The use of radar techniques and endoscopy in investigating old masonry: the case of Dafni Monastery

E. Vintzileou
Laboratory of Reinforced Concrete, National Technical University of Athens

A. Miltiadou-Fézans
Directorate of Technical Research for Restoration, Hellenic Ministry of Culture

V. Palieraki
Laboratory of Reinforced Concrete, National Technical University of Athens

N. Delinikolas
1st Ephoreia of Byzantine Antiquities, Hellenic Ministry of Culture

ABSTRACT: This paper summarizes the results obtained from the application of two investigation techniques, namely radar and endoscopy, in the masonry of the Katholikon of Dafni Monastery (Attica). The two techniques were applied with the aim to investigate the type of construction of the perimeter masonry of the monument. The application of the two techniques proved to be very efficient, since their results offered reliable information regarding the thickness of stones, hence, the thickness of the internal filling material in the three-leaf stone masonry of the monument.

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, Bouras, 1998, Delinikolas et al., 2003). The Katholikon of the Monastery (Figure 1) has suffered serious 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 for the conservation of the monument (its mosaics included), a series of research programs were carried out with the aim to acquire information that is necessary for the assessment of the monument and, subsequently, for the stage of interventions. A part of the research programs was dealing with the evaluation of the mechanical characteristics of masonry.

The investigation of the construction type of masonry constitutes an important step towards the evaluation of the mechanical properties of masonry. Given the architectural value of the monument, and the resulting constraints regarding the techniques that can be applied, and taking into account the limitations of each investigation technique, the decision was made to apply a combination of two techniques, namely radar and endoscopy, in order to reach enhanced reliability of the data. In fact, radar technique (a non-destructive one) was the main one to apply to the

1 A Scientific Committee was set by the Ministry of Culture, to follow the progress of the investigations, studies and works. Members of this Committee are Professors Ch. Bouras, T.P.Tassios, H.Mariolakos and N.Zias.
monument. Endoscopy was applied in places where the information obtained by the radar technique was considered of low reliability. It should be noted, however, that endoscopy, thanks to the direct visual contact of the observer with the interior of masonry, offered additional valuable information regarding the type of construction materials, and the presence of internal discontinuities in masonry.

For both techniques, the equipment available at the Laboratory of Reinforced Concrete/National Technical University of Athens was used.

2 A SHORT DESCRIPTION OF THE APPLIED TECHNIQUES

2.1 Radar technique

Using a radar system, consisting of a central unit and various antennas, electromagnetic signals are emitted through the material under investigation. The antenna is moved along a straight line on the surface of the considered material or element. When the signal meets an interface (be it a void or a discontinuity within the material or a different material), part of the emitted radiation is reflected and recorded by the central unit and part of it travels deeper into the material. Thus, by appropriately processing the recorded reflected pulse, one may have a picture, more or less clear of the in-depth geometry of the investigated element.

Radar technique was first applied in the field of geophysical investigation. Its application especially in masonry structures is still rather limited, although this non-destructive technique seems to be adequate for structures of high architectural values. It has to be admitted that the numerous interfaces that the electromagnetic pulse can meet when traveling through masonry are of unknown nature, they may cause multiple reflections of the pulse, thus giving a rather unclear picture of the internal state of masonry.

2.2 Endoscopy

This technique, borrowed from medical applications is a slightly destructive method. Holes (approximately 25 mm in diameter) are drilled in masonry. After meticulous cleaning of the hole from dust and loose material, the endoscope is introduced into the hole. The core of the endoscope, consisting of optical fibres, allows for direct observation of the walls of the hole. In addition, pictures can be taken at any depth of the hole.

It should be mentioned that, since the diameter of the drilled holes is rather small, the application of this technique is acceptable even in case of structures of high architectural value.

3 APPLICATION OF TECHNIQUES – PROBLEMS ENCOUNTERED

(a) It is well known (Daniels, 1996) that, when using the radar technique, the accuracy of the picture depends on the frequency of the emitted signal: Low frequency signals allow for more in-depth investigation giving, however, less clear results; on the contrary, higher frequency signals result to rather limited penetrability. Nevertheless, in this case, the obtained picture is clear for the limited depth that is investigated. Given the scope of this application, a rather high frequency antenna was selected (1500 MHz). In fact, available historical data regarding previous interventions on the monument (Delinikolas et al., 2003), as well as cores taken in selected locations prove that the (approximately 0,80 m thick) masonry of the Katholikon is a three-leaf masonry. Thus, the scope of the investigation was (i) to obtain data regarding the thickness of stones in both the internal and the external leaves and (ii) to check whether there are stones connecting the two leaves of masonry. On the other hand, the radar technique was not expected to give reliable information regarding the intermediate leaf, given its nature (it consists of rubble material-pieces of stones and bricks loosely cast in mortar) and the numerous interfaces between various materials. It has to be mentioned that the applicability of the radar technique in Dafni Monastery was investigated, during a preliminary stage, by the specialized staff of LCPC-France (Côte et al., 2002). This investigation gave very promising results.

(b) Although the aim of the research was to investigate the type of masonry construction along all perimeter walls of the monument, the investigation was finally limited to parts of the south and west walls. For example, the application of the technique in the eastern wall of the church was not feasible, due to the complex geometry of the wall (Figure 2, the section is polygonal from outside and curved from inside),

Figure 2. The eastern wall of Katholikon.
as well as due to the extensive use of bricks around the openings (since lime affects the accuracy of the signal).

(c) Even in south and west walls, the paths along which the radar was moved were selected respecting various limitations, namely: (i) Accessibility (availability of scaffolding allowing for the personnel to work, as well as for the equipment to be safely installed), (ii) Accessibility (if possible) both from the exterior and the interior, in order to gather information for the same part of masonry from both sides, (iii) Masonry without plaster or mosaic on the interior surface, whenever possible: As the antenna is moved along a pre-selected path, when the length of stones and the thickness of the mortar joints are known, the interpretation of the results is greatly facilitated, (iv) Since in several cases endoscopy was also applied to enhance the accuracy of the results, paths selected for the application of radar technique as well should not belong to regions with mosaics or original Byzantine mortar.

(d) In places where endoscopy was applied, the following problems had to be faced: (i) To allow for observation along the drilled holes, meticulous cleaning was needed. In fact, powder produced by drilling through mortar had to be removed, as well as small mortar or stone pieces, (ii) In several cases, due to the large thickness of mortar compared to the diameter of the hole, it was not possible to detect the ends of the adjacent stones, finally, (iii) In some places, drilling was limited to a depth smaller than the predetermined one. This occurred when the drilling device met a stone that could not be pierced.

Taking into account the aforementioned limitations, radar technique was applied to more than 90 paths (vertically or horizontally, from the exterior and/or from the interior face of masonry). The total length of scanned masonry was over 200 m. On the basis of the results obtained from this technique, the locations for application of endoscopy were selected. Endoscopy was applied in 32 locations, selected respecting the aforementioned limitations as well.

In the following sections, the results obtained by applying the two techniques are presented and commented.

4 RESULTS OBTAINED BY RADAR TECHNIQUE

The following Figures 3–5 show the typical presentation of measurements taken by the radar technique.

The location of the path scanned with the antenna is shown on a drawing. The path shown in Figure 3 belongs to the western upper part of the south wall of the monument. The arrow shows the direction of movement of the antenna on the wall.

Figure 4 shows the raw data of Path G, before any processing. The horizontal axis corresponds to the length of the path, whereas the vertical axis is expressed in time (in nanoseconds). The vertical white
dotted lines in the upper part of the picture (one of them is marked with a circle on Figure 4) show the location of mortar joints among consecutive stones. The location of joints is manually introduced to the respective file by the observer during scanning of the path and they allow for easier interpretation of the results. This is the reason why it is preferable to apply the technique on uncovered masonry (without plaster). The continuous dark gray line (indicated on Figure 4 by the white arrow) constitutes the reflection of the surface of masonry. Raw data, as presented in Figure 4, are not liable to interpretation. Thus, using the possibilities offered by the software accompanying the equipment, the file containing the raw data is subject to various modifications (such as overall gain, migration, etc.). In this way, a new file is created (Figure 5a). The vertical axis is now in meters (in depth of masonry). One can distinguish on the graph, at a depth of approximately equal to 0.25 m, a zone of disturbance. This zone corresponds to the end face of the series of stones scanned along path G. The findings are then presented in a drawing (Figure 5b) showing (in scale) the length and the thickness of the stones.

It should be reminded here that a relatively high frequency antenna was used with the aim to obtain as accurate as possible results regarding the thickness of stones. In fact, as shown in Figure 5, the data corresponding to the part of masonry deeper than the first leaf of stones cannot be evaluated.

On the same Figure 5, a white ellipse shows a hyperbola, which was assumed to indicate the location of a metallic material in the internal leaf of the wall. In order to check whether this assumption was correct, that region was investigated also by endoscopy, as described in the following section.

5 RESULTS OBTAINED BY ENDOSCOPY

As mentioned in the Introduction, endoscopy was applied mainly in order to check the validity of radar measurements in some locations, in which the obtained picture was not clear enough. The results of observation using the endoscope are presented as shown in Figures 3, 6–8: The location of the drilled hole is first indicated on the respective drawing (e.g. E21 on Figure 3). A detail of the region in which the hole (25 mm in diameter) is drilled is shown in Figure 6a, together with a sketch based on the visual inspection by the observer (Figure 6b). The presentation is completed with the pictures taken by the observer (Figure 7).

As shown in Figures 6b and 7, endoscopy has confirmed the findings of radar measurements in the same location (compare with Figure 5). In fact, the thickness of stones was measured and it was found practically equal to that determined by the radar measurements.

Figure 6. (a) Detail of the region of E21, (b) Sketch of the results of observation.

Figure 7. Picture taken inside the hole of E21. The limit of the right stone is shown (compare with Figure 6b), as well as the metallic object in the far front of the hole.

In addition, a metallic object2 (detected also by the radar) was found, as shown in Figure 7.

It should be noted that the observation through endoscope offers, thanks to the direct visual contact of the observer with the inside of masonry, the possibility of detecting discontinuities and holes (Figures 8

2 During the extensive interventions carried out in 1895, the original materials were used for reconstruction. Cracked stones were also used. In such cases, iron [-shaped connectors (like the one detected by endoscope) were used to bridge the crack.
and 9), as well as to obtain qualitative information about the state of materials (Figure 10).

This kind of information is valuable during the decision making stage for interventions. In fact, it may allow for a rough estimation of the percentage of voids within masonry, which in turn affects the proportioning of grouts to be injected, as well as the anticipated strength enhancement of masonry. It may also affect the procedure of injecting grouts. In fact, special measures have to be taken to avoid damages to mosaics when large internal holes are present at their vicinity.

Figure 8. Picture from E6: One may observe two stones, as well as the mortar between them. It is obvious that the joint between the two stones is only partially filled.

Figure 9. Picture from E6. The nature of the material filling the space between the two leaves of masonry can be seen: It consists of mortar and pieces of stone. Holes in the filling material are apparent.

Figure 10. Picture from E19. The mortar between stones is disintegrated. Roots of a plant can also be seen.

It has to be mentioned, however, that this last aspect has not yet been thoroughly investigated.

6 COMPARISON OF RESULTS OBTAINED BY RADAR AND ENDOSCOPY

Figure 11 shows some plots of horizontal sections of masonry, as obtained by radar. In each plot, the part of the path for which results by endoscopy as well are available, is magnified and presented on top of the complete path. It may be observed that in several cases, the measurements of the two methods correlate remarkably well (as in the two first paths). In other cases, however, it seems that the thickness of stones was not accurately determined on the basis of radar measurements.

In general, the results of endoscopy are considered to be more accurate, since they are based on visual inspection. Thus, the pictures taken by radar measurements are—where needed—corrected accordingly. Nevertheless, in some cases, inspection through endoscope was proved to be inconclusive: Holes for inspection through endoscope were drilled mostly through mortar joints, to allow for the thickness of adjacent stones to be determined. However, the fact that either the mortar joint is excessively thick or the back face of the stones is not perfectly cut (Figure 12), does not always allow for the end face of stones to be clearly detected. In such cases, the results of both techniques were re-evaluated and the most reliable ones were selected as final. It should be noted, however, that even in cases of disagreement between the two methods, the basic geometry of masonry in its depth is not substantially affected (see Figure 11). In fact, the purpose of this investigation is served by the applied techniques in a satisfactory way.
endoscope were plotted on horizontal and vertical sections of masonry. As mentioned in preceding sections, it was attempted to take measurements along more or less the same locations both from inside and outside of the walls, in order to reach pictures of the complete section of masonry. Some of the results are shown in Figures 14 to 17. Before commenting on the sections presented on the Figures, let us give some more information regarding the type of masonry in various regions of the monument. As shown in Figure 13 (as well as in Figure 2), one may clearly distinguish two different types of masonry in the exterior face of the vertical elements. In fact, there is a lower zone (from foundation level to the first row of windows), built with large dimension stones, their length placed horizontally or vertically, in order to form crosses. In the space between the large stones there are smaller cut stones, as well as solid bricks in the perimeter of stones. In the upper part of the walls, masonry is constructed with smaller stones. Here again, solid bricks are used both within the horizontal and several vertical mortar joints. Both regions were investigated. Nevertheless, since the lower zone is expected to exhibit higher mechanical properties (this is confirmed by the observed pathology of the monument, see Miltiadou et al. 2004), the investigation was concentrated mainly on the investigation of the upper (more vulnerable) zone of masonry.

Figure 14 shows two horizontal sections of masonry representing the lower zone with large dimension stones in the outer leaf. One can clearly distinguish the different type of construction of the two masonry leaves. In fact, the external one (outside—"O" on the Figure) is made of stones as thick as 0.5 m to 0.6 m in some cases, whereas the internal leaf (Inside—"I" on the Figure) is made of stones whose thickness varies between 0.1 m and 0.2 m. The intermediate leaf (filling material) is of varying thickness along the wall (due to the varying thickness of stones). It may be, however,
considered to be continuous, since there are no transverse stones connecting the external leaves between them.

This picture was confirmed by measurements in the vertical direction (Figure 15). On the basis of the available measurements, one may conclude that the lower zone consists in an outer strong leaf, of average thickness equal to 0.39 m, an inner weak leaf, approximately 0.17 m thick and an intermediate leaf of filling material 0.24 m thick approximately.

Figure 16 shows three horizontal sections representing the type of construction of the part of walls from the lower row of windows up to the arches and domes (Figure 13). In Figure 17, vertical sections of masonry in the same zone are presented. One may observe that (a) there is still a difference of thickness between the outer and the inner leaf of masonry. Nevertheless, this difference is less pronounced than for the lower zone of masonry. In fact, the average thickness of the outer leaf is approximately equal to 0.28 m, whereas the average thickness of the inner one is of 0.20 m approx., (b) due to the smaller thickness of stones of the external leaf, the average thickness of the filling material is larger than in the lower part of masonry (approximately equal to 0.32 m), (c) in some cases (see Figure 16c), in the inner leaf, there are stones placed with their length along the thickness of the wall, thus reducing locally the thickness of the filling material.

A general remark valid for either zone of masonry is that the construction type is much more complex than that of a masonry consisting of three leaves of practically constant thickness both horizontally and vertically. In fact, in masonry of the Dafni Monastery, the use of stones varying in thickness, both in-length and in-height of masonry leads to increased interface between external leaves and filling material. Thus, a positive effect of the geometry on the mechanical properties of masonry could be expected.

The information gathered thanks to the investigation presented in this paper will serve the purpose of determining the mechanical characteristics of masonry. As mentioned in the Introduction, part of the strategic plan of preservation of the monument is
devoted to the estimation of the mechanical properties of masonry. At a first stage, an attempt was made to estimate some basic mechanical properties, such as the compressive strength of masonry. To this purpose, samples of stones were tested in Laboratory and their compressive strength, tensile strength, Young's modulus of elasticity and Poisson's ratio were determined. In addition, the fragments test (Tassios et al., 1989) was applied to pieces of mortar taken out of various zones of masonry. Thus, the tensile strength of mortar was determined. On the basis of the available literature, this tensile strength was translated into compressive strength of mortar. Subsequently, in order to estimate the compressive strength of masonry, several empirical formulae were applied. Those formulae, which express the compressive strength of masonry as a function of the compressive strength of constituent materials, resulted to unacceptably scattered values for the compressive strength of masonry. It is obvious that the adoption of the lower value, that might constitute a sensibly conservative assumption in case of a building of rather low architectural value, is definitely unacceptable in case of a monument like the Katholikon of the Dafni Monastery. In fact, such a conservative assumption would lead to extensive interventions that might not be needed and that would inevitably alter the architectural value of the monument. Thus, the decision was taken to construct wallettes following the construction type determined on the basis of radar and endoscopy investigations and to test them in compression or in shear, in order to reach reliable data regarding the characteristics of masonry. In addition, since the Central Archaeological Council has already approved the proposal for injecting grouts to the monument, the wallettes-after testing-will be injected and then retested, in order to measure their improved mechanical properties. This part of the research is in the stage of construction of wallettes.

A last comment regarding the accuracy of the results obtained by the two techniques should be added here. In Figures 14 to 17, where the profiles obtained from both sides of masonry are plotted together, one may see also the regions of uncertain data (marked on the profiles by dotted lines). The following can be observed: (a) The presentation of both single-side profiles allows for further correction of the data obtained by radar and endoscopy. In fact, as shown-for example-in the last profile of Figure 16, in the region marked with an ellipse, the thickness of the stone belonging to the outer leaf of the wall was not reliably determined. However, the fact that the thickness of the respective stone of the inner leaf was accurately measured, suggests that the smaller of the two possible thicknesses should be adopted for the stone in the outer leaf, (b) There are cases, however, in which the uncertainty regarding the thickness of some stones remains (see, for example, the part of the same profile marked with a rectangle). Nevertheless, one could accept this inaccuracy, since the overall geometry of masonry does not seem to be affected by the uncertainties related to the dimensions of a limited number of stones.

8 CONCLUSIONS

On the basis of the material presented in this paper, one may conclude that

(a) The application of radar techniques to masonry can yield reliable results regarding the geometry of masonry-in-depth. To this purpose, however, rather high frequency antennas should be used; thus, the depth for which the results are accurate enough is limited to part of masonry thickness.

(b) The combination of this non-destructive technique with the slightly destructive technique of endoscopy may enhance the accuracy of the results. In addition, endoscopy may provide information regarding the nature and the state of materials inside masonry.

(c) For the purpose of the investigation that serves the needs of preservation of the Dafni Monastery, the two techniques provided sufficient information that allowed for the construction type of masonry to be determined in various parts of the monument.

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