Pathology of the Dafni Monastery: survey, monitoring of cracks, interpretation and numerical verification

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ABSTRACT: This paper summarizes the work carried out in the Katholikon of Dafni Monastery with the aim to study the pathology of the monument. Damages observed after the 1999 earthquake in Attica are briefly presented and qualitatively interpreted, based on historical pathology as well. Selected results of cracks measurements taken on the monument over a long period of time after the earthquake are presented and commented. Finally, the results of the effort undertaken to reproduce analytically the observed pathology are briefly presented.

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 (Bouras, 1998, Millet, 1899 and Delinikolas et al., 2003). The Katholikon of the Monastery (Figures 1 and 2) has suffered severe damages during the September 1999 earthquake that affected the region of Attica.

Within the framework of a strategic plan1 undertaken by the Ministry of Culture (with the financial support of the E.E.) for the conservation of the monument (its mosaics included), a systematic study of the pathology of the monument was undertaken. This study that includes various steps (detailed survey of damages, monitoring of various cracks, qualitative interpretation of pathology, as well as the preparation of a detailed computer model of the monument which was used for parameter analyses) aims at a-as complete as possible-documentation of the monument, necessary for adequate intervention measures to be selected.

1 A Scientific Committee was set by the Ministry of Culture, to follow the progress of the investigations. Members of this Committee are Professors Ch. Bouras, T.P. Tassios, H. Mariolakos and N. Zias.
Interventions for its preservation were applied in the 19th and 20th centuries. Even a brief presentation of the long history of the monument is beyond the scope of this paper. It is believed, however, that some basic information should be provided to the reader of this paper regarding the historical pathology of the monument, as well as about major interventions. This information (taken from Delinikolas et al., 2003) is presented in Figures 3 to 5, in which the reconstructed parts of the monument are shown. The most severe damages and extensive reconstruction must date back to the occupation of Athens by the Francs. The Cistercians (13th–15th c.) reconstructed the gallery and repaired the vaults of the narthex. During the last two centuries, although the monument has suffered numerous earthquakes, it seems that some of them have affected more severely the church. One should mention the 1889 earthquake, the 1894 earthquakes (estimated magnitudes 6,7 and 7,0 on the Richter scale), the 1914 earthquake (estimated magnitude 6,0R) and the 1981 (M 6,7) earthquake. Interventions aiming at the preservation of the monument date back to 1885, when the Archaeological Society is founded and the first efforts to save the Christian churches are undertaken. The major intervention (1890 to 1897) includes the following: Demolition and reconstruction of the (heavily damaged) central cupola, repair in the lower parts of the church, removal and partial replacement of mosaics that were heavily damaged. Three concentric iron rings (T-beams) were inserted at the base of the drum of the cupola. The 1894 earthquake caused new damages and led to the need of further interventions (reconstruction of the narthex and its collapsed groined vaults, reconstruction of the NE parekklesion, etc.). In the period of 1897 to 1907, the two
Figure 6. Typical presentation of damages.

3 SURVEY OF DAMAGES

The survey of damages started soon after the September 7th, 1999 earthquake and it was completed in two phases. During the first phase, only damages of the lower part of the monument were reported to drawings. After the installation of scaffoldings, the higher part of the monument (cupola and arches included) could be reached and, thus, the completion of the work was made possible. All cracks were reported to drawings with indication of their opening, as well as displacements, out-of-plane deformations, etc. All this information is available in electronic form, as shown in Figure 6. It should be noted that the thickness of cracks is associated with their width (thicker lines correspond to larger crack openings).

On the basis of the survey of damages, the following can be observed: The 1999 earthquake caused severe damages to the monument (both to its structural part and to the mosaics). Numerous cracks (ranging from hair cracks to those several centimeters wide) have appeared, whereas numerous old ones (due to previous earthquakes) increased in length and width. Local disintegration of masonry occurred in some cases, as well as out-of-plane displacements of vertical elements. Extensive cracking of arches and cupolae was also recorded. Severe damages in the N-E corner of the monument made the construction of external steel buttresses imperative. The central cupola (reconstructed in the end of the 19th century and damaged already soon after its reconstruction) has also suffered severe damages: As shown in Figure 7, horizontal cracks appeared along the perimeter of the drum (both at its base and top).
The most severe damages were recorded in the 16 pillars of the drum. In those parallel to the East-West direction diagonal cracks appeared, whereas in pillars parallel to North-South direction, mainly horizontal cracks are recorded. In the intermediate pillars, in which cracks of mixed type appear, the damage level is, however, lower. This pathological image does seem to confirm seismological data regarding the predominant direction of the 1999 earthquake. It should also be noted that out-of-plane displacements were observed along the cracks in the pillars. The critical state of the drum of the central cupola led to immediate measures taken to avoid any further deterioration.

4 MONITORING OF CRACKS

The main concern after the September 7th, 1999 earthquake (M5.9) and during the aftershocks period was whether the monument can carry safely its own weight and resist the aftershocks. Thus, the decision was made to monitor several cracks considered to be critical for the behaviour of the monument. The first measuring devices were installed soon after the earthquake. They showed a tendency of the cracks in some regions to increase in width due to aftershocks. This led to the decision for taking urgent measures to protect the N-E corner (external steel buttresses were constructed), as well as the drum of the central cupola (a steel tying system to confine the pillars of the drum was installed). A detailed description of the urgent measures is presented elsewhere (Miltiadou et al., 2003). In addition, immediate measures were taken to protect people working in the monument for the preservation of mosaics (scaffoldings were appropriately designed and constructed inside, as well as in the perimeter of the monument). Thus, systematic monitoring of cracks can be distinguished into two phases. It was initially started (a) in lower easily accessible parts of the church and (b) in the region of the central cupola, immediately after the installation of scaffoldings. After completion of immediate measures, monitoring of cracks was extended to other regions of the monument as well. Crack openings were measured in 83 locations in total. In 75 places, pairs of stainless steel locating discs were glued on masonry (in both sides of cracks) to allow for the width of cracks to be measured using dial gauges. In the drum of the central cupola, in order to avoid manual work at a height of approximately 20 m, eight (8) LVDTs were fixed and crack openings were automatically recorded at predetermined time intervals. Data were stored in the computer installed in a protected place near the monument. Crack width measurements taken using dial gauges were also stored in the computer. The time interval between consecutive measurements was not constant. In a first period, measurements were taken almost every day. Later, and as aftershocks were less in number and magnitude, measurements were taken every 7 or 15 days. In addition, since the manual collection of measurements takes several hours, cracks that were proved to be practically constant in width for several months were, subsequently, measured at longer time intervals. In order to check whether temperature and moisture changes affect the opening of cracks, four (4) digital thermometers/hygroimeters were installed in selected places in the monument. Measurements were automatically recorded. Their evaluation did not show any substantial effect of either temperature or moisture changes on crack openings.

The evaluation of the results obtained from 83 locations along major cracks (Vintzileou, 2002), allowed for the following conclusions to be drawn:

(a) Damages observed in the monument are due to the seismic events occurred during its life. This conclusion is supported by the fact that no dangerous increase in crack openings was recorded under normal loads. It is also important to note that the aftershocks that occurred some months after the main shock (and after completion of urgent measures) did not deteriorate the state of the monument. Nevertheless,

(b) Since the monument is heavily damaged, several cracks exhibit changes in their openings (either positive or negative) that cannot be neglected (Figure 8). It seems, therefore, that the kinematic conditions of parts of the monuments are such that structural interventions are a sine qua non condition for the protection of the monument against future earthquakes.
5 QUALITATIVE INTERPRETATION OF DAMAGES

During the survey of cracks, 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. Thus, once all cracks were reported on drawings, the following simple calculation was done: On longitudinal and transverse sections of the church (such as those of Figure 6), the openings of all cracks were summed up at various levels along the height of the monument. Thus, for example, on the South façade, the following results were obtained: At level +5.55 m, the sum of all crack openings is equal to 9 mm approximately. At level +7.70 m this sum becomes equal to 11 mm, whereas at level +9.00 m (level of arches under the central cupola) the total crack opening is as large as 20 mm. The same tendency is observed also in the N-S direction of the monument. The increase of crack openings with height is more pronounced along the transversal axis. In fact, for the section of Figure 6c, at the same levels as for South façade, the respective total crack openings are 8.5 mm, 26 mm and 44 mm.

It is, 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 was confirmed by the photogrammetric survey, carried out by the National Technical University of Athens (Georgopoulos et al., 2003). In addition, this feature is confirmed 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 (Figure 4). Figure 9 shows the region between the original and the reconstructed part of that façade. One may clearly see the permanent out-of-plane deformation of the original part, which proves that the feature we observe now in the monument is an inherent characteristic.

The difference in behaviour along the two main axes of the monument (a) could be attributed to the larger sections of vertical elements available along the E-W axis (see Figure 3).

(b) seems to be confirmed also by previous interventions. In fact, as described in Section 2 (see also
Figures 3 to 5), a systematic effort was undertaken to retain the monument in the N-S direction by means of the external stone buttresses (in the N-façade), as well as by the metallic trusses (in the S-façade). However, the pathology of the monument proves that those measures were not sufficient to alter in a positive way its behaviour.

It is believed that the (increasing with height) tendency for out-of-plane deformations may interpret the damages observed in the drum of the main cupola. 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. As described in Section 3, most of the pillars 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 incapable to be deformed accordingly, the pillars of the drum (being rather flexible out-of-plane) are the elements that try to follow the deformations of the substructure.

An additional comment should be made here, regarding the effect of foundation and foundation soil on the behaviour of the monument. A shallow foundation (0.5 m deep in the middle of South perimeter wall, 1.25 m deep in the N-E parekklesion) is provided to the perimeter walls. The foundation was strengthened by a 2.0 m deep wall in the region of the N-W parekklesion, before its reconstruction in 1896. Nevertheless, there are no signs of any differential settlements that might have contributed to the damages of the monument.

### 6 NUMERICAL VERIFICATION OF THE PATHOLOGICAL IMAGE

It is well known that one of the major steps in the procedure of assessment is the reproduction of the pathological image of the structure by analytical means. On the other hand, even the most powerful analytical tool cannot be expected to reproduce the complex state of a monument that dates several centuries of life. In fact, ageing of materials, previous extreme loading situations that caused damages, alterations of the architectural scheme, as well as of the structural system, interventions (to repair or to strengthen the structure) constitute parameters that affect the behaviour of the structure. Those parameters are quite often unknown or insufficiently known by the Designer of today. Therefore, any effort for “back analysis” trying to reproduce the history of a monument is liable to uncertainties related to the available data, as well as to the limitations of the computer code itself. This is especially the case of monuments like the one considered in this work, whose geometry and interconnection of wall elements, domes and cupolae are very difficult to be accurately modeled.

Nevertheless, one could not overemphasize the importance of an analytical effort towards interpretation of, at least, major damages observed in a monument. An analytical model that allows for the numerical verification of the pathology—be it qualitative—constitutes a valuable tool for the Engineer. In fact, it allows the Designer to understand the overall behaviour of the structural system, to detect the more vulnerable parts of it, to identify the loading cases responsible for the major damages and to assess the margins of safety against various actions expected to occur. Such an analytical model may also allow for the effectiveness of alternative intervention scenario to be assessed.

Based on this reasoning, the authors of this paper have proceeded to the parameter analyses needed to verify numerically the pathological image of the monument. To this purpose the computer code ACORD3.0.2 was used. The structure was modeled by shell elements, whereas the mechanical properties of elements belonging to various parts of the structures were assumed on the basis of the available data from in-situ and in-Laboratory tests. Figure 10 shows the model of the structure. Various colours indicate regions of different geometry (planar or curved elements) and/or of different mechanical properties (lower and upper region of perimeter masonry).

Linear elastic analyses were performed for various combinations of actions. It was subjected to normal actions (i.e. to self-weight), as well as to self-weight combined with seismic action. It should be mentioned that for the first set of analyses that were carried out, the seismic action was calculated according to the Greek Aseismic Code (taking into account the importance factor, as well as a behaviour factor equal to 1.5...
Figure 11. Inner face of shell elements. Tensile stresses due to self-weight of the structure.

(valid for plain masonry). The design acceleration calculated according to the Code was equal to 0.35g. The seismic action was statically imposed along either of the N-S or E-W axes of the monument simultaneously with 30% of the seismic action in the other direction.

Dynamic analyses were also carried out with the aim to evaluate the dynamic characteristics of the monument. This presentation, however, is focusing on the results of analyses based on the equivalent static method.

Figure 11 shows the stresses developed in 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, even for the self-weight of the monument alone. In fact, it seems that tensile stresses are developed in the apex of several arches, in the domes of the narthex, in the base of the central cupola, as well as in the interconnections of domes. It seems that this feature is inherent to 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 Figure 10), as well as to 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) cupolae arranged around the central one, are transferred to rather flexible stone masonry piers (see Figure 3). 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 12. One can even observe the more pronounced lateral deformation along the N-S axis of the monument, although the stone and iron buttresses, added one century ago, are also introduced in the model. On the same Figure, the excessive out-of-plane deformation of the exonarthex is apparent.

Obviously, this behaviour is expected to be deteriorating when a seismic event occurs (Figure 13).

In order to check whether the cracking condition of the monument can be predicted by analysis, plots of principal tensile stresses obtained from analysis are compared with the respective drawings on which the cracks are reported. In the following Figures, some of those comparisons are presented. It should be noted that a comparison between the magnitude of the calculated tensile stresses and the tensile strength of masonry elements is not attempted due to the high uncertainties related to the estimation of both stresses and strengths. Therefore, the comparisons presented in Figures 14 to 15 should be assessed in a qualitative way only.

Figure 14 shows the crack pattern of the east façade of the monument, as well as the principal tensile stresses distribution as obtained from analyses for self-weight, seismic action along N-S direction and 30% of the seismic action in E-W direction. One may observe that the results of analysis seem to confirm the location
and the inclination of numerous cracks that appear in this region of the monument (e.g. shear and flexural cracks in the pillars of the drum, oblique cracks in the apex of the arches in windows, cracks in the lower zone, etc.).

Similar comments can be made on the results shown in Figure 15, which refers to the damages appearing in a section along the longitudinal axis of the monument. In general, the observed crack pattern seems to be confirmed by the analytical results in all regions of the monument. Analyses for loading combinations including the seismic action show a critical concentration of tensile stresses in arches at various levels, as well as in the pillars of the drum. In addition, extensive damages in vertical elements (masonry in the perimeter of the monument, as well as piers) are confirmed.

It should be noted that the analytical work is still in progress. A failure criterion is adopted, taking into account the anisotropy of masonry, whereas data on the mechanical properties of materials obtained from tests will also be introduced to the model to enhance its accuracy.

This model will also be used during the redesign stage, to check the efficiency of various intervention techniques.

Figure 14. East façade. Comparison between crack pattern and analytical results for earthquake along transversal axis (±y).
7 CONCLUSIONS

The study of the pathology of the Katholikon in Dafni Monastery allows for the following conclusions to be drawn:

(a) The monument is heavily damaged. Extensive and severe cracking is observed both in vertical elements and in the system of arches and domes.
(b) The detailed survey of damages showed that damages become more severe with height. This tendency is more severe in the N-S direction.
(c) Based on the on site observations, as well as on historical pathology, a qualitative interpretation of the pathological image is offered.
(d) Monitoring of cracks in more than 80 locations proved that the monument, although heavily damaged, can withstand safely its self-weight. Nevertheless, the need for structural interventions is imperative. It was also proved that the immediate protective measures, taken in regions considered as critical for the bearing capacity of the monument, were efficient, since they led even to reduction of major crack openings.
(e) The analytical investigation carried out within the project allowed to detect the inherent sensitivity of the structural system, even under normal actions. Finally,
(f) The modeling of the structure (through finite elements technique) proved to be successful, since it provided a qualitative confirmation of the pathological image of the monument.

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