THE USE OF RADAR TECHNIQUE AND BOROSCOPY IN INVESTIGATING HISTORIC MASONRY: APPLICATION OF THE TECHNIQUES IN BYZANTINE MONUMENTS IN GREECE

V.PALIERAKI

PhD Candidate
Laboratory of Reinforced Concrete
National Technical University of Athens, Greece

E.VINTZILEOU

Associate Professor
Laboratory of Reinforced Concrete
National Technical University of Athens, Greece

A.MILTIADOU-FEZANS

Director for Technical Research on Restoration
Hellenic Ministry of Culture, Athens, Greece

SUMMARY

This paper summarizes the results obtained from the application of two investigation techniques, namely radar and boroscopy, in the masonry of three Byzantine Monuments in Greece. The techniques were applied to investigate the type of construction and the presence of timber ties in the masonry. The application of the two techniques proved to be efficient, as their results provided reliable information regarding both the thickness of stones, and the presence and the state of timber ties. In the paper, problems encountered and constraints related to the application of the techniques are commented upon.

INTRODUCTION

Dafni Monastery (in Attica) and Osios Loucas Monastery (in Boeteia) (UNESCO World Heritage Monuments) as well as the church of Panagia Krina (in the island of Chios) are monuments of high architectural and artistic value (Figure 1).

The three monuments built in the period of 11^{th}-12^{th} centuries AD, decorated with marble works, as well as mosaics and frescoes, have suffered severe damages during their

lifetime, due also to earthquakes. The Hellenic Ministry of Culture has taken the decision to intervene with the aim to repair damages and to improve the seismic behaviour of the monuments. One of the steps taken was the in situ investigation of the construction type of three-leaf masonry. Information about the construction type of masonry is of paramount importance both for the assessment of the mechanical properties of masonry in the actual state, as well as for the stage of decision-making regarding interventions to be applied. The aim of in situ investigations was (a) to detect the thickness of stones from both faces of masonry and that of the intermediate filling material, (b) to check whether there are stones connecting the external leaves of masonry, (c) to collect data regarding possible large voids within masonry and (d) to check whether there are timber ties within masonry, as well as to check the state thereof.

Figure 1. The Katholikon of Dafni Monastery, the Church of Panagia Krina and the Katholikon of Osios Loucas Monastery.

APPLICATION OF TECHNIQUES- PROBLEMS ENCOUNTERED

Investigations by Radar

Radar technique, first applied in the field of geophysical investigation, is based on the theory of electromagnetic signals. 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 examined 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. By appropriately processing the recorded reflected pulse, one may obtain a picture, more or less clear of the in-depth geometry of the investigated element. It is a non-destructive technique, therefore adequate for structures of high architectural value.

The results of the radar technique are expected to be less conclusive in case of a rubble three-leaf stone masonry than for other more regular types of masonry. Nevertheless, the fact that this method is a non-destructive one, leads to an increase of the interest on an international, and mainly European scale, and many researchers are developing the radar technique for masonry structures, for monuments and historic centers (Binda et al., 2005). In general, the radar technique is used in combination with other investigation techniques, so that the accuracy of the results can be enhanced (Binda et al., 2003 [1], Binda et al., 2003 [2], Binda et al., 2004 and ONSITEFORMASONRY, 2005).

The radar technique is applicable to masonry provided that the conditions mentioned hereafter are satisfied:

(a) An antenna of adequate frequency is used, as the accuracy of the picture obtained through radar depends on the frequency of the emitted signal (Daniels, 1996): 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, when higher frequency signals are emitted, the obtained picture may be sufficiently clear for the limited depth that is investigated. In the cases presented in the here, the antenna of 1500 MHz has been used, given that high accuracy in relatively small depths was needed.

(b) Since the antenna is moved on the surface of the wall, for this movement to be smooth and for the contact of the antenna with the medium to be continuous, the surface of masonry has to be free of protruding and recessing parts.

(c) The application of the radar technique is not quite efficient in case of brick masonry, as clay affects the accuracy of the emitted and received signal, because of the pronounced attenuation of the signal (Daniels, 1996).

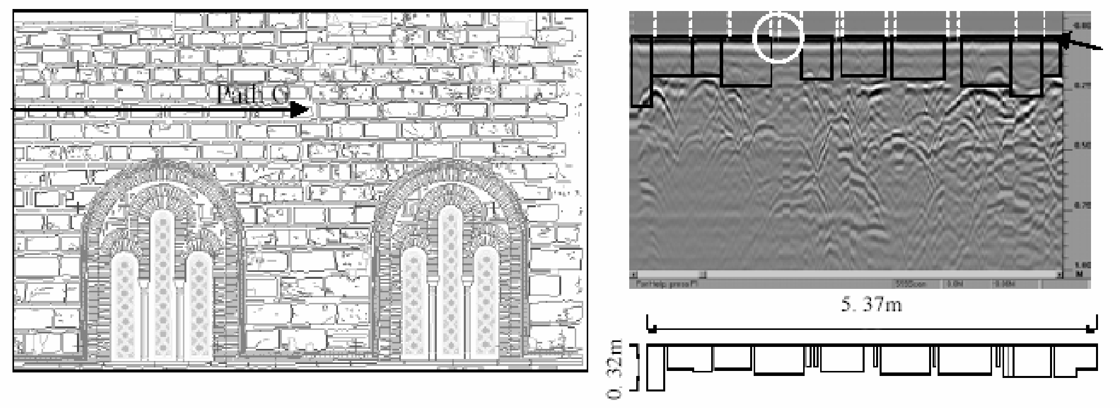
(d) Unplastered masonry surface is preferred for two reasons: (i) As the antenna is moved along a pre-selected path, when the length of stones and the thickness of the mortar joints are known, the interpretation of the results is greatly facilitated, and (ii) the clarity of the results is affected by the nature of the materials the plaster or the mosaic bed is made of (Palieraki et al., 2007).

In the profiles obtained by the radar, the in-depth dimension is expressed in time units (ns). This time expresses the two-way travel time (to and from the target). Using the dielectric constant of the investigated medium, the time is converted to length, so that the depth at which the emitted pulse is reflected can be read on the profile. The dielectric constant is assessed by a number of so-called "static tests", in positions where the thickness of the wall can be measured.

Once calibration is completed, the technique can be applied. Figure 2 shows the typical way measurements are presented (Vintzileou et al., 2004): The location of the path scanned with the antenna is shown on a drawing; the arrow shows the direction of movement of the antenna on the wall.

Figure 2 shows the radar profile of Path G, after processing using the software accompanying the equipment. The vertical white dotted lines in the upper part of the picture (two of them are marked with a circle) show the location of mortar joints between consecutive stones. The information regarding the location of joints is manually introduced and it allows for easier interpretation of the results, because in this way, one of the dimensions of the stones appears on the profile. The continuous dark grey line (indicated by the white arrow) constitutes the reflection of the surface of masonry. One can distinguish on the graph, at a depth of approximately equal to 0.25m, a zone of disturbance. This zone is assumed to correspond to the end face of the series of stones scanned along path G. The findings are then presented in a drawing showing (in scale) the length and the thickness of the stones.

Due to the fact that as mentioned previously, a relatively high frequency antenna was used, with the aim to obtain as accurate as possible results regarding the thickness of stones, the data corresponding to the part of masonry deeper than the back face of the first row of stones cannot be evaluated (Figure 2).



(a) (b)

Figure 2. (a) Location of Path G (radar). (b) Presentation of radar profile and of the results in a drawing (horizontal section of masonry).

Results obtained by boroscopy

Boroscopy, first applied in medicine, is a slightly destructive method. Small diameter holes are drilled in masonry. After meticulous cleaning of the hole from dust and loose material, the boroscope is introduced into the hole. The core of the boroscope, 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.

The boroscopy technique is used by many researchers, and it is preferred because of the possibility for direct observation of masonry. The boroscopy technique is generally used as a complimentary tool, in combination with other techniques (Binda et al., 2003 [3]).

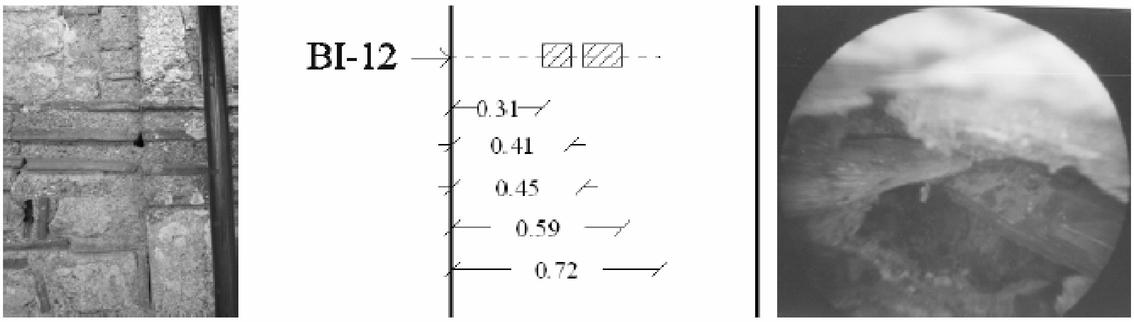
Even though boroscopes of very small diameter are available, in the investigations presented here, holes of 25mm in diameter were drilled. This is because (a) the depth of masonry that should be reached from each face of the walls was of the order of 0.5m and (b) drilling holes of approximately equal diameter with the thickness of mortar joints allows for visual contact with the stones in both sides of the mortar joint. Holes were drilled in areas where the authentic Byzantine pointing mortars were already damaged or missing. The diameter of the drilled holes being rather small, the application of this technique is acceptable even in case of structures of high architectural value. In any case, after the completion of the investigation, the holes that have been drilled should be adequately sealed.

In places where boroscopy was applied, the following difficulties were faced: (i) To allow for observation along the drilled holes, meticulous cleaning was needed, (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, (iii) Although the location of timber ties was estimated before drilling holes, the position thereof was not always adequate. Finally, (iv) In some places, drilling was limited to a depth smaller than the predetermined one,

when the drilling device met a stone that could not be pierced or, in some cases, metallic objects.

The way the results of observation using the boroscope are presented is shown in Figure 3: The location of the drilled hole is indicated, together with a sketch based on the visual inspection by the observer. The presentation is completed with pictures taken by the observer at various depths.

The observation through boroscope offers, thanks to the direct visual contact of the observer with the inside of masonry, the possibility of detecting discontinuities and holes, as well as to obtain qualitative information about the state of materials that may contribute to a more clear picture of the state of masonry.



(a) (b) (c)

Figure 3. (a) The perimeter masonry of Panagia Krina; location of drilled hole BI-12, (b) Sketch based on visual inspection; location of timber elements, (c) Photo of the interior.

CONCLUSIONS REGARDING THE MASONRY OF THE INVESTIGATED MONUMENTS

Katholikon of Dafni Monastery

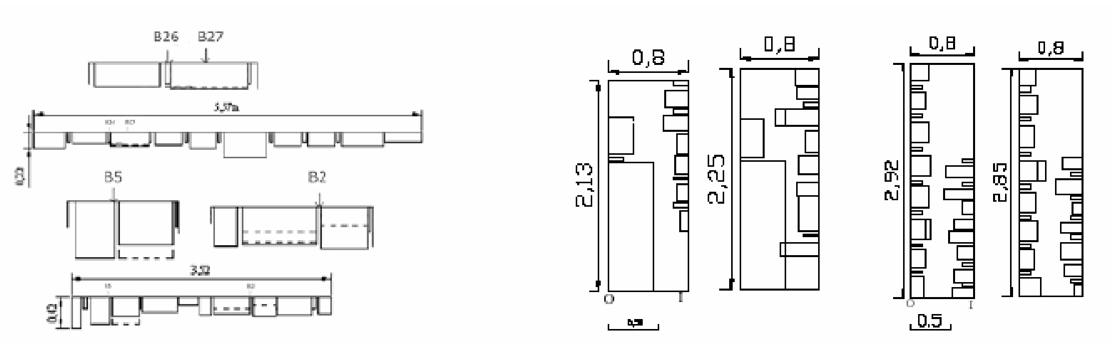
The systematic application of radar followed a preliminary stage (by the specialized staff of LCPC-France, Côte et al., 2002) that gave promising results. The investigation presented here included several parts of the perimeter walls of the monument: A total length of more than 200m was investigated along horizontal and vertical paths. Those paths were selected respecting various constraints, namely: (i) Accessibility (locations to be reached by scaffoldings), (ii) the geometry of the monument (accessibility of the same part of masonry both from the exterior and the interior; that this would be desirable in order to gather information about the complete in-depth geometry of masonry), (iii) the existence of plaster or mosaics on the interior surface of masonry, (iv) for the application of boroscopy, holes should not be drilled to regions with mosaics or with original Byzantine mortar.

In this case, boroscopy was applied in positions where the results obtained by the radar technique were not clear enough. In general, the results of boroscopy are considered to be more accurate, since they are based on visual inspection. Thus, where needed, the pictures taken by radar measurements are corrected accordingly. Nevertheless, in some cases, inspection through boroscope was proven to be inconclusive.

The results of both techniques were re-evaluated and the most reliable ones were selected as final. Even in case of disagreement between the two methods, the basic geometry of masonry in its depth (Figure 4a) is not significantly affected. Taking into account the practical purpose of this investigation, it may be assumed that the construction type of masonry was identified in a satisfactory way.

All measurements taken by the radar, evaluated and adequately corrected on the basis of the results obtained by boroscopy were plotted on horizontal and vertical sections of masonry.

Two different construction types of masonry are distinguished in the exterior face of the vertical elements. There is a lower zone (from foundation level to the first row of windows), built with large dimension stones, with their length placed horizontally or vertically, 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. Horizontal and vertical sections, representing the type of construction of masonry of both zones, are shown in Figure 4.



(a) (b)

Figure 4. (a) Comparison of results obtained by radar and boroscope in horizontal sections. Dotted lines indicate the results of boroscopy. (b) Vertical sections of masonry.

A general remark valid for both the lower and the upper 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, 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 was expected; this was confirmed by mechanical tests (Vintzileou et al., 2006).

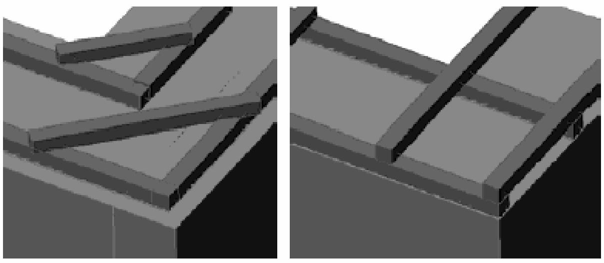
Church of Panagia Krina

The bearing system of the monument consists of three-leaf masonry that presents a variety of construction types in different positions. The external leaves are made of ceramic bricks or stones, with the most frequent type being that of brick masonry in the outer face. A peculiar construction type (with the bricks recessed by almost 20mm from the surface, every second row-Figure 3a) results to a non-planar surface. Rubble stone masonry is met only in the lower part of the walls, in small areas.

Although it was known that timber ties are arranged within masonry, both their exact location and their state were to be investigated. Timber-ties play a significant role in improving the structural behaviour of historic buildings as they confine masonry (thus improving its mechanical properties), they provide connection between external leaves and filling material within the thickness of masonry, they improve the shear and the out-of-plane flexural behaviour of walls, etc. Their degradation, however, becomes a source of weakness, as their structural effect is diminished or even cancelled, whereas the cross sectional dimensions of masonry are significantly reduced. Furthermore, replacement or substitution of degraded or completely destroyed timber ties is a difficult intervention that needs to be based on a good knowledge of both the geometry and the state of original timber ties.

Because of the geometry of the outer face of masonry, the radar technique could be applied only in the plane surface of the internal face of the walls. Nevertheless, the results of this method proved to be unclear and, therefore, inconclusive: As the interior face of masonry is covered with frescoes, it was not easy to identify the type of masonry (brick or stone masonry). Furthermore, the difficulties in applying the radar technique in case of brick masonry, the effect of the type of mortar/plaster on the reliability of results, as well as the numerous interfaces (between bricks and stones, between masonry leaf and filling material, voids in places of degraded timber ties, etc.) the signal meets when passing through masonry, led to a very limited applicability of the technique.

Thus, information about the construction type of masonry was collected in regions of severe damages (by direct visual inspection or by boroscopy). Boroscopy was applied in a systematic way in order to locate timber ties and assess the state thereof. For this purpose, existing holes within the thickness of masonry were used. In areas without holes, or where the existing ones were not sufficient for the investigation, new holes were drilled. Their positions were chosen carefully, so that: (a) to drill only the absolute necessary holes; and (b) to avoid drilling in regions of old mortars or frescoes in the interior of the Church.

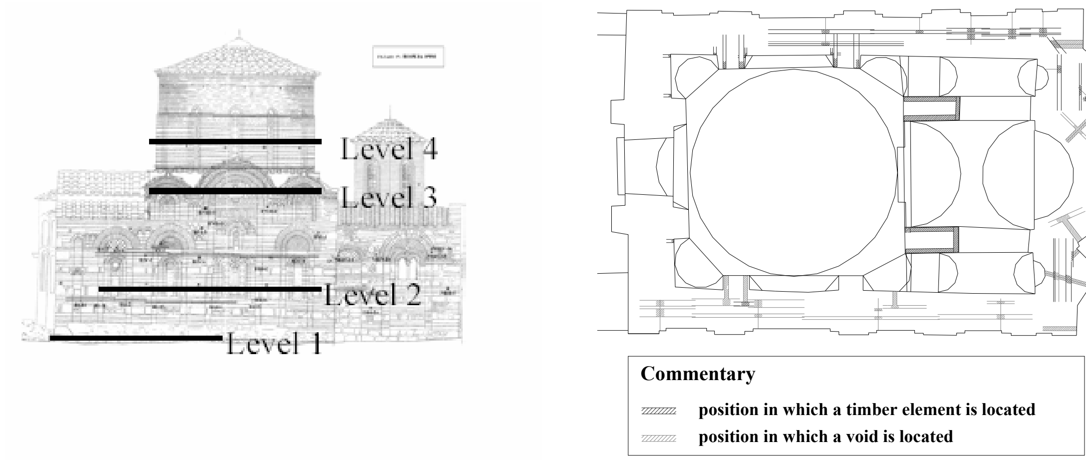


(a) (b)

Figure 5. The relative location of longitudinal timber elements in transverse walls: (a) Timber elements in the same level, connected by a diagonal element, (b) Timber elements in different level, connected directly between them.

It should be mentioned that in the case of the Church of Panagia Krina, the exact position of the holes to be drilled could not be decided upon a priori. The findings in every position were guiding the authors to identify the next position to be investigated. For this purpose, assumptions had to be made (and step by step checked and corrected) regarding the geometry of the timber ties system. For example (Figure 5), the relative location of longitudinal timber elements in transverse walls depends on the type of their connection in the corners of the structure. Both cases were identified on the examined monument.

The mapping of the timber ties system in the Church of Panagia Krina was based on the results of investigation through boroscope in almost 100 positions. Figure 6 shows the four levels at which timber ties were identified, as well as the arrangement of timber elements in the first level.

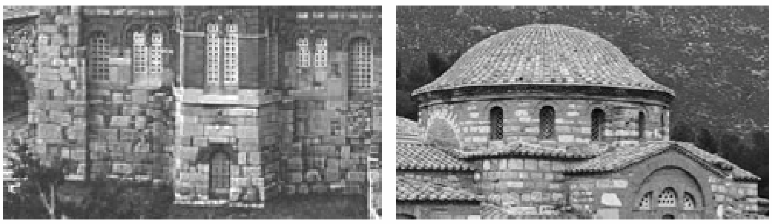


(a) (b)

Figure 6. Church of Panagia Krina: (a) North facade, timber ties as located in four levels, (b) Arrangement of timber ties in level 1.

Katholikon of Osios Loucas Monastery

The in situ investigations in the Katholikon of Osios Loucas Monastery are still in progress. The aim is to realize the constructional analysis of the Katholikon, namely to conclude about the way in which the loads are taken by the various bearing elements and they are carried to the other elements or to the foundations. For the constructional analysis it is necessary to know the constructional type of masonry. Preliminary investigations, necessary for planning the entire program were carried out.



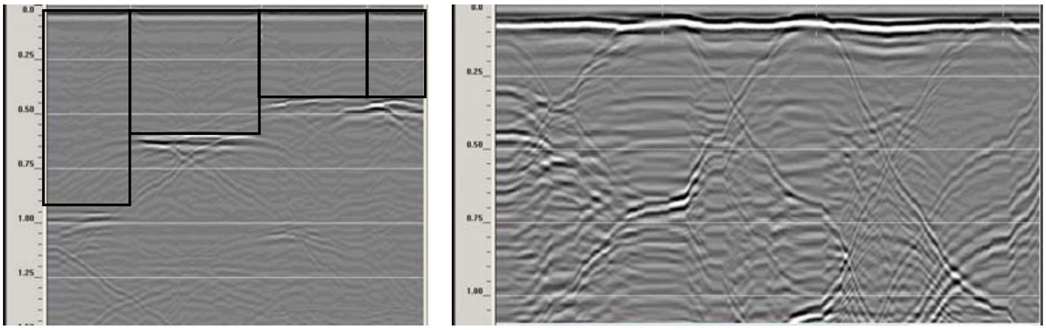
(a) (b)

Figure 7. Katholikon of Osios Loucas Monastery: (a) Lower and (b) Upper zone of masonry.

The three-leaf masonry of the Katholikon in Osios Loucas Monastery consists of two zones (Figure 7): The upper zone is made of smaller dimension stones than the lower one. In the outer leaf of the walls, which is unplastered, trial measurements were made in regions where the geometry of the stones is known (e.g. in the corners of the walls). The results were satisfactory (Figure 8a), and allowed for adequate settings for the radar.

The interior face of masonry is covered either with marble, or with mosaics, frescoes or plaster. The accuracy of radar measurements is significantly affected, thus making the

assessment of the results rather questionable. As in many positions the marbles and/or the plaster are detached from masonry, strong reflections of the emitted pulse are observed (Figure 8b), not allowing for the in-depth investigation of masonry. Thus, systematic application of boroscopy is planned, respecting, of course, the constraints ensued from the importance of the monument and its components.



(a) (b)

Figure 8. (a) Radar profile of the exterior of the Katholikon masonry, (b) Radar profile in the interior of the Katholikon masonry.

CONCLUSIONS

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

(a) The application of radar techniques to masonry can yield reliable results regarding the in-depth geometry of unplastered masonry. For this purpose, rather high frequency antennas (a 1500 MHz antenna, or in some cases a 900MHz antenna could be appropriate) should be used; thus, the depth for which the results are accurate enough is limited to part of masonry thickness. The effect of unavoidable local inaccuracies in estimating the thickness of individual stones is not significant, since the mechanical properties of masonry are rather insensitive to the local geometry.

(b) Nevertheless, when masonry is plastered or covered with frescoes or mosaics or it has a non-planar surface, the information gathered by means of radar measurements may be inconclusive or ambiguous. Therefore, the technique should be applied with caution. Furthermore, personel taking radar measurements should preferably be familiar not only with the technique but also with the examined monument as well; this is a prerequisite for adequate interpretation of measurements.

(c) In any case, the combination of this non-destructive technique with the boroscopy may enhance the accuracy of the results. In addition, boroscopy may provide information regarding the nature and the state of materials inside masonry.

ACKNOWLEDGEMENTS

Thanks are due to Dr Ph. Côte and Dr X.Dérobert (LCPC, France) who trained the authors in using the radar equipment and processing the data.

The projects were financed by National Funds and by the E.U.

REFERENCES

Binda L., Cantini L., Fernandes F., Saisi A., Tedeschi C., Zanzi L. “Diagnostic investigation on the historical masonry structures of a Castle by the complementary use of non destructive techniques”, *13th International Brick/Block Masonry Conference RAI Amsterdam July 4- 7, CD-ROM,* 2004.

Binda L., Lualdi M., Saisi A., Zanzi L. “The Complementary Use of On Site Non Destructive Tests for the Investigation of Historic Masonry Structures”, *9NAMC (9th Int. North American Masonry Conf.), Clemson, South Carolina, USA, CD-ROM,* June 2003 [1], pp. 978-989.

Binda L., Saisi A., Tiraboschi C., Valle S., Colla C., Forde M. “Application of Sonic and Radar Tests on the Piers and Walls of the Cathedral of Noto”, *Construc. Build. Materials, 17(8),* 2003 [2], pp. 613-627.

Binda L., Saisi A., Tongini Folli R., Zanzi L. “Boroscopy, Flat-Jacks and NDT as complementary tools”, *Prooc. Int. RILEM Workshop On Site Control and Non-Destructive Evaluation of Masonry Structures, Mantova, Italy, Binda L., de Vekey R.C. (Eds.),* 2003[3], pp. 279-287.

Binda L., Zanzi L., Lualdi M., Condoleo P. “The use of georadar to assess damage to a masonry Bell Tower in Cremona”, *Italy, Int. Journal NDT&E, 38,* 2005, pp. 171-179.

Côte Ph., Dérobert X., Abraham O. “Daphni : Etude de faisabilité de techniques CND Radar et Impact Echo. Rapport final”. 2002.

Côte Ph., Dérobert X., Miltiadou-Fezans A., Delinikolas N. and Minos N. “Mosaic-grouting monitoring by ground-penetrating radar”, *SAHC2004: IV Int. Cong. on Struct. Analysis of Hist. Constr., Padova, Italy,* November 2004, pp. 401-406.

Daniels D.J. 1996, “Surface-penetrating radar”. *The Institution of Electrical Engineers, Radar, Sonar, Navigation and Avionics Series, Editors Prof. E.D.R.Shearman and P.Bradsell, London.*

Geophysical Survey Systems, Inc. 2004, “Radan 6, User’s Manual”.

ONSITEFORMASONRY, “Results and Research Methodologies of ONSITEFORMASONRY”, *EC Project financed by the European Commission, CD-ROM,* 2005.

Palieraki V., Vintzileou E., Miltiadou-Fezans A., Delinikolas N. 2007, “The use of radar techniques and boroscopy in investigating old masonry: The case of Dafni Monastery”, *accepted for publication in “International Journal of Architectural Heritage: Conservation, Analysis and Restoration”.*

Vintzileou E., Miltiadou-Fezans A., Vrouva A., Anagnostopoulou S. “Mechanical properties of three-leaf stone masonry”, *SAHC2006: V Int. Conf. on Struct. Analysis of Hist. Constr., N. Delhi, India,* November 2006, pp. 783-790.