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Pathology of the Katholikon of Hosios Loukas Monastery and Preliminary Structural Analysis

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Abstract This paper summarizes the work carried out in the Katholikon of Hosios Loukas Monastery with the aim to study the pathology of the monument. The load bearing structure of the church is briefly presented along with its historical pathology and damages observed after the 1981 earthquake of Boeotia and slightly deteriorated since then. Finally, the results of a preliminary analytical study performed with the purpose to interpret the observed pathology are also presented.

Keywords: Byzantine monument, historical pathology, structural analysis

Introduction

The Byzantine Monastery of Hosios Loukas in Boeotia, Greece, is one of the most important and well known monuments of the middle byzantine period. This monastic complex of high architectural and artistic value (UNESCO, World Heritage List, 1990) built on the slopes of mount Helicon, is a living monument that comprises several buildings, constructed over a long period starting from the 10th century. In the centre of the monastic complex there are two churches; the old Church of Panagia (built in the10th century) and the famous octagonal Katholikon of Hosios Loukas built in the early 11th century (Chatzidakis, 1969), decorated with marble revetments, frescoes and mosaics (Figures 1& 2) of excellent art.

Figure1: The Katholikon of Hosios Loukas

Figure2: Internal view of the dome

Being situated in a highly seismic area, the Katholikon of Hosios Loukas has sustained numerous earthquakes throughout its history. Those actions have caused serious structural problems that affected also the mosaics. The monument was subject to various restoration and conservation works over the period of 1923 to 1964. After the 1981 Boeotia earthquake hair cracks were observed in the vaulted roof of the west part of the monument (Delinikolas, 1982); some of those cracks still continue to open (at a very slow rate though). The monument being the largest and the best preserved Byzantine church in central Greece, the need to thoroughly study its structural behaviour and to identify the main causes of its historical and recent pathology at this very early stage of damage was recognized; the

final objective of such an endeavour is to take the preventive repair and/or strengthening measures that will be judged as necessary, in order to protect the monument in case of a strong earthquake.

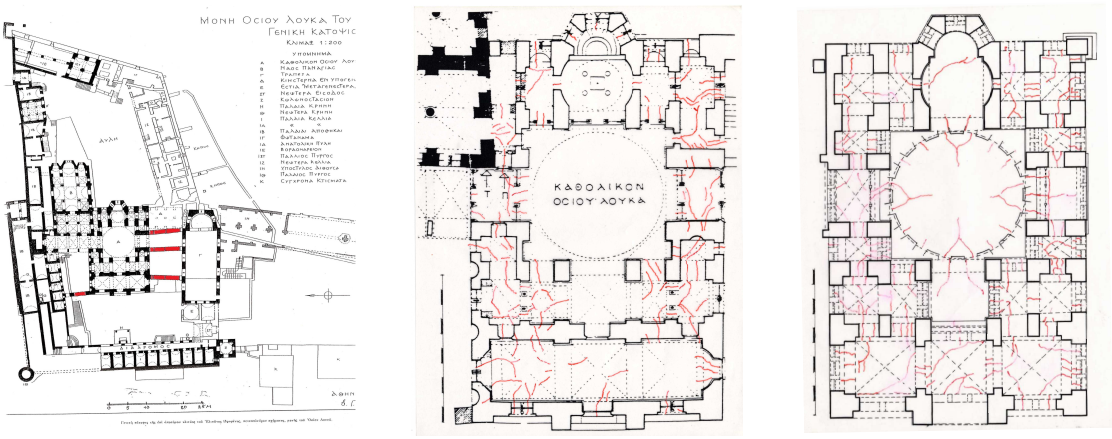
Within the framework of a strategic plan undertaken by the Hellenic Ministry of Culture for the monument's restoration and conservation, a series of studies and research programs were planned and are still in progress. This paper focuses on the pathology of the Katholikon, as well as on the results of preliminary elastic analyses, which has allowed to better understand the structural behaviour of the monument and to interpret the observed pathology (Miltiadou-Fezans, 1999); they have therefore served the purpose of guiding in situ investigations (such as monitoring and NDT applications).

Brief Description of the Load Bearing Structure of the Monument and its Pathology

The Katholikon of Hosios Loukas is a two storey structure with gallery in the first floor (extended in all the church around the central domed area with the exception of the east and west arm of the cross) and a large crypt together with empty inaccessible spaces below the ground floor, due to the inclination of the foundation rock. It comprises: the main church, the sanctuary, the narthex and four chapels, which complete its orthogonal plan (Fig. 3). The central part of the main church is cross-shaped in plan and belongs to the octagonal type. Over the square nave, rises the dome carried on eight pendentives, four semicircular arches, and four squinches in the corners, achieving in this way the transition from circle to square (Fig. 2). The hemispherical dome is carried on a 16-sided polygonal (almost cylindrical) drum. Its diameter is 8,80 m and its height including the drum is 5,18 m. The east arm of the cross over the sanctuary is covered with a dome on pendentives, the north and west arms are groin-vaulted, while the south arm of the cross is covered with a barrel vault. All the other parts of the church are groin vaulted, both in the ground floor and in the gallery. The exterior face of the vertical perimeter walls are built with large dimension stone blocks (often, reused material), in combination with layers of byzantine bricks around them; the type of construction of the section of the walls is under investigation using radar and endoscopy (Vintzileou et al., 2009). Plain brick masonry was used for the entire vaulted roof and for all the arched openings.

The monument, during its life (from 11th century up to date) has been subjected to various modifications; it suffered numerous earthquakes, whereas major interventions for its preservation were applied in the 19th and 20th century. Even a brief presentation of the long history of the monument is beyond the scope of this paper. In what follows some basic information is provided, regarding its historical pathology and the major structural interventions.

Due to earthquakes occurred the mosaic representing the Pantokrator was destroyed; thus during the 17th century the intrados of the hemispherical vault of the dome was decorated with frescoes (Fig. 2). Probably at the same period, the majority (10 from 16) of the windows of the drum of the dome were built to avoid further deterioration of the damage. Moreover, the west pier of the drum was demolished and a relieving arch was built to transmit the loads to the adjacent piers (Figure 1), probably due to serious damage observed in the vaulted structure below. A question is raised if at the same period severe damage led to the replacement of the groined vault of the south arm of the cross with a barrel vault, or this happened later, during the 18th century when, due to out of plane deformation of the south wall, three stone buttresses were added towards the external south façade (Fig. 1 and red colour in Fig. 3a). In the same period another buttress was constructed, connecting the NW masonry pier of the church with the existing structures to the north, to avoid further increase of it's out of plane deformation (Fig. 1 and Fig 3a). During the 19th century, the exonarthex added to the west part of the Katholikon in the 12th century was demolished; it is not yet well documented if this was done due to extended damage or morphological reasons (Filippidou-Boura, 1970-1971). In the late 19th and early 20th century severe damage due to earthquakes, further deteriorated by rain water and vegetation (cracks 5-10 cm wide, local disintegration of masonry, etc) were reported (Troump &Balanos ,1895, Orlandos & Soulis, 1918, Eugenios 1921); the out of plane deformation of the piers of the west wall was estimated to reach the 1,5% of their height (Eugenios, 1921).



(a) (b) (c)

Figure 3: (a) General plan of the Katholikon and adjacent structures (Stikas, 1970) and crack pattern on the intrados of the vaulted roof of the ground floor (b) and of the gallery (c)

Thus, in 1923, the heavily cracked extrados of the cupola was repaired, and a second brick masonry hemispherical cupola was constructed over it, at a distance of approximately 70 cm (Orlandos, 1924 and recent measurements). In the same period an iron ring was placed for the confinement of the base of the hemispherical vault of the central cupola (Fig. 1). Furthermore, as reported by Stikas (1970) from 1938-1964 extended works took place for the repair of the severely damaged masonry, by local reconstructions, re-pointing of joints with cement mortars, sealing cracks and local gravity cement grouting. To this end, a large number of damaged mosaics have been detached from the walls and reattached using cement mortars, often reinforced with steel grids. Many marble revetments were also removed and replaced after the repair of masonry. Cement renderings were used to fill the losses of mosaic decoration. Moreover, all the cracks of the extrados of the vaulted roof were as well locally repaired with cement mortar re-pointing, and new ceramic tiles were installed on the roof after the construction of a rigid cement coating.

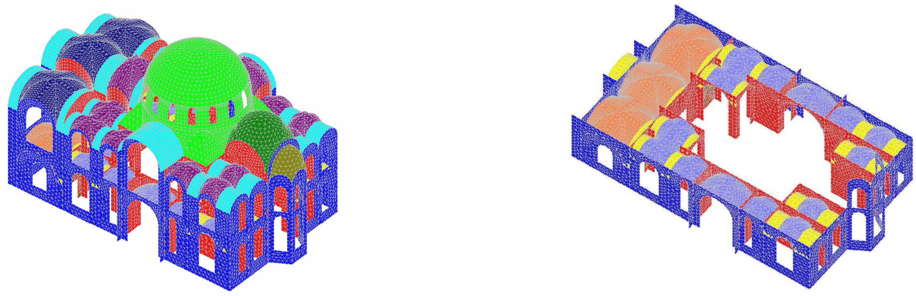
After the Boeotia or Kaparelli 1981 earthquake some hair cracks appeared in the vaulted roof of the monument; the damages became more apparent after the 1995 (Aegion) earthquake and continue to slightly deteriorate until nowadays. In Figure 3b a survey of the cracks of the intrados of the vaulted roof of the ground floor is presented, while in Fig. 3c the cracks of the intrados of the vaulted roof of the gallery are shown (Miltiadou-Fezans 1999, reported on the drawings of Stikas and Schultz & Barnsley). The cracks have max width 3mm, and they are deteriorating from the exterior to the interior and from the lower to the upper parts. They have appeared in almost all the groined vaults and arches around the central core, as well as in the intrados of the dome. As proved by the comparison with old photographs (Stikas, 1970) and technical reports (Eugenios, 1921) many of the cracks coincide with the old ones, as they appeared in almost the same position. Some cracks are present as well in the masonry walls. The most apparent are situated on the west façade of the monument, the SW corner pier and the east wall of the narthex, showing once again the vulnerability of the west part of the monument, already proved by its historical pathology, presented above.

Summarizing the above brief description one could say that the main cause provoking this pathology is inherent to the structural system and the geometry of the load bearing structure of the Katholikon. In fact, this is composed by vaulted roofs (double central dome, perimetric groined vaulted elements extended in most cases in two levels or even three taking into account the crypt), and a system of masonry piers (Figure 3a-3c), which are the elements to sustain the vertical and horizontal actions. The lack of a system of wooden or metallic ties that could sustain the horizontal thrust of arches and vaults has to be underlined. As shown for a similar bearing system, namely the Katholikon of Dafni monastery (Miltiadou et al., 2005), the major problem of such structures consists in tensile stresses due to the horizontal thrust of the vaulted roofs. Those stresses develop in the region close to

the piers supporting the vaulted roofs, even under vertical loads alone. This behaviour is deteriorated under seismic actions and leads to the appearance of cracks in the vaults and arches and to out of plane deformation of the masonry piers (which are rather slender). It seems that the observations made for Dafni monastery are valid also for the Katholikon of Hosios Loukas, as indicated by the historical and the recent pathology of the monument, as well as by the structural restoration measures taken in the past. However, in the case of Hosios Loukas the gallery has a positive effect on its structural behaviour (at least as far as the out of plane deformation of piers is concerned).

Preliminary Structural Analysis and Numerical Verification of the Main Pathology

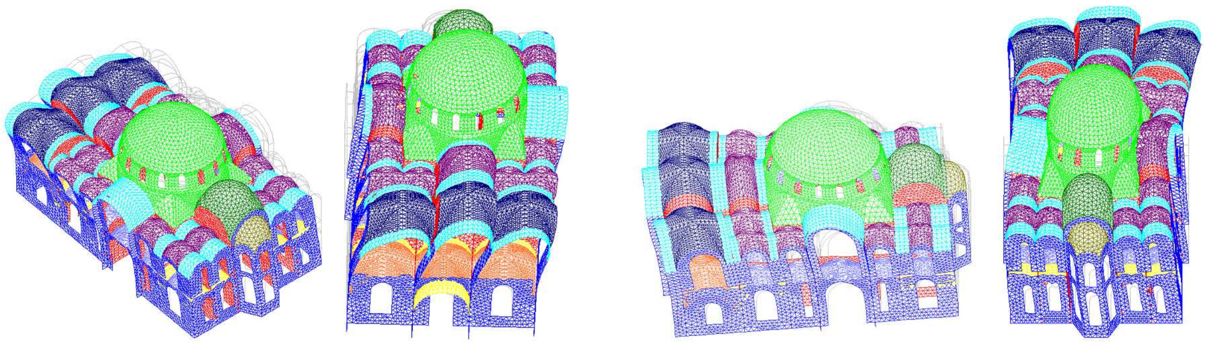
The structure was modeled-using the computer code ACORD 3.0.2 for Windows-with combined plane and shell elements (Figure 4a and 4b). The geometry of the monument (including thickness of each individual element) was reproduced in detail; in Figure 4 various colours indicate regions of different geometry and function (planar or curved elements) and/or of different mechanical properties (external and internal walls). Young's moduli were also allotted to the members depending on their material (stone or brick masonry), on the basis of the available data of the in situ and Laboratory investigations, as well as the experience gained from the analysis of a similar structure (Miltiadou-Fezans et al. 2005).



(a) (b)

Figure 4: (a)The entire model of the structure;, (b) view of vaulted elements of the ground floor

The church was assumed to be fixed either on rock (e.g. its northern mart) or on the stiff basement walls (e.g. in its southern part). The model will be further improved in the future, to account for foundation conditions, on the basis of the results of geotechnical investigations and archaeological excavation in selected areas now in course. Moreover, constraints due to the adjacent church of Panagia and to the stone buttresses will be also taken into consideration.



(a) (b)

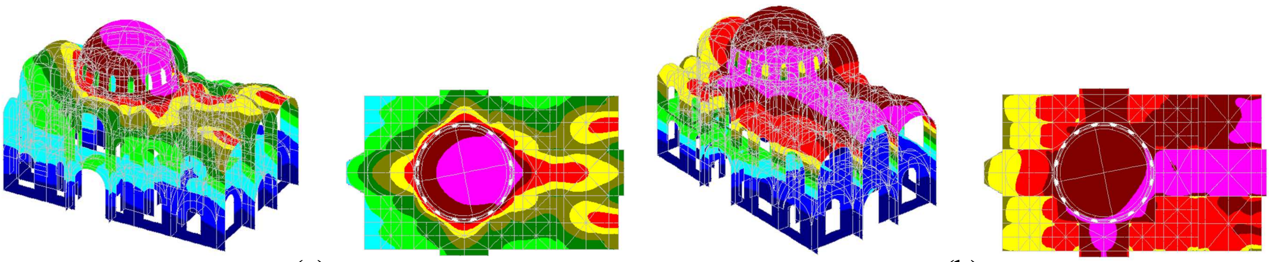
Figure 5: (a) First mode of vibration (N-S axis), f*requency equal to 2,34* Hz. *(b) Second mode of vibration (E-W axis*), f*requency equal to 3,05* Hz

A calibration of the model was attempted, on the basis of in situ measurements of its dynamic behaviour. The monitoring system installed in the monument since 2002 has recorded the response of the church during several earthquakes of medium to low magnitude. Figure 5 shows the deformed shape of the model following the first and the second modes of vibration. It can be observed that the

calculated frequencies (see Fig. 5) fit quite well those measured to be equal to 2.611Hz along the N-S axis and 2.638Hz along the E-W axis of the church (Mouzakis, 2004). On the basis of this calibration, the mechanical characteristics of the various parts of the monument were finalized

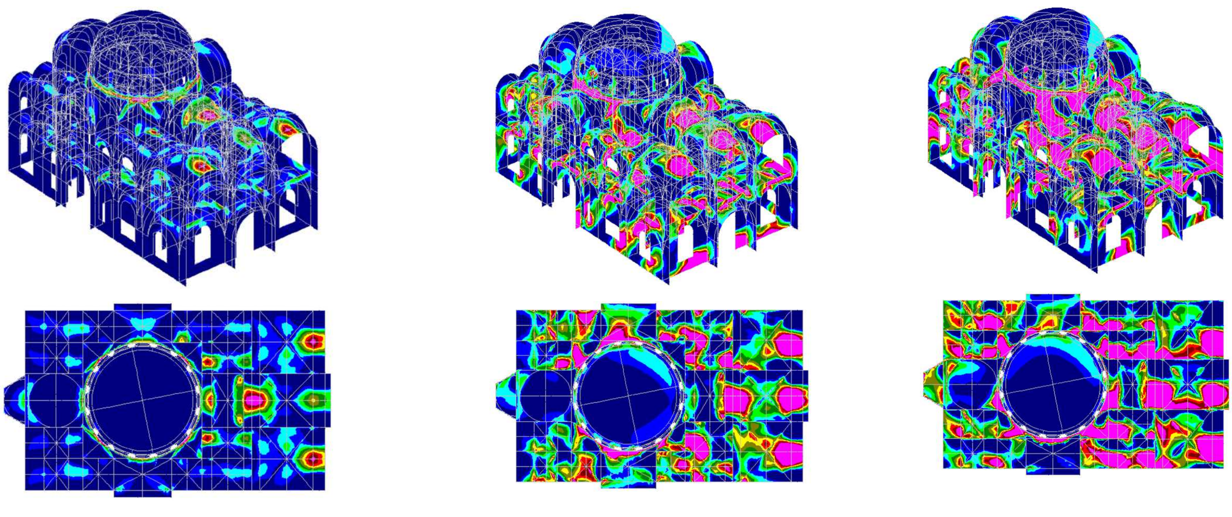
The model was analyzed under permanent loads (the self weight of the structure) alone or combined with seismic action along the N-S or the E-W axis of the church. Taking into account the provisions of the Greek Seismic Code, a horizontal "seismic" force was calculated, equal to 0.412 times the mass of the structure. The structure was subjected to various load cases. In combinations comprising the seismic action, the seismic force along one main axis was combined with 30% of the seismic force along the other main axis. In this section some selected results are presented and commented upon.

Displacements-Deformations Although elastic analyses were carried out and, therefore, deformations are underestimated, it was proven that there are vulnerable regions (such as zones of support of domes and vaults on vertical elements, as well as the western part of the church), where the deformations are rather pronounced (Figure 6a and 6b). This result is in accordance with the aforementioned historical and recent pathology.



(a) (b)

Figure 6: Isovalues of displacements (a) under self weight (g_1, max=6,2mm) and (b) under self weight and seismic actions ($g_1+e_y+0.3e_x$, max=29,7mm)



(a) (b) (c)

Figure 7: Isovalues of tensile stresses (view from NW and above): (a) under self weight, g_1 / max 0,55 MPa, (b) under self weight and seismic actions $g_1+e_x+0.3e_y$ / max 1,39 MPa, and (c) $g_1+e_y+0.3e_x$ / max 1,86 MPa

Stresses As expected, similar behaviour is observed when maximum tensile stresses are plotted. In Figure 7, stresses over a limit of 0,3 MPa are indicated with the same colour (pink), to allow for comparison between various load cases. Although the tensile strength of various types of masonry is not expected to be higher than 0,1MPa (based also on laboratory tests), a less conservative value of 0,3MPa was selected just for the clarity of the images. Actually, Figure 7a shows the isovalues of the tensile stresses (on the interior face of shell elements) under the self weight of the structure. One may

observe that, even without the seismic action, there are regions in which tensile stresses larger than the 0,3MPa limit are developed. Critical regions are located in several parts (e.g. in the supports of vaults, in arches, as well as in the western part of the church). Again, this result seems to be in accordance with the observed pathology. Needless to say that, the situation becomes significantly more critical when seismic actions are taken into account (Figure 7b and 7c).

Conclusions

The study of the pathology of the Katholikon in Hosios Loukas Monastery allowed for the following conlusions to be drawn:

(i) The recent pathology observed is similar with the historical pathology of the monument; damages become more severe with height and in the west part of the church.

(ii) The finite elements modeling of the structure proved to be successful, since it provided a qualitative confirmation of the pathological image of the monument; furthermore, the preliminary analytical investigation allowed to detect the inherent sensitivity of the structural system, even under normal actions, and to highlight its vulnerability under seismic actions.

On the basis of these results, a detailed architectural and structural survey of the monument and its pathology was proposed, as a prerequisite for further developing the investigation of the structural behaviour of the structure. Moreover, this study guided the installation of the static and dynamic monitoring system, as well as the realization of in situ investigations with NDT and MDT to determine the way of construction and the mechanical characteristics of the masonry. Finally, archaeological excavations and geotechnical research were proposed in selected areas. All this indispensable complementary information will be taken into account in further analyses, in order to better clarify the structural behavior of this important monument.

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