. It comprises the main church, the sanctuary, the narthex and four chapels, which complete its orthogonal plan. In the western part, only the perimeter walls of an exonarthex or portico and those of a spiral stairway tower leading to the upper floor have survived (Figs 1, 2, 5). The central part of the main church is

Figure 2. N-E view of Katholikon.

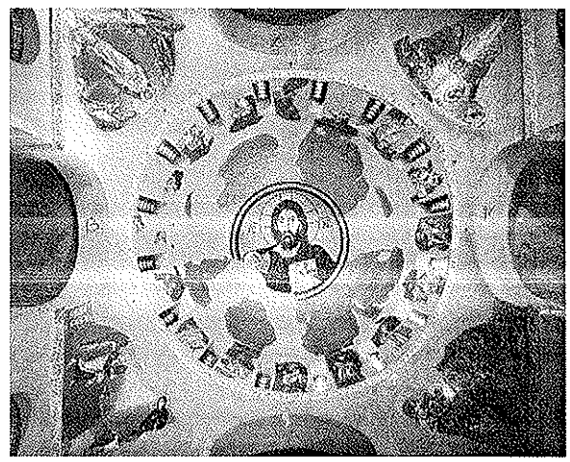


Figure 3. The central dome and its drum, carried by eight pendentives and eight arches.

cross-shaped in plan, the hemispherical dome rising over its square core. The dome is 8,2 m in diameter and 16,4 m high, and rests on an almost cylindrical drum with 16 piers and 16 vaulted windows. The dome and its drum are carried by eight pendentives and eight arches (four semicircular and four embodied in the squinches of the corners), forming an octagon and achieving in this way the transition from circle to square. Thus, twelve piers (laying out in a square plan), provide support to the dome together with the groin vaulted arms of the cross, situated in a higher level (Figs 3 & 4). All the other parts of the monument are covered with byzantine groin vaults.

As one can clearly distinguish in Figures 1 and 3, the exterior face of the vertical perimeter walls are built according to the enclosed brick system (stones with bricks around them), following two different masonry construction types. In fact, there is a lower zone, built with large dimension stones (often, reused material), their length placed horizontally or vertically, in order to form crosses, and un upper zone constructed with ashlar masonry, using smaller and perfectly cut orthogonal stones (Delinikolas et al. 2003). Bricks are placed in all horizontal joints, and in most of the vertical ones. The thickness of mortar joints is of 3 cm approximately. Plain brick masonry was used in the construction of all the windows and doors (Fig. 2). In the internal face of the perimeter walls, as well as in internal masonry elements in general, the enclosed brick system is not followed systematically, whereas in various locations, a mixture of cut, semi-cut and rubble stones are used together with bricks. Thus, the thickness of masonry joints is varying. Finally the entire vaulted roof was constructed with plain brick masonry.

Both the lower and upper parts of the perimeter walls are constructed following the three-leaf masonry type, with varying widths of the leaves, as will be more analytically presented below (Section 9).

3 CONCEPT AND BRIEF PRESENTATION OF EMERGENCY INTERVENTIONS

The emergency interventions were designed taking into account specific demands deriving from the importance of the monument and the necessity for implementation of final restoration works without removing the supports and scaffoldings. Thus, they had to be reversible, easily assembled and allowing for gradual disassembling in the interior, as well as adjustable to the deformed geometry of damaged elements. Moreover, any contact with the vulnerable mural mosaics was to be avoided.

To this end various alternative solutions were examined (Miltiadou-Fezans et al. 2003a). Figure 4 shows schematically the retained one. In the NE corner of the building, three double-framed steel raking shores was constructed, as in this area a pronounced tilting of the external walls has been noticed and the telltales installed just after the earthquake, indicated further opening of cracks and a tendency of the corner to detach (Fig. 5). In the interior, and in the exonarthex, vertical steel props were built beneath the main arches, in order to provide vertical support to their cracked structure (Fig. 6).

Both the raking shores and the vertical props were self supported elements, which would be activated only in case of further increase of the deformations of the structure. Thus, between the metal framework and masonry walls, a 12 cm full layer of wooden beams and wedges (together with a 3 mm soft packing) were inserted, to provide good contact with the masonry without harming the surfaces, while allowing relative movement, unless the structure did start to move towards them. Moreover, the upper part of the exonathex walls and the NW and SW piers were confined using steel plates and bars.

Regarding the drum of the dome, specially designed steel elements were constructed to brace the windows and confine in two levels the masonry piers (Fig. 7),

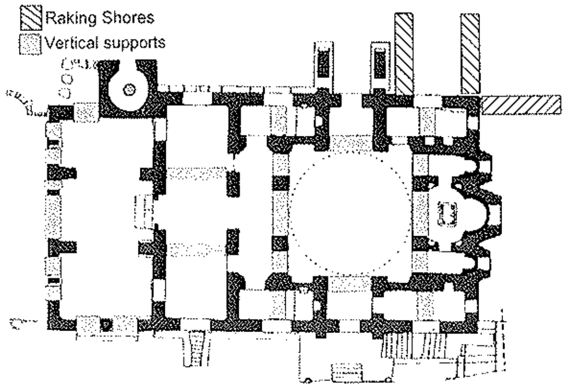


Figure 4. Plan of the Katholikon and schematic presentation of the arrangement of the raking shores and vertical props.

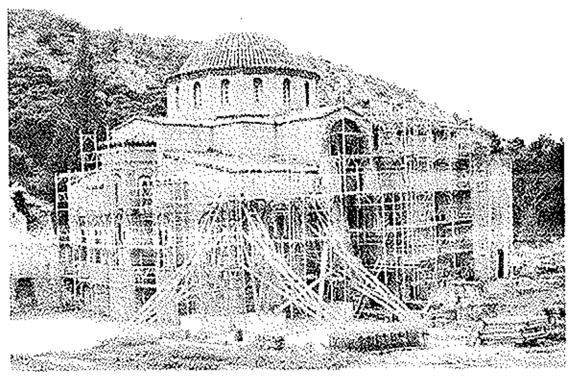


Figure 5. Raking shores installed in the NE corner.

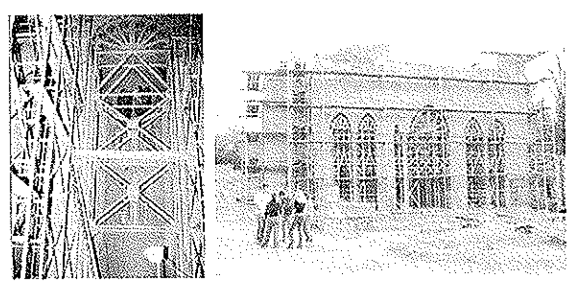


Figure 6. Vertical steel props installed in the interior of the church, and in the exonarthex.

taking special care to assure the in situ assemblage of all these structures without harming the mural mosaics. Furthermore, the following measures have been undertaken: (a) the installation of adequate types of scaffoldings in the interior and exterior of the church, in order to offer safe working conditions for the personnel, and (b) the removal of the tiles of the roof and the application of temporary water isolation membranes just below them, to protect the cracked extrados of the vaulted structures, and hence the mural mosaics from leaking water.

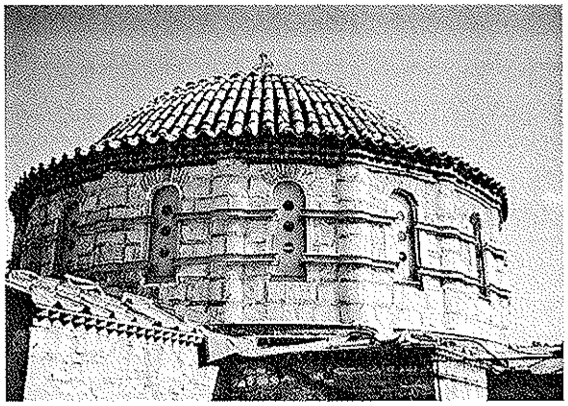


Figure 7. Emergency measures applied to the dome's drum.

4 HISTORICAL PATHOLOGY AND PAST INTERVENTIONS

The Monastery is situated in a Neocene tectonic graben between the mountains Egaleo and Korydallos at the west side of Athens, 150 m away from the E-W trending marginal fault between the alpine Mesozoic limestone and the post-alpine deposits (Mariolakos et al. 2000). Located in a tectonically active area, many intensive earthquakes damaged Dafni Monastery throughout the centuries (from 11th c. to our era). Partial collapses and extended damage were provoked to the structure and the mural mosaics, which led to major interventions. Detailed presentation of the long history of the monument is reported in Delinikolas et al. 2003, whereas a concise summary is given in this paragraph.

Two main phases of construction have been identified in the Katholikon of Dafni Monastery, both dating back to the middle Byzantine period. Although the construction type of masonry is similar in the two phases, the composition and final texture of pointing mortar used is different, thus allowing for the two phases to be identified in situ. The first phase comprises the main church and the narthex (Fig. 8). A reddish mortar containing crashed bricks was used for the pointing of the joints of the monument's external façades. At a second phase, a portico or exonarthex was added to the church (in its west part); masonry piers in the corners and marble ionic columns in the middle were used to support the arches of the added perimeter walls. Over the portico and the west part of the church a first floor was also added. Finally a spiral staircase tower was constructed in the NW corner of the narthex (Fig. 9). A whitish mortar with a yellowish patina was used for the pointing of the joints of the external façades.

Severe damage was provoked to the church during the 13th century, when Athens was occupied by the Franks. The first floor and the three groined vaults

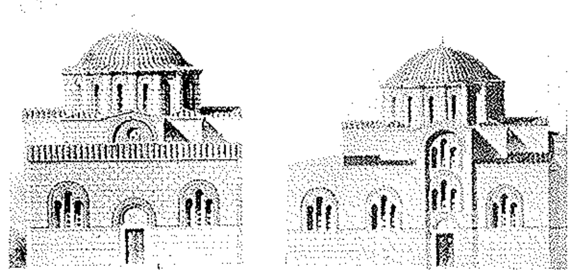


Figure 8. West and south façade: 1st construction phase, drawings of Benouville as modified by Delinikolas (Millet 1899, Delinikolas et al. 2003).

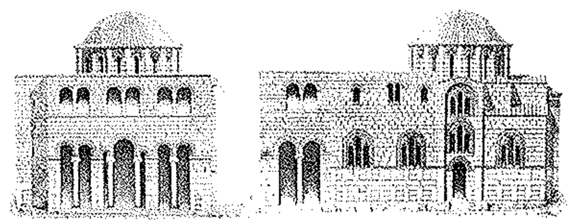


Figure 9. West and south façade: 2nd construction phase, graphical representation of Stikas as modified by Delinikolas (Stikas 1962, Delinikolas et al. 2003).

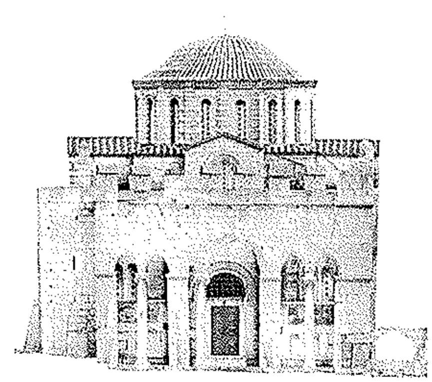


Figure 10. Graphical representation of the W façade of the portico as restored by the Cistercians (Delinikolas et al. 2003).

of the exonarthex have probably collapsed, provoking severe damage to the rest of the structure. The narthex, the dome and its supporting system were as well severely damaged. Thus, extensive interventions were undertaken by the Cistercian monks mainly in the west part of the monument (13th–15th c.). The upper part of the west wall and the majority of arches, were reconstructed with curved stones following the gothic style (Figure 10). Furthermore the exonarthex was covered with a timber roof and bastions were built on the top of the walls. The remains of the constructions of the first floor, the narthex and the rest of the church were also locally repaired. These extended interventions in

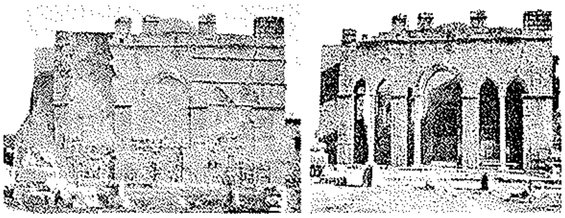


Figure 11. West façade of the exonarthex before and after Stikas restoration interventions (photos Stikas, 1962).

the west part of the Katholikon can be considered as the third construction phase of the building.

During Othoman occupation strong earthquakes provoked further deterioration of the damages of the entire church. Cracks appeared on the vaulted roof of the crypt and the narthex, whereas severe damage and partial collapse occurred to the exonarthex and the spiral staircase. Thus, the arches of the exonarthex perimeter walls were filled with masonry, and extended alterations took place in the west part of the monument. During that period some of the ionic columns were taken by Lord Elgin to England.

The structural condition of the monument was further deteriorated during the 19th and the 20th centuries, due to numerous earthquakes occurred and major interventions were applied for the preservation of the monument. One should mention the 1889 and 1894 earthquakes (estimated magnitudes 6,7 and 7,0 on the Richter scale), the 1914 earthquake (M 6,0R), the 1981 earthquake (M 6,7R) and finally the 1999 one (M 5,9R). After the 1889 earthquake, the heavily damaged dome and its drum were removed and reconstructed. Three concentric iron rings (I-beams) were inserted at the base of the drum of the dome, as identified during the recent restoration works. Before removing the old dome, the mosaics were detached and, after their conservation, partially re-attached to the monument by Italian Conservators. During these interventions, the lime based mortar of the mosaics substrata was replaced with a hydraulic lime based one. The 1894 strong earthquake caused further damages; even the recently reconstructed dome and its drum were once again cracked. Extended interventions took place to the west part of the monument, including the reconstructions of almost the entire narthex (Troump, 1896). In the period of 1897 to 1907, two stone buttresses both sides of the north entrance to the church were constructed, while metallic trusses (fixed on new foundation) were installed both sides of the south central piers, together with iron plates and bars inserted at three levels, in order to confine them. In 1914, the suggestion is made for external confinement of the central cupola with an iron ring. This solution, however, was applied 40 years later.

In that period of 1955–1960 the ottoman interventions were removed from the exonarthex (Fig. 11) and the Cistercian construction phase was restored by Stikas (Stikas 1962). The collapsed part was rebuilt and the missing ionic columns were replaced by masonry piers. A concrete beam was installed in the interior of the reconstructed parts, without affecting the byzantine remains of the SW pier. The upper part of the SE chapel was also reconstructed, while extended local re-pointing took place in various areas of the Katholikon, using mainly cement based mortars. Fortunately the non deteriorated old mortars were not removed. Thus, they survived to our days in better condition than those used by Stikas, which presented extended decay and during the recent restoration works were removed.

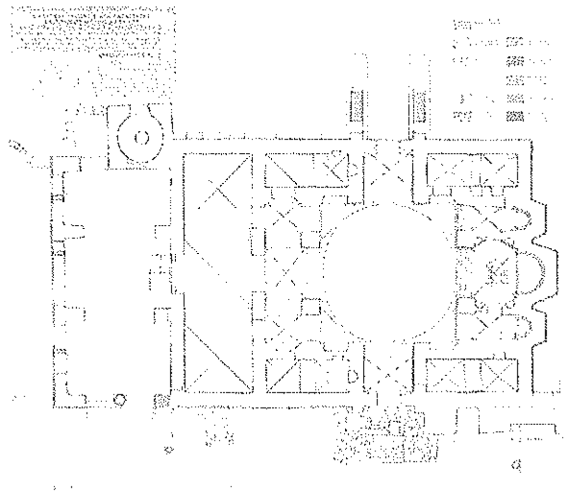


Figure 12. Interventions to the monument: Plan.

Figures 12 to 14, taken from Delinikolas et al. 2003, present the historical pathology and past interventions on drawings. The reconstructed parts of the monument are shown with solid colors. Yellow: 13th–15th c., orange: 1891, green: 1895, purple: 1897–1907, dark blue: 1955–60.

The 1981 earthquake (Alkyonides islands) caused numerous hair cracks to the building and severe damages to the mosaics. Thus, the pathology observed in the monument after the 1999 earthquake was only partly due to this severe earthquake.

5 SURVEY OF DAMAGES AFTER THE 1999 EARTHQUAKE

The systematic survey of damages after the September 7th, 1999 earthquake, reported in Miltiadou-Fezans et al. 2003b and 2004, is summarized in this section. In Figure 15 some typical drawings of cracks and deformations survey are presented, showing the severe damages observed in the monument (both to its structural part and to the mosaics).

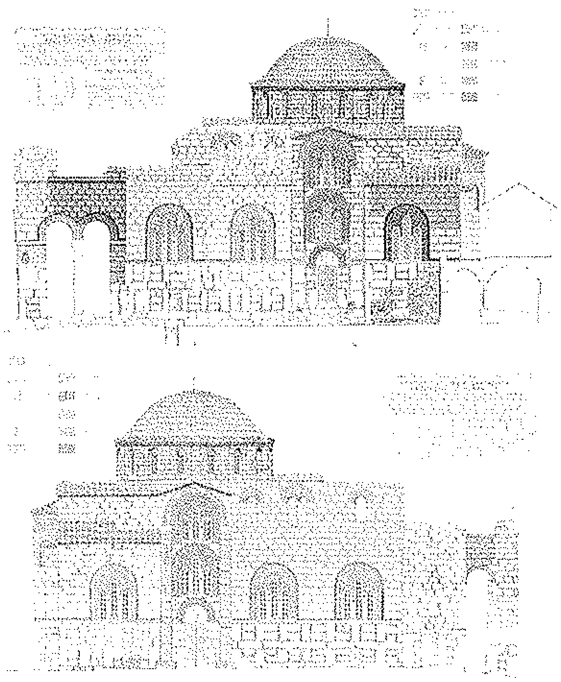
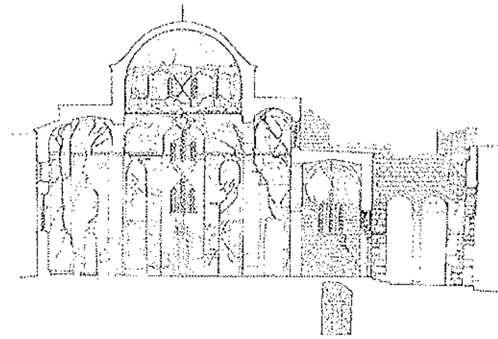


Figure 13. Interventions to the monument: S and N façade.

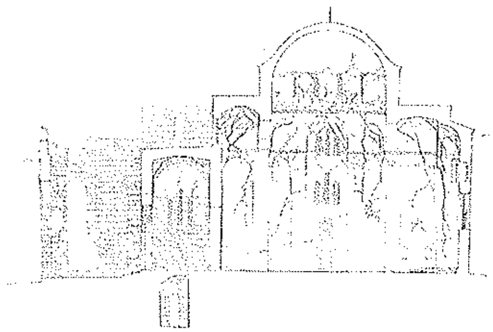
Figure 14. Interventions to the monument: West façade of (a) the church and (b) the exonarthex.

An extensive network of shear and bending cracks (ranging from hair cracks to those several centimeters wide) has appeared on the walls and piers of the monument, whereas numerous old cracks (due to previous earthquakes) increased in length and width. Severe structural dislocation and outwards movement of the walls was recorded in the NE corner of the main church (~14 cm to the N and ~10 cm to the E). Significant out-of-plane displacement of the N and S arms of the cross (~16 cm and 21 cm respectively), and of the free standing west wall of the exonarthex were also recorded, due to further deterioration of previous deformations (~16 cm in the corners and ~25 cm in the middle).

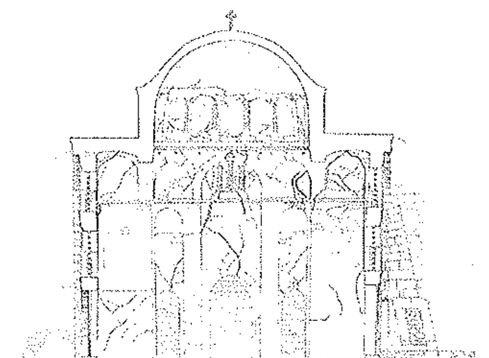
The damages were more extensive in the higher parts of the structure, especially in the sanctuary, the arms of the cross and all the arches below the dome area. As shown in Figure 15, the NE and NW small



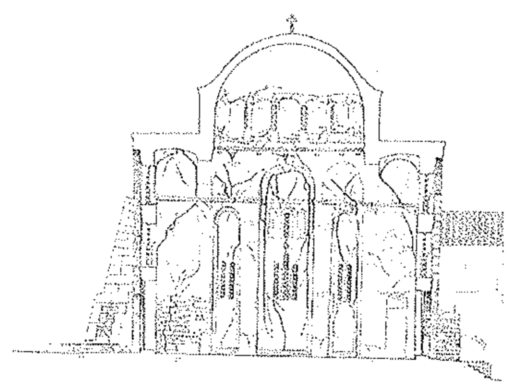
(a) East-West section. View to South



(b) East-West section. View to North



(c) North-South section. View to West



(d) North-South section. View to East

Figure 15. Typical presentation of damages.

arches just below the squinches presented severe dislocation near their crown, followed by out of plane deformations of the squinches themselves. Cracks appeared also in all the groin vaults of the church. The structural condition of the dome (reconstructed at 1891 and damaged soon after its reconstruction at 1894), was assessed as extremely critical immediately after the earthquake (Delinikolas et al. 1999, Miltiadou et al. 2003a, 2003b). Horizontal cracks have appeared along the perimeter of the drum (both at its base and top). In the piers of the drum that are situated perpendicular to the East-West direction, horizontal cracks (due to out-of-plane bending) have opened at their top and bottom. In the piers that are situated parallel to the E-W axis, diagonal or bi-diagonal (shear) cracks have appeared. In the intermediate piers, mixed type of (less severe) cracks was observed. This pathological image does seem to confirm seismological data regarding the predominant direction of the 1999 earthquake. Thanks to the external upper metal tie-rod, confining the hemispherical dome near the springing level, the occurrence of severe cracking of the dome's shell was prevented.

6 QUALITATIVE INTERPRETATION OF DAMAGES

As reported in Miltiadou-Fezans et al. 2004, it was observed that the number and the opening of crack in the vertical elements of the Katholikon increase from the base to the top of the monument. It was therefore obvious that the monument exhibits the tendency to "open" from the base to the top along both main directions. This deformed shape of the church, verified by the photogrammetric survey (Georgopoulos et al. 2003), is confirmed also by the history of the monument. The South façade of the narthex reached in 1894 a total out-of-plane deformation larger than 200 mm and it was reconstructed (Fig. 13,14). The photo in Figure 16 shows the region between the original and the reconstructed part of that façade, where one may clearly see the permanent out-of-plane deformation of the original part.

However, even this reconstructed part of the monument presents today a total out-of plane deformation of 90 mm (drawing in Fig. 16). This is another element proving that the feature we observe now in the monument is an inherent characteristic (due to its initial construction scheme and the extended alterations/interventions undertaken during its lifetime).

Thus, out of plane deformations were reported both for the perimeter walls and for all the main arches bearing the dome in the central area of the monument, followed by a geometrical deformation (and loss of initial shape) of the arches themselves. The lack of wooden or metallic ties (typical structural elements for the Byzantine architecture) or other horizontal elements connecting the vertical walls, pillars and piers

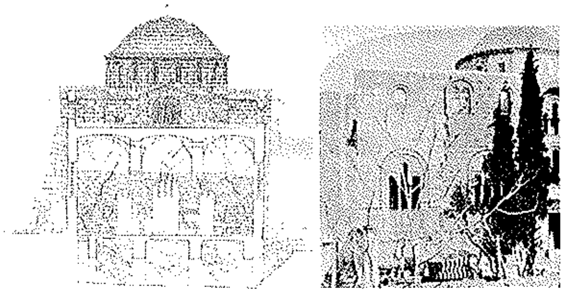


Figure 16. N-S transversal section in the narthex. The south wall, although reconstructed in 1896 (see photo), presents today a 90 mm out-of-plane deformation.

should have played an important role towards this pathology.

Moreover, the increase of crack openings with height was found more pronounced along the transversal axis (N–S), than along the longitudinal one (E–W). Such a difference in behaviour is usual in churches with an orthogonal plan and could be attributed to the larger number and sections of vertical elements available along the E–W axis in the main church (see Figure 12). This behaviour was also noticed in the past, whereas previous interventions were applied with the aim to alleviate this problem (external stone buttresses in the north, metallic trusses and confinement of piers in the south), as described in Section 4 (Figs 13 &14). Although those corrective measures were in the right direction (allowing the church to withstand the 20th century earthquakes without local collapse), they were proven to be insufficient to prevent extensive cracking of the monument.

The damages observed in the drum of the cupola may, therefore, be attributed to the (increasing with height) tendency for out-of-plane deformations of the church. It should be reminded here that the damages that made imperative the demolition and reconstruction of the cupola at the end of the 19th century were of the same nature, as those observed now; this is proved by the missing parts of the mosaics. As described in Section 3, most of the piers in the drum exhibited out-of-plane deformations. Since the substructure on which the system of the cupola rests is deforming out-of-plane and the cupola itself (being very stiff) is practically non deforming, the piers of the drum (being rather flexible out-of-plane) are called to follow the deformations of the substructure.

Some final comments should be made here, regarding the foundation and foundation soil of the monument and their effect on its behaviour. The recent pathology does not give signs of major differential settlements that might have contributed to the damages of the monument. This is also confirmed by geotechnical investigations conducted immediately after the 1999 earthquake (O.T.M., 2000). On the other hand during the application of urgent measures local investigations revealed that rather shallow foundations (0.5 m deep in the middle of South perimeter wall, 1.25 m deep in the N–E chapel) are provided to the perimeter walls).

Thus, in order to collect qualitative information on foundation elements and on eventual empty underground spaces or local variations of the ground material characteristics, geophysical investigation was also undertaken, using mainly 3D seismic tomography (Polymenacos et al. 2005). This investigation suggested that, in the north-northwest part of the church and exonarthex, inferior ground material quality has to be expected, as low velocities were recorded. Moreover, archaeological excavation in the region of the N–W chapel revealed that Troump had probably noticed that the foundation were relatively shallow and has dictated their strengthening during the extended reconstruction of the upper part of the north wall in 1896. For this purpose, a 2.0 m deep wall was constructed under the NW perimeter wall of the church. To this end extensive excavations had to be undertaken in that area, thus disturbing the foundation soil. This fact could probably explain the lower velocities found with the seismic tomography. Nevertheless, all the above information and eventual further investigations concerning the foundation conditions of the church and exonatrhex have to be further examined during the design of the interventions of the second phase.

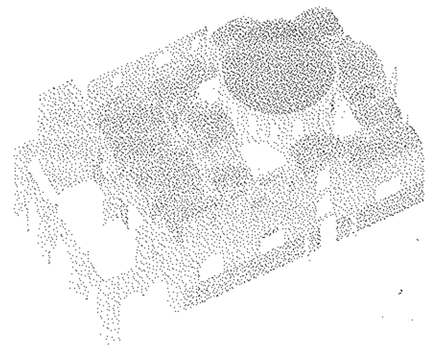


Figure 17. The model prepared for parameter analyses.

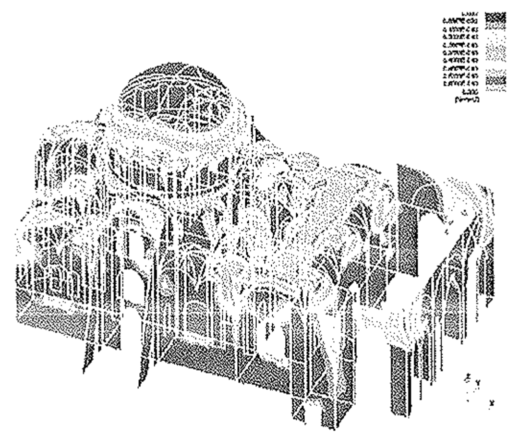


Figure 18. Inner face of shell elements. Tensile stresses due to self-weight of the structure.

7 NUMERICAL VERIFICATION OF THE PATHOLOGICAL IMAGE

One of the major steps of the assessment of an existing structure is the analytical reproduction of its pathological image. In the case of the Katholikon, preliminary linear parameter analyses were performed (Miltiadou-Fezans et al. 2004), as a means for selecting adequate emergency interventions. Those analyses provided a quite satisfactory numerical verification of the pathological image of the monument. For the preliminary analytical study, using the computer code ACORD, the structure was modeled by shell elements (Fig. 17), whereas the mechanical properties of elements belonging to various parts of the structures were assumed on the basis of the available data for the construction materials. Linear elastic analyses were performed for various combinations of actions (self weight alone or combined with seismic action). Both static and dynamic analyses were performed.

Figure 18 shows the calculated stresses for the inner face of shell elements, due to vertical loads. Irrespectively of the accuracy of numerical values of stresses, one may clearly distinguish the vulnerability of the region of arches and domes (especially in the west part), even for the self-weight of the monument alone. As expected, tensile stresses are developed in the apex of several arches, in the groin vaults of the narthex, in the base of the cupola and that of its drum, as well as in the four squinches. The obtained results are conform with the qualitative interpretation of the pathology of the monument and they prove the inherent vulnerability of the structural system, in which (a) a stiff central cupola is resting (through the drum) on four major arches parallel to the two main axes of the church (see Figures 3, 4), as well as on four arches oblique in respect with the longitudinal and the transverse axis, (b) the vertical, as well as the horizontal component of the self weight of the whole system of (intersecting) groin vaults arranged around the central dome, are transferred to rather flexible stone masonry piers, and (c) there are not currently ties in the arches and vaults, or other elements to confine critical structural elements or link the various parts among them. Therefore, the tendency of the structural system to deform laterally in its upper region is expected to be apparent even under self-weight alone.

This working hypothesis seems to be confirmed by the deformed shape of the structure in-plan, shown in Figure 19. One can even observe the more pronounced lateral deformation along the N–S axis of the

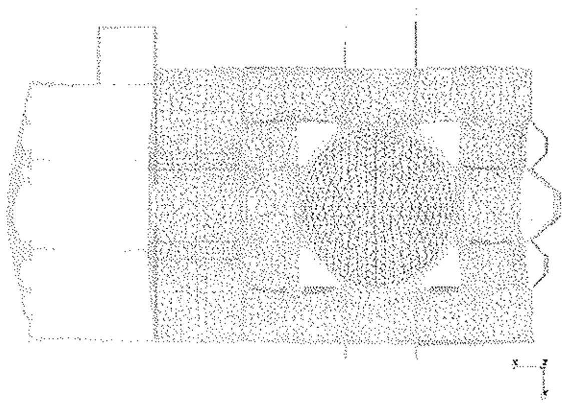


Figure 19. Deformed shape of the monument in-plan under self-weight.

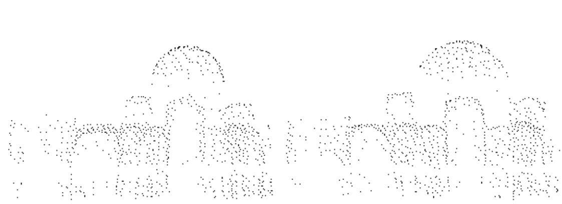


Figure 20. Deformed shape of the structure looking from the N. Dynamic analysis; seismic action along the longitudinal axis.

monument, as well as the out of plane deformation of the perimeter walls of the narthex, which historically has been proved to be a vulnerable part of the structure, already reconstructed in 1896 and deformed again as measured after the 1999 earthquake. On the same Figure, the excessive out-of-plane deformation of the exonarhtex is also apparent.

Expectedly, this behaviour is deteriorating when a seismic event occurs. In Figure 20, the out of phase movement of the east and west parts of the monument is shown. Such a movement can explain the severe damages occurred to the drum of the dome, as well as to the arches and vaults supporting the dome. In general, the analyses for loading combinations including the seismic action have shown a critical concentration of tensile stresses in arches at various levels, as well as in the piers of the drum. In addition, extensive damages in vertical elements (masonry in the perimeter of the monument, as well as piers) were confirmed.

Furthermore, in the framework of this preliminary work, the plots of principal tensile stresses were compared with the respective drawings on which observed cracks were reported (Miltiadou et al. 2004). This comparison proved to be quite satisfactory, as, in general, the observed crack pattern (location and inclination of cracks) seems to be confirmed by the analytical results in all regions of the monument.

Although this preliminary analytical work allowed for a better understanding of the structural behaviour of this important monument, it was judged that a more accurate assessment of its seismic behaviour was of primordial importance for the design of optimum interventions.

8 STRUCTURAL RESTORATION SCHEME

The pathological image of the monument (both the historical and the current ones), as well as the fact that the Katholikon is built in a tectonically active area, suggest that in addition to interventions that are necessary for the repair of observed damages, adequate measures should be taken with the aim to alleviate the inherent vulnerability of the structure and, thus, to improve its future behaviour in some critical regions. Due to the high values of the monument, its vulnerability and the fact that interventions should not drastically alter the initial structural system, the decision was taken to investigate thoroughly its structural behaviour. To this end additional data were necessary in order to avoid conservative assumptions (both for actions and resistances). Such assumptions would lead to extensive interventions that might not be needed and that would inevitably alter the architectural value of the monument.

On the basis of the aforementioned reasoning, it was decided to implement the structural restoration works in two phases, thus giving the possibility for these additional data to be collected. The first phase of works comprises all those considered necessary to achieve the better possible repair and strengthening of masonry elements (mainly stitching and deep re-pointing where necessary, systematic grouting injections, local reconstructions, etc). The second phase concerns the various strengthening interventions that will be designed and selected as optimum, in order to improve the overall behaviour of the whole building (such as installation of ties, diaphragmatic structures in the extrados of the vaults and the exonarthex, etc). Due to the type and extend of damages, it was judged as absolutely necessary the first phase of interventions to be applied in priority, in order to avoid further deterioration of damages, which could lead to a total disruption of continuity and even local collapses, in case of further seismic events. Besides, during this first phase of works a better structural survey of invisible parts of the monument (internal face of masonry elements, extrados of vaults) could be possible.

The implementation of the first phase of structural restoration interventions has been now accomplished, together with the most of the research and investigations undertaken to support both phases of works, briefly presented below. Preliminary proposals for the second phase of interventions have also been approved, but their final design is still under elaboration.

9 DESIGN OF GROUTS AND INVESTIGATION OF MASONRY BEHAVIOUR BEFORE AND AFTER GROUTING

9.1 *Design of alternative grout compositions and tests on cylinders simulating the infill material*

The design of high injectability grouts was carried out on the basis of the methodology proposed by Miltiadou & Tassios 2006. First, were taken into account the performance requirements deriving from the structural restoration study (Miltiadou et al. 2003b), and then the following target values were set for the basic mechanical properties of the grouted masonry: tensile strength approximately double than that one of the masonry before grouting, and compressive strength approximately equal to 3.0 MPa.

On the basis of the available literature (Vintzileou et al., 1995 and Tassios, 2004), it was estimated that the compressive strength of the grout at the age of six months should lie between 6 MPa and 10 MPa; a grout flexural strength of the order of 2 to 3 MPa was required. In addition, the physical-chemical properties of the raw materials should be selected in a way that the durability of the structure and its precious mosaics would not be jeopardized. Finally, the grouts should have high injectability capacity, so that, under low pressure (~ 0.075 MPa), they enter and fill fine voids and cracks, with a nominal minimum width (W_{nom}) equal to two tenths of millimeter. Two main categories of grouts could satisfy injectability, strength and durability requirements: (i) ternary grouts composed of lime, pozzolan and a low cement content (30%) and (ii) natural hydraulic lime – based grouts.

Thus, various grout mixtures, belonging to the above two categories, were designed and tested (in order to assess their physical, chemical and mechanical properties) at the laboratory of the Directorate for Technical Research on Restoration of the Hellenic Ministry of Culture (DTRR/HMC). The main results of the research are reported in Kalagri et al. (2007) and Miltiadou et al. (2007).

In order to determine injectability characteristics, the penetrability, fluidity and stability of the suspensions were fully examined in various water/solids ratios, with or without superplastisizer. The compositions presenting satisfactory injectability capacity were further tested to evaluate their behavior to salt decay and estimate their mechanical characteristics (compressive and flexural strength). Furthermore, six alternative grout formulations presenting similar injectability were injected into twenty eight cylindrical specimens, simulating the infill material of three-leaf stone masonry. The cylinders were then subjected to compression in different hardening ages (Kalagri et al, 2007). After comparative evaluation of the results, two grout compositions (a ternary grout and a NHL5-based grout) fulfilled simultaneously the injectability, the strength and durability requirements (Table 1). Therefore, they were selected to be applied to six three-leaf stone wallettes, simulating the masonry of the upper parts of the monument. It has to be noted however that the hydraulic lime based grout presented a better sulphate resistance than the ternary one (Miltiadou – Fezans et al. 2007).

Table 1. Mechanical and injectability characteristics of the grouts selected to be injected in the wallettes.

Grout properties	Ternary (1)		NHL5-based grout (2)			
T36 (sec) Sand column 1.25/2.50 mm (W_{nom} ~.0.2 mm)	19		22.5			
Bleeding	2%		3%			
App.viscosity $t_{d=4.7}$ (sec)	20.5		22			
	Age (days)					
Compressive and flexural strength (MPa)	28		90		180	
	f_{gc}	f_{gt}	f_{gc}	f_{gt}	f_{gc}	f_{gt}
Ternary	4.08	2.11	8.16	2.29	10.6	3.13
NHL5-based grout	2.82	2.47	4.50	2.52	6.36	3.87

(1) Ternary: 30% white Danish cement, 25% Lime (powder), 45% natural pozzolan Petr. (<45 μ m), superplasticer 1%, water 80% of the solid phase of the grout (2) NHL5-based grout: 100% NHL5 (St Astier), superplasticer 1%, water 80% of the solid phase of the grout

9.2 *Construction and testing of wallettes*

In order to estimate in the best possible way the mechanical characteristics of the masonry before and after grouting, considerable effort was devoted to the identification of the construction type of masonry. For this purpose, radar and endoscopy were applied in a systematic way. The in-depth geometry of the perimeter stone masonry was rather accurately identified (Vintzileou et al., 2004). As anticipated, both the lower and upper parts of the perimeter walls belong to the three-leaf masonry type, with varying widths of the leaves. Although both regions were examined, the investigation was concentrated mainly on the upper (more vulnerable) zone of masonry. In Figure 21 characteristic examples of vertical sections of the lower and upper zone of perimeter masonry are shown.

The materials characteristics (stones, bricks and mortars) being determined in the Laboratory on samples taken from the monument and the type of masonry being determined in-situ, an attempt was made to

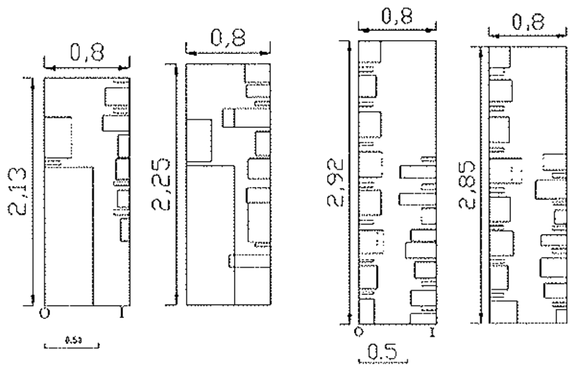


Figure 21. Vertical sections of lower (a) and upper zone (b).

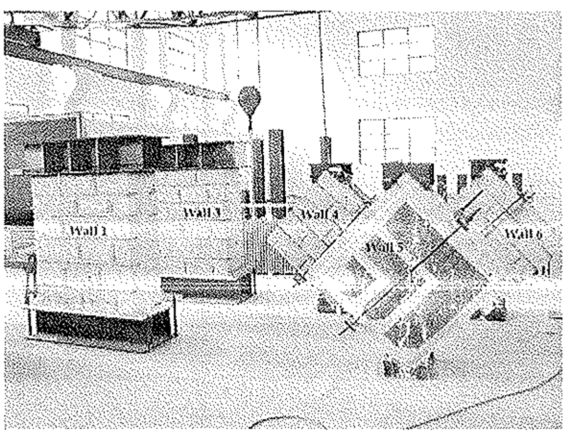


Figure 22. The walletes prepared for grouting.

estimate its compressive strength using empirical formulae available in the literature. The calculated strength values were unacceptably scattered, thus making unsafe or over-conservative the selection of any of the calculated compressive strength values (Vintzileou 2002). Thus, the decision was made to construct wallettes and to determine basic mechanical properties by testing them before and after grouting (Vintzileou et al. 2006, Miltiadou et al. 2006). The geometry of the wallettes was chosen to simulate the upper and more vulnerable part of perimeter masonry. In order to avoid scale effects a scale 2:3 was selected. Six three-leaf stone masonry wallettes were constructed using materials of similar characteristics as the in-situ ones. Half of the wallettes were tested in compression and the other half in diagonal compression up to their maximum resistance. After unloading, the wallettes were grouted using one of the selected grouts of the Table 1 (Fig. 22). The injections were carried out using a specific methodology and the total grout consumption (calculated as the ratio of grout volume consumed for each wallette per total volume of wallette) was of the order of ~10%. Subsequently, they were tested

Table 2. Basic mechanical properties of Wallettes before and after grouting.

W	(MPa) f_{w0}	f_{ws}	f_{ws}/f_{w0}	ε_{v0} (‰)	ε_{vs} (‰)	(GPa) E_0	E_s	E_s/E_0
1	1.82	3.00	1.65	*	−1.76	1.00	1.20	1.20
2	1.74	3.75	2.16	−1.6	−2.50	1.44	1.55	1.08
3	2.26	3.73	1.65	−2.25	−3.39	1.50	1.30	0.87
	$f_{t,0}$	$f_{t,s}$	$f_{t,s}/f_{t,0}$					
4	0.1	0.21	2.10					
5	0.1	0.33	3.30					
6	0.1	0.22	2.20					

W2 and W5 injected with the ternary grout; W1, W3, W4, W6 injected with the hydraulic lime based grout.

again in compression or in diagonal compression to failure. The main results are summarized in Table 2.

Both grouts applied to the specimens were able to achieve homogenisation of masonry by filling cracks and voids of wallettes. Thus, the wallettes exhibited substantial improvement of their behaviour, in terms of compressive strength, tensile strength and reduction of the separation between the three leaves of masonry, without substantial increase in their stiffness, and proved to be efficient from the mechanical point of view. From the two alternative compositions, the natural hydraulic lime based grout was selected for the application to the Katholikon of Dafni Monastery, due to the substantial (compressive and tensile) strength enhancement of wallettes, the rather ductile behaviour under diagonal compression (compared to that of masonry grouted with the ternary grout), and the better durability properties (Miltiadou et al. 2007) that contribute to the protection of mosaics and frescoes.

9.3 *Optimum grout composition*

In order to further improve the hydraulic lime based grout, the addition of fine natural pozzolan (dmax < 45 μm) in various proportions was investigated. The addition of a small percentage of pozzolan (10%) was decided, on the basis of additional data, deriving from porosity measurements, salt durability tests and from in situ pilot trials.

The mix proportions and the injectability characteristics of the optimum grout composition are presented in Table 3, whereas more detailed information is given in Miltiadou-Fezans et al. 2007, 2008. This optimum grout composition was used for the repair of the monument. Moreover it was used for the repair of a large scale model of a Byzantine groin vaulted structure, constructed and tested on a earthquake simulator, as briefly presented below.

Table 3. Optimum grout composition and injectability characteristics measured in the laboratory and in situ at the first pilot preparation.

Grout composition		
NHL5 (St Astier)	90%	
Pozzolan Petrotechniki	10%	
Superplasticizer (1), (2)	1%	
Water (1)	80%	
Grout properties	In lab	In situ
T36 (sec) – Sand column 1.25/2.50 mm ($W_{nom} \sim .0.2$ mm)	19–22	
Bleeding	<1%	1%
Apparent viscosity – $t_{d=4.7}$ (sec)	In lab	In situ
0 min after mixing	21	22
60 min after mixing (agitated)	23	25
Apparent density (gr/cm^3)	In lab	In situ
0 min after mixing	1.5050	1.4978
60 min after mixing (agitated)	1.4986	1.4870

(1) % of the solid phase of the grout.
(2) superplasticizer based on polycarboxylic ether.

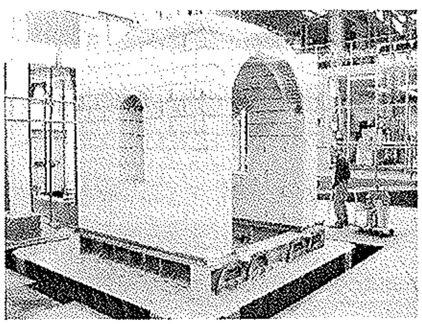


Figure 23. The groin vaulted structure on the seismic simulator.

9.4 *Construction and testing of a large scale structure covered with a byzantine groin vault*

As aforementioned in section 2, byzantine groin-vaults are used for covering the most of the parts of the Katholikon of Dafni Monastery, including the arms of the cross, where severe damages have been occurred. Thus, important effort has been undertaken for achieving a better knowledge of the dynamic behaviour of such structures. An experimental research was carried out by DTRR/HMC in collaboration with the Laboratory of Earthquake Engineering of NTUA. A model of a byzantine groin-vaulted structure bearing locally mural mosaics was constructed. The materials and the construction type used for its masonry walls were exactly the same with those used for the construction of the wallettes, whereas bricks and mortar were used for the construction of the arches and the groin vault (Fig. 23).

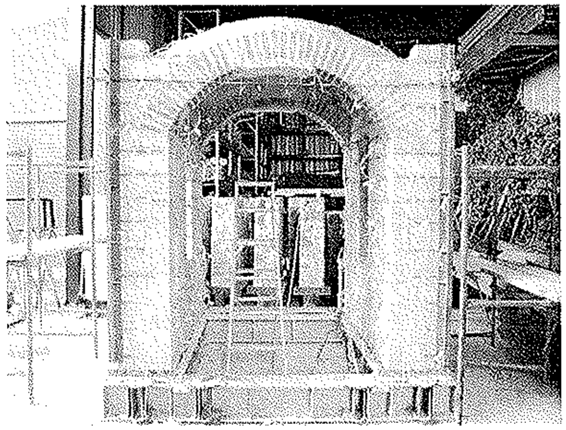


Figure 24. The groin vaulted structure after grouting.

It has to be noted that the groin vault was built without any formwork, following the traditional way of byzantine masons, as reported by Delinikolas et al. 2003. The total dimensions of the model are in plan 2.70 m × 2.60 m; the thickness and the height of the walls are 0.45 m and 2.60 m respectively, whereas the thickness of the vault in its centre is 0.20 m. The total height of the model is 2.85 m. These dimensions were selected taking into account the limitations imposed by the capacity of the seismic simulator.

The model was tested after nine months from its construction by imposing seismic loads gradually increasing, until rupture. Then local application of grouts and installation of ties to the arches was performed and after a suitable period of time the tests were repeated, until rupture. The model was then injected with the final grout composition (Table 3) to homogenize the whole structure, following the same methodology with that used for the injection of the wallettes and the injection of the monument itself (Miltiadou-Fezans et al. 2006, 2008). Tests were again repeated until rupture. In Figure 24 the model after the grouting application is shown. As expected, it was observed that the dynamic characteristics of the model were changed after the application of grouting to the whole structure, and the model could suffer stronger base motions. The results of this experimentation are still under elaboration and are going to be presented in a separate paper. An attempt will be made to correlate these results with those of the wallettes and the in situ seismic monitoring.

10 BRIEF PRESENTATION OF THE WORKS OF THE FIRST PHASE

As reported in the relevant study, (Mitiadou-Fezans et al. 2003b), the main objective of this first phase of structural restoration interventions was (i) to improve

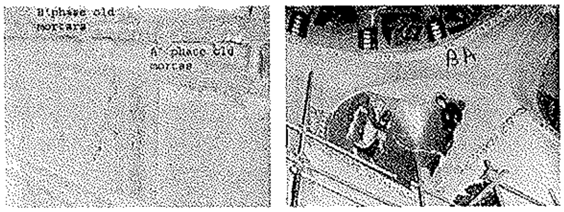


Figure 25. Old mortars of first and second construction phase and cracked mosaics that have to be preserved in situ.

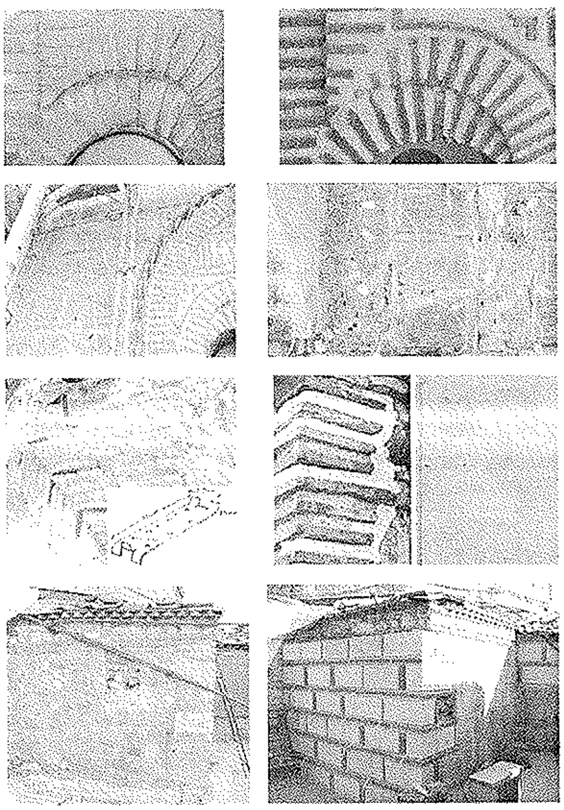


Figure 26. Typical examples of the first phase structural restoration interventions (Recent mortars removal, grouting preperation, stiching of cracks, local reconstruction).

in the best possible way the mechanical behaviour of the masonry elements by reinstating their continuity (lost due to the numerous cracks) and increasing their resistance (mainly to traction and shear), without side effects due to possible durability matters. This objective had to be achieved taking into account the existence of mural mosaics, frescoes and old pointing mortars, that had to be preserved and conserved in situ. In fact all uncolored joints of Figures 12 & 13 still preserve the old Byzantine pointing mortars.

This first phase of masonry repair interventions comprised mainly the following works (Fig. 26): i) very careful removal of plasters and deteriorated pointing mortars applied during previous interventions,

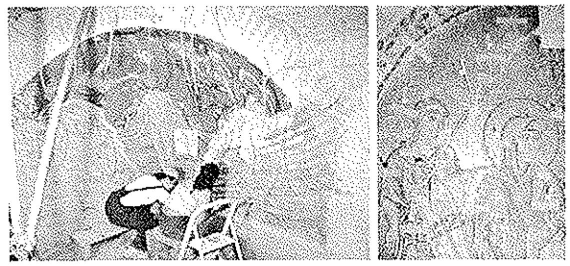


Figure 27. Typical examples of in situ mural mosaics conservation works (including installation of fine tubes for grouting).

without harming the old ones, adjacent to or underneath them, ii) removal of tiles and other covering and filling materials to reach the extrados of all vaulted structures, iii) stitching of the most severe cracks, using long stones, bricks, or thin titanium plates, iv) few local reconstructions necessary either for the repair of dislocated or collapsed parts or for the restoration of past morphological alterations, v) deep re-pointing where necessary and preparation of the masonry for injection grouting, vi) implementation of injection grouting, vii) removal of all injection tubes, (viii) in situ conservation of all deteriorated old mortars using frescoes techniques, ix) execution of all necessary works to ensure the protection of the extrados from rainwater.

In parallel with the works for the masonry repair, the competent Conservators have carried out all the necessary works for the in situ conservation (including grouting) of severely damaged mural mosaics, (Chryssopoulos et al. 2003). As anticipated, in most cases, the cracks on the masonry affected also the mosaics beard on its internal face (Fig. 27).

From the above brief presentation of the works undertaken, it is ensued that the application of adequate mortars and grout compositions, constitute a key parameter in order to ensure a successful intervention, both for the masonry and the mosaics.

Thus, extended laboratory and in situ pilot tests have been undertaken for the formulation of the adequate mortars compositions taking into account the characteristics of the existing materials, the requirements set by the architectural and structural study and the worksite conditions. For the majority of the re-pointing works adequate lime-pozzolan based mortars were used. For the local reconstructions, deep re-pointing of extremely damaged critical areas and stitching with thin titanium plates, hydraulic lime based mortars were applied. Detailed information concerning the properties of existing mortars is given in Papagianni 2002, while all the results concerning both the properties of existing materials and those designed and applied to the monument are reported in Anagnostopoulou & Miltiadou-Fezans 2007. In order to ensure the protection and in situ conservation of old pointing mortars, on the external facades, the upper central area just below the dome, and the groin vaults of the sanctuary, the deep re-pointing works have been executed by experienced Conservators.

As anticipated special attention has been given to the design of the adequate grouts, not only because grouting constitutes the main of the works undertaken that can substantially improve the mechanical behaviour of the masonry, but also due to the fact that it is an invisible and irreversible intervention, which affects the masonry elements and all the mosaics, frescoes and old mortars beard on them. Furthermore, as the proper design of a grout composition cannot ensure on its own the successful execution of the grouting intervention, a specific application methodology has been developed and applied. The most important aspects of this methodology are reported in Miltiadou-Fezans et al. 2008. This application methodology permitted the implementation of injections to this important monument, bearing mosaics, frescoes and old mortars that had to be preserved in situ, in a more rational and fully controlled way. The monitoring results and those obtained by sonic tomographies summarized below, gave important information for the effect and the efficiency of the whole grouting intervention, and enhanced the validity of the methodology applied.

During the whole project, all interventions have been documented in a detailed way (adequate as built drawings have been elaborated), together with all the new findings concerning the materials, types of construction, past interventions and pathology of various invisible elements (i.e extrados of groin vaults). Thus the historical and recent pathology drawings have been updated and all necessary information has been collected to be taken into account in the study of the second phase interventions.

11 SEISMIC MONITORING SYSTEM AND APPLICATION OF NDT'S

As aforementioned, in order to increase our understanding of the seismic structural response and to decrease the uncertainty of the seismic action, the installation of an earthquake monitoring system was decided. The system was installed on the central core of the monument at 2003, after the implementation of the aforementioned emergency measures, and before the beginning of restoration works.

Thus, when the hydraulic lime grouting application started (Miltiadou et al. 2008), in June 2006, the system was functioning and had already recorded two weak earthquakes. The first took place before the beginning of masonry repair (26-9-2004) and the second during the preparation of masonry for grouting

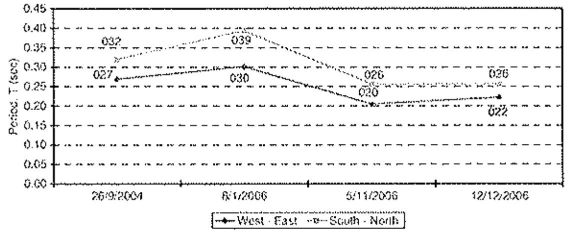


Figure 28. Variation of the period of the first mode.

by stitching of cracks and local deep re-pointing (8/1/2006). After three and four months from the end of the first grouting period, during which grouting was implemented up to the springing level of groin vaults, two more weak earthquakes were recorded (5/11/2006 and 12/12/2006). The analyzed data, have shown that the monitoring system installed can give important information for the overall behaviour of the structure, before during and after the implementation of various interventions. Detailed information is given in Mouzakis et al. (2008).

As shown in Figure 28, during the earthquake of 08/01/2006 occurred after the urgent measures and while preparing the masonry for grouting, the natural period of the first mode was increased, and hence the stiffness of the structure was decreased. This is totally expected, as only local deep re-pointing and stitching of some cracks had been applied at that moment, while the emergency measures have not been designed to undertake seismic actions. Moreover an increase of damping was recorded. These results may indicate a slight deterioration of damages. On the contrary, as a result of the implementation of grouting injections up to the springing level of groin vaults, the period and the damping of the first mode were decreased, along the EW and the NS directions. This result was reached by analysing the data of both seismic events, happened three and four months after the first grouting period. Thus, it was proved that the effect of interventions and more specifically of grouting on the overall behaviour of the structure can be evaluated by a seismic monitoring system. This promising finding led to the decision to install in 2007 complementary instrumentation, with the aim to cover the whole structure.

The extended seismic monitoring system has recently recorded two more earthquakes (6/1/2008 and 30/1/2008), and the data are still under processing. These recent seismic events took place after nine and ten months from the end of masonry repair works (28/4/20070), during which grouting has been carried out to the entire structure below the level of the base of the dome's drum. Thus, it is expected that the seismic monitoring records will give further information for the effect and efficiency of all the interventions undertaken until now.

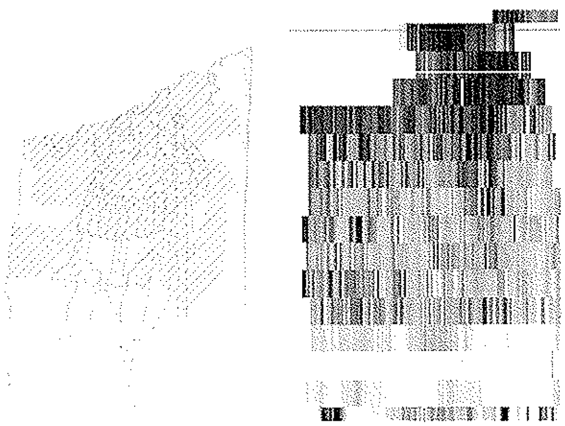


Figure 29. Manual-sonic and sub-surface radar maps of "Saint-Orestes". Damaged zones are in dark.

12 APPLICATION OF NDT'S FOR MAPPING MOSAICS SUBSTRATA AND GROUTING MONITORING

In 2005, an exhaustive high frequency ground-penetrating radar survey has been realized on the fifty main mosaics of the Katholikon of Dafni Monastery, with the aim to investigate the possibility of GPR application to locate doubtful zones (delaminations, changes of substrata mortar or other buried heterogeneities, etc), related to the mosaics very near bearing-structure. As presented in Côte et al. 2004 & 2008, a methodology has been developed for the execution of specific parallel radar profiles, the processing of data and the construction of gray-color scale maps from chosen trenches of the structure, related to the amplitude of the echoes in the selected trench. These gray-scale maps were correlated to a level of detachment or other heterogeneities by comparison with manual-sonic maps and pathology ones realized by the Conservators of the mosaics (see Fig. 30). It has been shown that the GPR maps, giving a more detailed and less subjective qualitative evaluation of mosaics substrata, can be a very useful tool for the Conservators in order to locate doubtful zones in a more refined way. Furthermore, the possibility of using GPR procedures to monitor the movement of the grout behind the mosaics, in real time, during injection was also investigated; detailed information is given in Côte et al. 2008.

Investigations have been also realized to control the grouting effect into the masonry walls, using seismic techniques, including some sonic 2D travel time tomographies. The objective herein was to propose a simple survey methodology which gives information for the mechanical characterization of the materials inside the structure, before and after grouting. The processing of the results after the completion of grouting is still in progress. In Figure 30 two indicative tomographical reconstructions of a grouted and in a non grouted area are presented. The comparison of these two cases permits to conclude that the grouting survey of such masonry structures may be achieved by the observation of the velocities of their inner part (Côte et al. 2008).

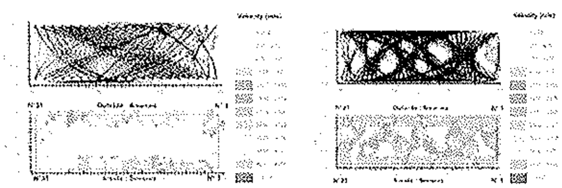


Figure 30. Tomographical reconstruction in a grouted and in a non grouted area.

13 CONCLUSIONS

The high values of the Katholikon of Dafni Monastery and, hence, the need for accurate information to serve the design of optimum structural interventions led to the adoption of a step by step multidisciplinary approach, both concerning the design and the implementation of the structural restoration interventions. This approach proved to be very efficient, as it gives the possibility to perform the in situ and laboratory investigations that are necessary for the design of the next step, as well as for the evaluation of the previous ones.

In this framework, a series of quite novel investigations were undertaken; the most important results are summarized below.

1. The holistic design of hydraulic grouts, carried out on the basis of rational criteria, laboratory and in situ pilot tests, led to the improved knowledge on the hydraulic lime based grouts and, hence, to the selection of appropriate mixes.
2. The experimental assessment of the mechanical characteristics of three-leaf stone masonry (before and after grouting) contributed to better understanding of the behaviour of this type of structures and proved that their repair with adequately designed highly injectable hydraulic grouts (hydraulic lime based ones or ternary grouts) can be very efficient.
3. A hydraulic lime based grout was considered as optimum composition to be applied in situ, on the basis of injectability, durability, strength and deformability characteristics.
4. Testing a scaled model of a byzantine groin-vaulted structure on an earthquake simulator (before and after grouting) provided valuable information

regarding the structural behaviour of this complex type of structures, as well as regarding the strengthening capacity of injections.

5. The developed methodology for grouting application gives the possibility for a more rational and fully controlled implementation of injections, not only to ordinary structures, but also to important monuments bearing mosaics, frescoes and old mortars, that have to be preserved in situ.
6. The entire procedure for the design and application of adequate lime-pozolan mortars enhanced our knowledge on this kind of mortars, traditionally used in the past.
7. The monitoring system, installed to record the seismic behaviour of the monument, provides valuable data on the effect of interventions, as they are applied in steps to the monument. Thus, the effects of interventions to various characteristics of the monument, as well as their efficiency can be continuously assessed. It should also be noted that, a similar monitoring system having been installed in another important monument (the Katholikon of Osios Loucas Monastery), the comparative evaluation of data obtained in the two churches will allow for a better understanding of the structural seismic response of middle-Byzantine churches of octagonal type.
8. The potential of NDT was further enhanced to serve the needs of investigating important monuments. High frequency GPR combined with endoscopy proved to be efficient for the identification of the masonry construction type. High frequency GPR contributed also to locate unsafe regions of mosaics substrata. Furthermore, sonic techniques, undertaken before and after grouting, were proven very efficient in checking the effect and efficiency of grouting intervention, whereas geophysical investigation by means of 3D seismic tomography provided valuable information about the foundation elements.

The entire plan of investigations has supported the rational design and implementation of the first phase of works, as well as the evaluation of their effect and efficiency.

The collected results are now being used for the design of the second phase interventions. A synthesis of all data provided by the situ surveys during the first phase of interventions, the results of the monitoring system and those obtained by testing the wallettes and the groin vaulted structure is under elaboration. Analytical work will be extended, with further development and calibration of detailed numerical models. This/these calibrated model/models will then be used to check the efficiency of various strengthening intervention techniques (installation of ties, metallic confinements, diaphragmatic structures in the extrados of the vaults and the exonarthex, etc). Thus, the final design of the optimum interventions will be carried out and the respective works will be implemented during the second and final phase of restoration works.

Last but not least, it is strongly believed that the experience and knowledge acquired by all levels of involved stuff in the framework of the structural restoration of this important monument of World Heritage constitute a solid base for similar investigations, studies and structural restoration interventions to other historical structures and monuments.

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