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INVESTIGATION PROCEDURES BASED ON THE COMPLEMENTARITY OF NON-DESTRUCTIVE AND SLIGHTLY DESTRUCTIVE ON SITE TESTS: APPLICATION TO THE TWO CASTLES OF AVIO (ITALY) AND PISECE (SLOVENIA)

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ABSTRACT

The paper presents and discusses the preliminary results of the investigations carried out by the authors on two Castles, considered as case histories within a project financed by the European Community (project EVK4-2001-00091 ONSITEFORMASONRY), coordinated by C. Maierhofer of BAM (Bundesanstalt für Materialforschung und prüfung, Germany). An extensive investigation programme (including sonic, radar, flat jack, coring, boroscopy, etc.) was planned to support the preservation and restoration actions of the two ancient Castles. The experience shows the importance of the diagnosis project in order to select the most relevant strategies and tests for each specific problem.

KEYWORDS: NDT, diagnosis, on site tests

INTRODUCTION

On-site investigations were carried out on the Pisece and Avio Castles in order to compare different non-destructive tests with the aim of understanding the effectiveness of non-destructive techniques. The research was part of a project financed by the European Community (project EVK4-2001-00091 ONSITEFORMASONRY), coordinated by C. Maierhofer of BAM (Germany) and finalised to the calibration of on-site investigation techniques for the structural evaluation of historic masonry buildings. From this point of view, the Castles represent two interesting sites for the application, calibration and study of the complementary use of some non destructive techniques (NDT). The applications, in fact, can help in the design for preservation of historic buildings, which also need control of the structure safety through the determination of its load carrying capacity according to the present codes.

Since no one test is usually sufficient to provide the required information, the complementarity of the different tests (sonic, georadar, flat-jack, etc.) was studied for the definition of the necessary physical and mechanical parameters of masonries. Georadar, sonic pulse velocity test, flat jack tests and other diagnostic techniques were applied to detect specific problems or damages of the masonry structures such as: (i) the state of conservation of the load bearing walls, (ii) their morphology and mechanical behaviour (iii) the presence of voids and other inhomogeneities.

Laboratory tests on materials sampled on site gave information about the characteristics of stones and mortar. Chemical analyses were carried out on mortar samples from the nearest possible point to the cut joints where flat jack tests were performed. The on site investigation shows the importance of the calibration and the necessity of a control procedure by complementary tests. This allows verification of the effectiveness of each technique and the possible application to a particular masonry problem. The collected information can be of great importance for the designers, to make the choice of appropriate repair techniques much easier.

DIAGNOSIS STRATEGIES

A correct intervention on a historic structure should start from an accurate diagnosis of the building in order to minimise the interference of the intervention with the historical value of the architecture. Furthermore, the study of the building rules and structural details, such as the wall sections, has great importance in studying the mechanical behaviour of the structure.

The structural performance of a masonry structure can be understood provided the following factors are known: (i) its geometry, (ii) the characteristics of its masonry components, single or multiple leaf walls, (iii) the connection between the leaves, (iv) the joints (empty or filled with mortar), (v) physical, chemical and mechanical characteristics of the constituents (stones, mortar), (vi) the characteristics of masonry as a composite material.

In order to fulfill these needs an experimental on site investigation should be required and recommended also by Codes of Standards in several countries. NDT can be helpful in finding hidden characteristics (internal voids, flaws and characteristics of the wall section), which cannot be known other than through destructive tests. Up to now most of the ND procedures give only qualitative results. The application of NDT to masonry, although advanced, can be frustrating due to several factors, like the different masonry typologies and materials, the high inhomogeneity of the materials, the interpretation of the results of each single technique, and also the harmonisation of the results. Furthermore, most of the NDTs come from other research fields and need a specific calibration.

The solution of very difficult problems cannot be reached with a single investigation technique, but with the complementary use of different techniques [1, 2]. In this way the designer is asked to interpret the results by using different ND techniques and use them at least as comparative values between different parts of the same masonry structure [3]. Within the EC contract, an atlas of different types of problems to be solved together with a description of the strategies of investigation involving the complementary use of on site and laboratory tests was set up. Finally guidelines were produced for the correct application of investigation techniques to diagnose problems for different classes of masonry [4]. The diagnosis process should be based on an accurate survey, which should document the current state of the building. A preliminary in-situ survey is useful in order to provide details on the geometry of the structure and in order to identify the points where more accurate observations have to be concentrated. Following this survey a more refined investigation has to be carried out, identifying irregularities (vertical deviations, rotations, etc.). In the meantime the historical evolution of the structure has to be known in order to explain the signs of damage detected on the building. The crack pattern should be classified and accurately documented by pictures and drawings on the geometrical survey and eventually a monitoring system can be installed. NDT or slightly destructive techniques can be applied in strategic points of the structure in order to solve the most difficult problems of hidden situations (Fig. 1). Finally, the definition of the structural model can be carried out not only on the basis of the geometrical survey but also on the crack pattern [5].

CASTLE DESCRIPTIONS

The castles have similar problems from the point of view of the structural characterisation of the stonework masonry. Extended crack patterns are visible on the main walls of the towers and many rooms are characterised by remarkable vertical cracks crossing the wall section (Fig. 2, 3). The crack-pattern survey and classification together with a mapping of the discontinuities and of the masonry textures was carried out in order to have an important evaluation of the existing structural state of the building.

The castle structures are mainly in stonework masonry, with local repairs in brick masonry. The constructions have timber floors. In general, the objectives of the investigation are the evaluation of the structural problems that affect the castles, starting from the crack pattern survey, to the monitoring of the main cracks, to the characterisation of the masonry and the control of the local state of stress and the stress-strain behaviour. In this way the structural elements were studied in order to evaluate the opportunity and the type of the intervention. The tests were finalised to the study of specific problems identified as most important for the restoration design.

The building complex of the Castle of Avio nestles around the Main Tower and is surrounded by the circles of walls (Fig. 4).

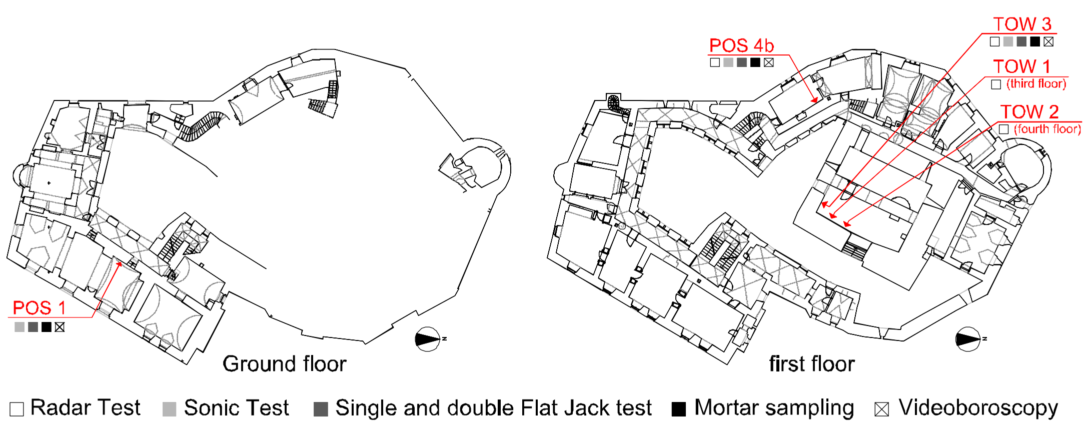


Figure 1 - Pisece Castle Plan (courtesy of ZAG and IRMA) with the test localisation

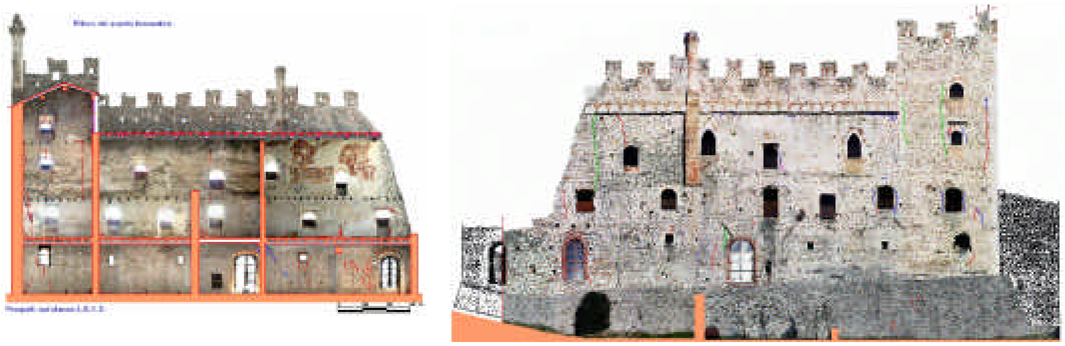


Figure 2 - Avio Castle Crack pattern survey of the South wall

The historic evolution of the building was evaluated by accurate documentary research, but also by the stratigraphical method. The stratigraphical method allows subdivision of the building into homogeneous blocks, characterised by relative chronological relationships. Any block corresponds to a unique building phase, recognized by the observation of constructive details; its relationship with the other blocks may be “preceding” or “subsequent”, often with no possibility for an absolute dating. Critical connections between blocks need to be investigated, so as to clarify the phases of expansion and transformation of the complex (Harris diagram). This information, together with an evaluation of the quality of the connections, is very important for the structural control of the building. The study can then be completed by the observation of dated elements like the brick type and dimensions, by the chronological characterization of the construction techniques and by the survey and characterization of the different masonry typologies.

C. Campanella and M. Tessoni – Associated Architects in Crema, carried out the geometrical survey of the Avio Castle while S. Bortolotto of the Dept. of Architectural Design (DPA) of the Politecnico of Milan carried out the stratigraphic survey. The research is reported in detail in [6].

CRACK PATTERN SURVEY

The most damaged among the structures of the Avio Castle is the Tower of the Palace. The cracks are close to the corners (Figs. 2, 5), and around the keystones of the upper arch windows. This could reveal the lack of connection of the outside walls, particularly in the upper part of the Tower where the timber floors are missing. Furthermore, cracks repaired with a dark grey mortar are visible, showing the long term existence of structural problems.

A significant deformation of the western upper corner in the south wall (Fig. 6a) is visible. This deflection does not produce wide cracks and could date back to the collapse of the closer Tower at the end of the XIXth century, when the corner did not have any covering and bond.
Fig. 6b shows that the outside wall is out of plumb with stone expulsion, which produces a crack pattern in the internal room. The cracks have similar slope.

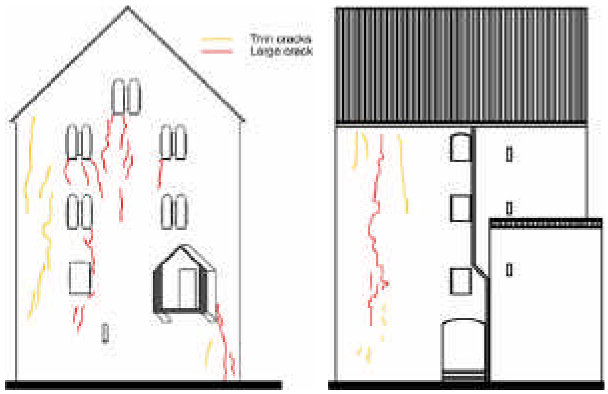
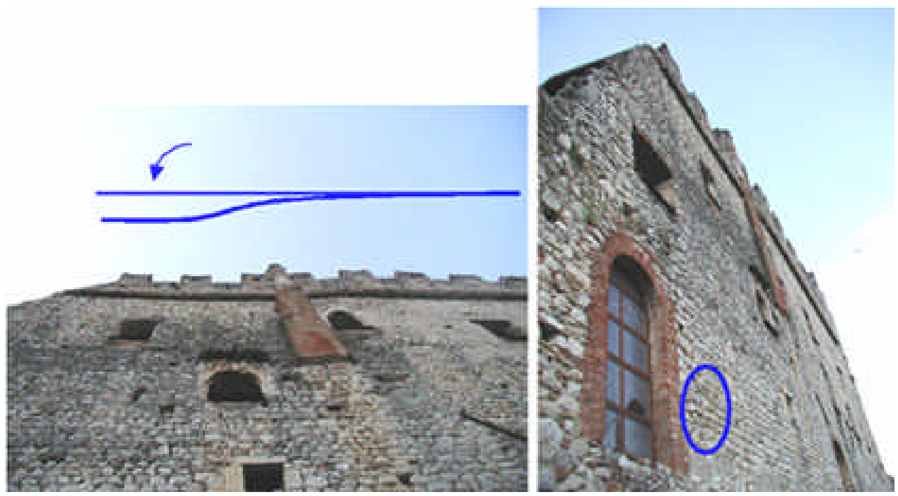


Figure 3 - Pisece Castle. Crack pattern survey of the Tower in the South and East side

Figure 4 - The Castle of Avio

Figure 5 - Avio Castle. Crack pattern survey of the Tower



a) b)

Figure 6 - Avio Castle. Deformation of the South facade toward the valley

The damage, being localised, is probably is not connected with the deformation due to the height of the wall. The masonry seems very inhomogeneous, with round stones, also of small dimensions, and damaged mortar joints. In many situations, the crack pattern is hardly readable, due to the lack of superficial mortar and the cracks are often around the stones. Several discontinuities are diffused around the passages of the internal partition walls and in the outside walls. Most of these could be connected to the presence of chimney flues. The internal partition walls are present only in the basement and at the ground floor and are not connected to the outside wall. They appear clearly detached being built subsequent to the outside walls (XIX century). The room at the base of the Tower is the most damaged.

The masonry is inhomogeneous, with brick insertion and poor mortar with wide voids. This poor workmanship could have affected the structural behaviour of the masonry.

Another significant crack pattern is easily visible on the Mastio Tower (the oldest and tallest one), at the moment not yet monitored (Fig. 7).

Figure 7 – Avio Castle. Crack pattern of the Mastio

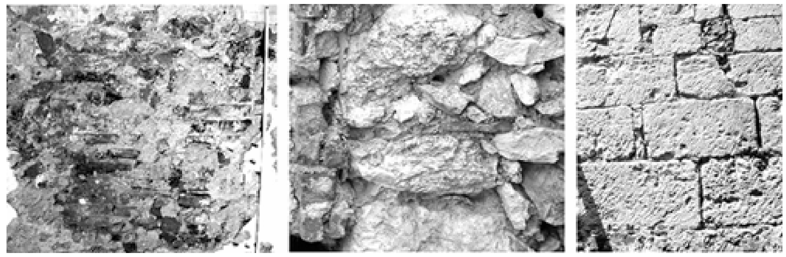


Figure 8 – Pisece Castle. Masonry typologies: irregular stones and regular bricks (POS1), irregular (POS4) and regular in stone (TOW3)

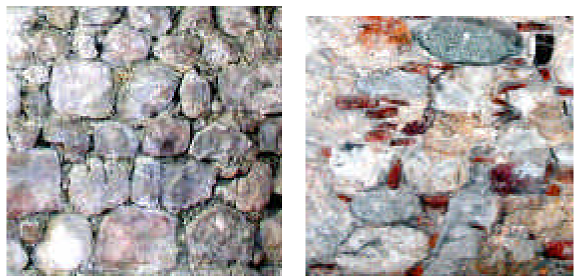


Figure 9 – Avio Castle. Masonry typologies of the external walls and of partition walls

MASONRY TYPOLOGY AND MATERIALS

The inspection of the surface texture gives only general information about the masonry characteristics. The most important parameter in the evaluation of the masonry quality is the cross section morphology. A regular surface texture can hide a weak masonry structure as often happens in rubble masonry where the external leaf is often regular.

The Castle of Pisece seems to be characterised by 3 different masonry typologies, as reported in Fig. 8, irregular stones and regular bricks, irregular and regular in stone. The tests carried out have also shown that the real characteristic of the walls can also be detected from the knowledge of their section.

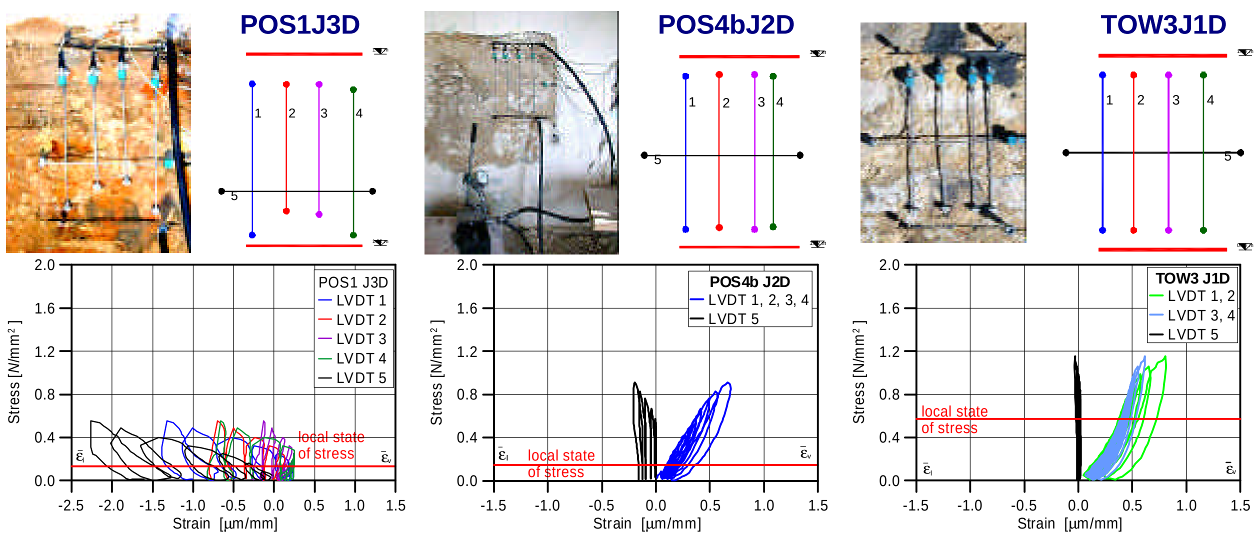
Fig. 9 shows the main masonry typologies of the Avio Castle. Three main masonry typologies can be distinguished: the external walls, most ancient, and the internal partition walls, in general not connected to the previous ones. The presence of cracks, in fact, stresses the discontinuity. The third masonry typology is the one of the Mastio.

SONIC TESTS AND DOUBLE FLAT JACK TESTS

The complementary use of sonic and double flat jack tests allows the qualification of the masonry characteristics. Detailed descriptions of the test procedures, limits and potentialities are reported in [1] and [2]. Sonic tests were carried out according to [7], while single flat jack and double flat jack according to [8, 9, 10, 11]. Preliminary application of sonic tests and radar is useful to control eventual anomalies like the presence of chimney flues or other voids [4]. This was the case of the test carried out at the position called POS1J3D at the Pisece Castle (Fig. 10a). Even if the masonry was compressed under the double flat jack test, the strain gauges measured vertical elongation (Fig. 10a). This fact was explicable following a successful investigation of the wall characteristic that revealed the presence of a wide void, a fireplace, enclosed by a thin brick wall. The measured vertical elongation is due to the instability of the thin wall produced by the compression.wall. The measured vertical elongation is due to the instability of the thin wall produced by the compression.

The unknown masonry morphology affected the results. Sonic tests, in fact, revealed the presence of a cavity behind the tested area. This is very clear considering the low sonic velocity measured (Fig. 11). The videoboroscopy inspection of Fig. 12 confirms this observation, revealing the presence of a real fireplace. The superficial brick masonry texture appears irregular.

Figs. 10 and 13 show the results of the single and double flat jack tests, respectively, on the Pisece and Avio Castle. The tests allow classification of the masonry quality.



Local State of Stress: 0.13 N/mm^2

a)

Elastic Modulus (10-30%): 1490 N/mm^{2}Local State of Stress: 0.14 N/mm^2

b)

Elastic Modulus (10-35%): 1700 N/mm^{2}Local State of Stress: 0.57 N/mm^2

c)

Figure 10 – Pisece Castle. Mechanic characterisation of the masonries typologies by double flat jack. The picture shows the stress-strain curves, the local states of stress, the tested masonry texture and the acquisition geometry and position. In POS1J3D the strain gauges measured vertical elongation due to the thin wall instability produced by the compression.

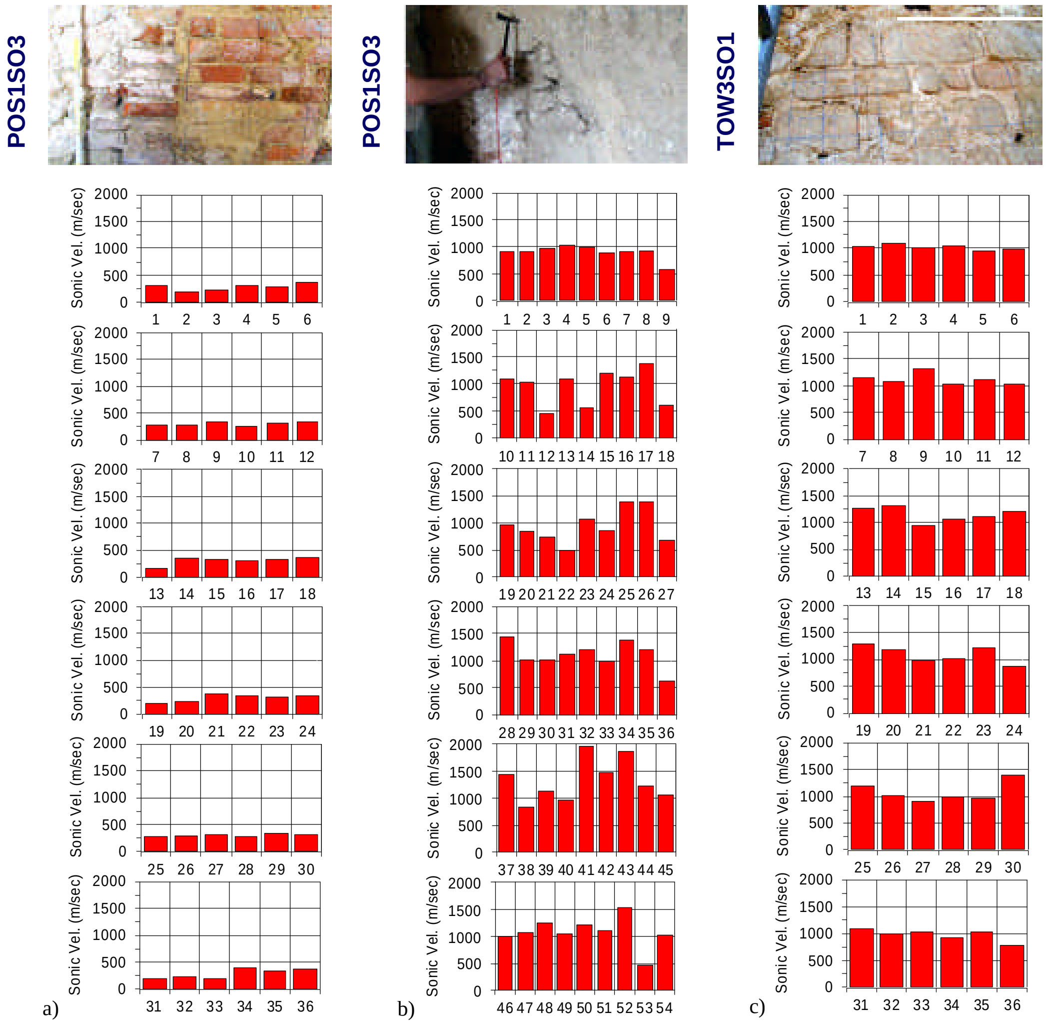


Figure 11 – Pisece Castle. Characterisation of the masonry typologies by sonic tests. The histograms show the pulse sonic velocities acquired by transmission in different points at 6 levels. The low values Fig. 11a could indicate the presence of a cavity.

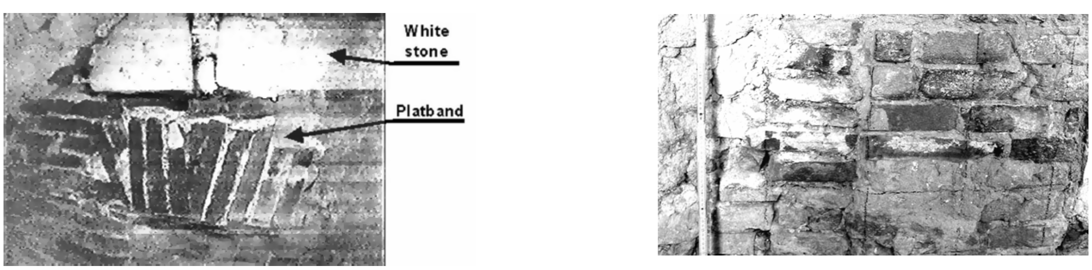


Figure 12 – Pisece Castle. Videoboroscopy and detail of the masonry in the position POS1

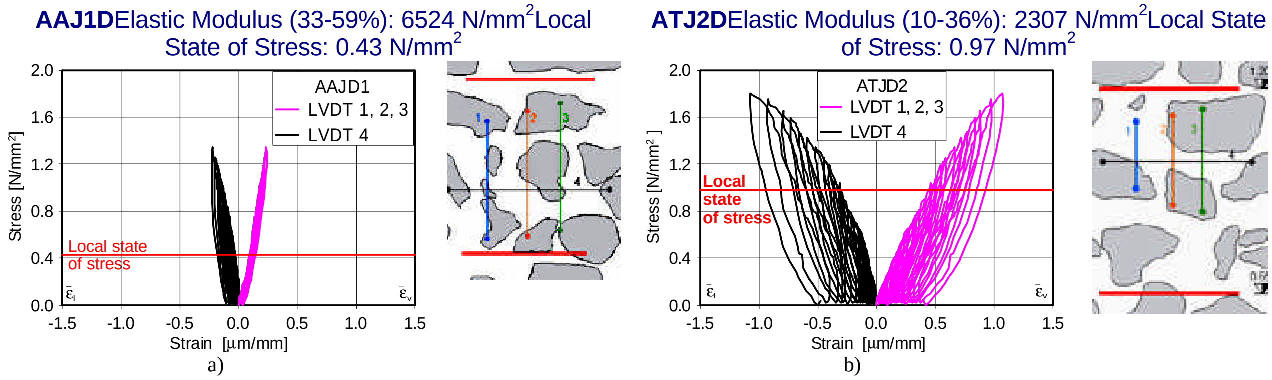


Figure 13 – Avio Castle. Mechanic characterisation of the masonries typologies by double flat jack. The picture shows the stress-strain curves, the local states of stress, the masonry texture in the tested area and the instrumentation geometry and position. The ATJ2D result shows a more deformable masonry and an higher state of stress then AAJ1D area.

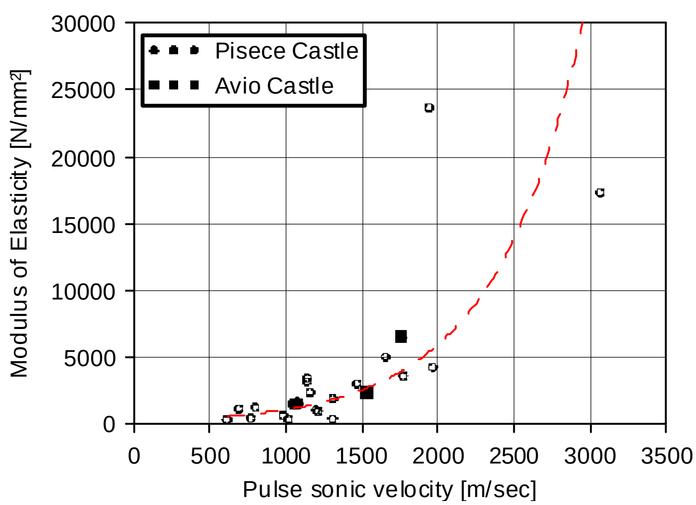


Figure 14 – Correlation between the pulse sonic velocity (average of the measured values) and the modulus of elasticity obtained by double flat jack on a group of 25 cases

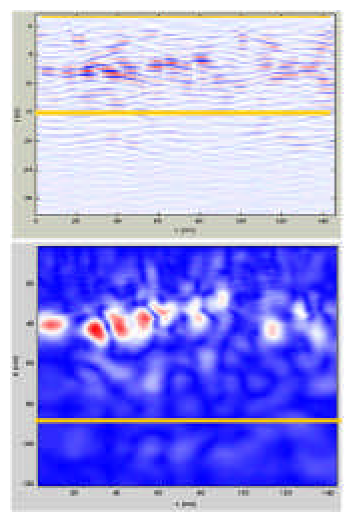


Figure 15 – Radar profiles which indicate the presence of a two leaves section. Red spots indicate high radar energy reflected by the transition between the leaves

Fig. 14 shows a tentative correlation between pulse sonic tests and the modulus of elasticity by the double flat jack on a group of 25 cases. The test results of Pisece and Avio Castles seem to be aligned with the other data.

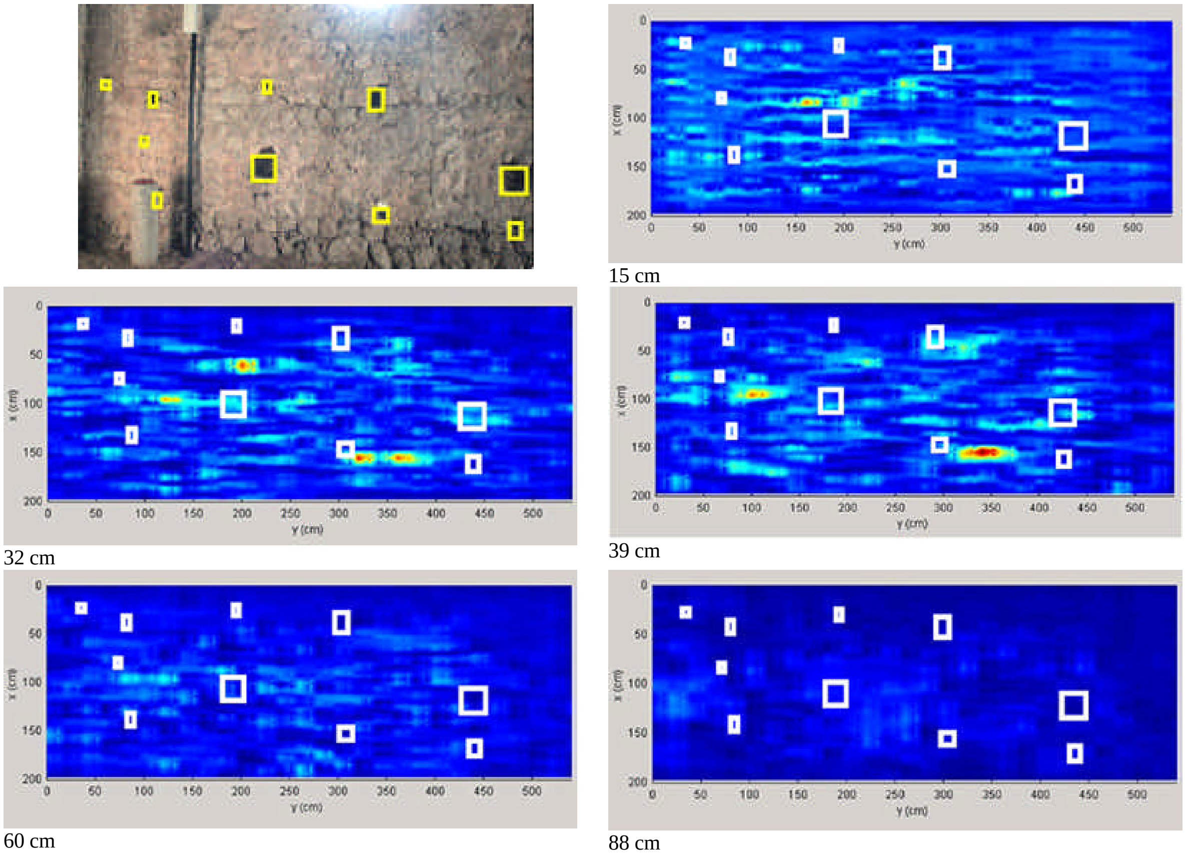


Figure 16 – Reconstruction of the radargrams respectively at the depth of: 15, 32, 39, 60, 88 cm. The elaboration enhances the presence of internal voids (red spots). White boxes identify the positions of surface cavities and missing stones

USE OF GEORADAR FOR THE DETECTION OF LOCAL DEFECTS AND FLAWS

The morphology of the wall is particularly important in cases where voids, cracks and flaws are suspected. For this purpose the use of georadar seems to be very effective. Detailed descriptions of the test procedures, limits and potentialities are reported in [1].

The wall of the Avio Castle at the basement level (Fig. 6), shows an evident out of plumb and some cracks which are monitored. Due to the large deformation, it was important to inspect the internal characteristic. Radar tests were carried out on parallel profiles in order to reconstruct the internal morphology. The radar inspection showed less compact materials in several areas (Fig. 15) that could be interpreted as local detachments of the two leaves of the masonry (Fig. 16). Fig. 16 shows the reconstruction of the radar profiles, enhancing the targets in a sequence of depth slices. Several voids are readable in the radargrams corresponding to the leaf interfaces. This conclusion was confirmed also by direct visual inspection. The material found is very poor with weak or even locally missing mortar (Fig. 17).

Finally, at the Pisece Castle an important crack pattern was inspected in order to evaluate its depth. A radar vertical profile was executed on the external side of the tower starting at a height of 190 cm from the base and moving upward (Fig. 18). The profile is parallel to the corner at a distance from the corner of 70 cm. The inspection was carried out in order to verify if radar was able to detect the presence and the depth of the wide cracks visible on the corner (Fig. 19).

The acquisition geometry has great importance on the effectiveness of the test for this type of application. In fact, the possibility of surveying the wall from a surface that is nearly parallel to the cracks is essential. Fig. 19 shows the processed radar profile rotated vertically to facilitate the correlation with the adjacent picture of the side of the tower while Fig. 20 presents the interpretation of the main reflections and diffractions apparently associated with three main cracks running at three different depths from the surface.

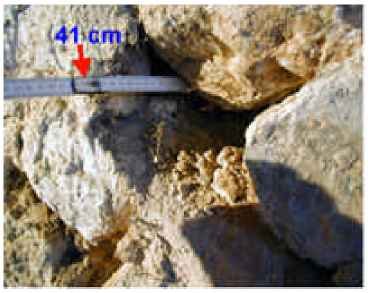


Figure 17 – Direct inspection which indicate the presence of a void

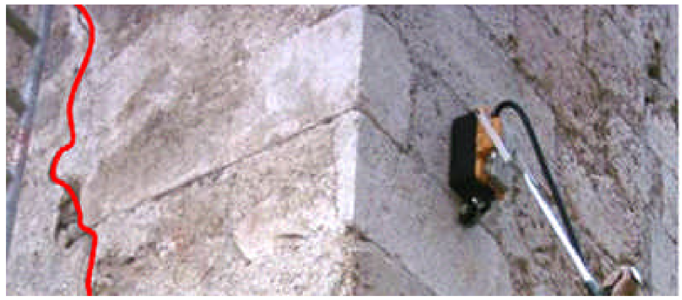


Figure 18 - Position of the vertical radar profile collected with a 1GHz antenna to map some important cracks

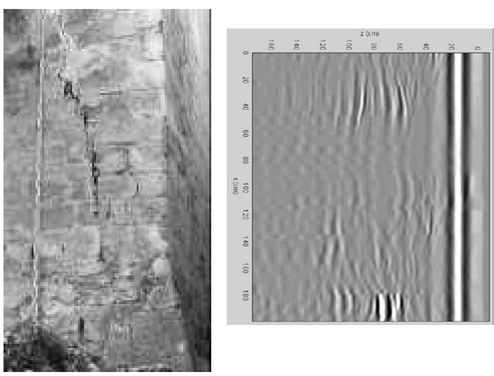


Figure 19 - Cracks as observed on the adjacent wall and processed radar section

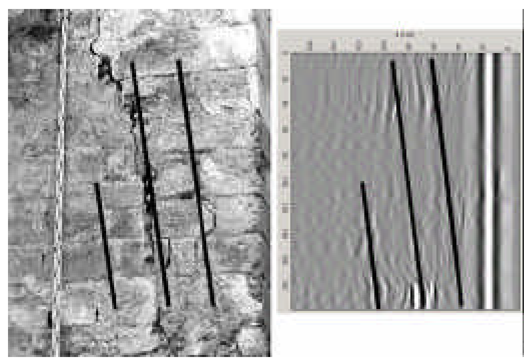


Figure 20 - Interpretation of the vertical radar profile. A system of three main cracks seems to be detected by the radar profile at increasing depth from the surface

These results show that radar profiles can detect the position and the depth of cracks when they are in corners of towers and massive buildings.

CONCLUSIONS

The research carried out within the framework of an EC Contract allowed close collaboration among the partners and direct application of techniques and procedures to chosen sites in the partner country. This was useful to control and compare the results of different NDT in various applications (Altes Museum in Berlin, Avio Castle in Italy, Pisece Castle in Slovenia, etc.).

The on site investigation procedures should be calibrated and controlled in order to verify their effectiveness and particularly the possible application to each particular masonry problem.
A great deal of research is still necessary for the interpretation of the NDT results and for their correlation with the masonry characteristics. Since no one test is usually sufficient to give the required information, the complementarity of the different tests (sonic and radar tests, flat-jack, etc.) also has to be studied for the definition of the necessary physical and mechanical parameters of the masonry. The research has shown clearly that the complementarity can support the intervention or preservation actions, allowing a deep knowledge of materials, structures and special features of the masonry walls, but only within a diagnostic programme, specifically designed for each case history.

Guidelines for the use of investigation procedures could also be drawn up.

Concerning the objectives of this paper some conclusion can be made:
- geometrical and crack pattern survey can be useful for an interpretation and hypothesis of damage;
- material characterisation and masonry morphology can be detected on site by flat jack tests and by sonic and/or georadar tests, respectively;
- sonic and flat jack tests seem to have a possible correlation. This can help with the application of flat jack, which gives very local information;
- hidden voids, inclusions and flaws can be detected by the use of georadar and/or sonic tests.

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