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DIAGNOSTIC INVESTIGATION ON THE HISTORICAL MASONRY STRUCTURES OF A CASTLE BY THE COMPLEMENTARY USE OF NON DESTRUCTIVE TECHNIQUES.

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Abstract

An on-site investigation was carried out on the Pisece Castle in order to compare different non destructive tests and to check their complementarity in the detection of unknown masonry features. Some typical problems solved by the authors with the combination of different techniques such as boroscopy, radar and sonic tests, flat-jack and others together with laboratory tests on sampled materials are presented.

Key Words

NDT, stone masonry, diagnosis.

1 Introduction

An on-site investigation was carried out on the Pisece Castle in order to compare different non destructive tests. The research is part of an extensive project financed by the EC (project EVK4-2001-00091 ONSITEFORMASONRY) and 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 Castle represents an interesting site for the application, calibration and study of the complemenatry use of some non destructive (ND) techniques. They can help in the design for preservation of historic buildings, which need a control of the structure safety through the detection of its load carrying capacity also according to the present codes (Colla et al. 1997), (Binda et al. 2000).

Therefore, the authors took the opportunity of the above mentioned necessities to apply some NDTs to the structures of the Castle in order to solve some unknown situations. The collected information can be of great importance for the designers.

Since no test is usually self-sufficient to give the requested information, the complementarity of the different tests (sonic, georadar, flat-jack, etc.) was studied for

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the definition of the necessary physical and mechanical parameters of masonries (Binda 2001).
An extended crack pattern is visible on the main walls of the Tower and many rooms are characterised by remarkable vertical cracks crossing the wall section.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 about the structural state of conservation of the building.
Georadar, sonic pulse velocity test, flat jack tests and other diagnostic techniques were applied (Fig. 1) to solve specific problems or damages of the masonry structures, like to evaluate the state of conservation of the load bearing walls, their morphology and mechanical behaviour and to detect the presence of voids and other inhomogeneities.
Laboratory tests on materials sampled on site gave information about the characteristics of stones and mortar. Chemical analysis on salts found on the masonry was also carried out. The presence of salt is connected to the damages due to their crystallisation. Mortar samples have been taken in the nearest possible point of the cut joints where flat jack tests were performed.
Inspections by videoboroscopy into drilled cores and the direct visual inspections after the removal of bricks or stones were very useful to connect the data from flat jack and sonic tests, with the information about the masonry morphology.
The on site investigation show the importance of the calibration and the necessity of a control procedure by complementary tests. This allows to verify the effectiveness of each technique and the possible application to a peculiar masonry problem.

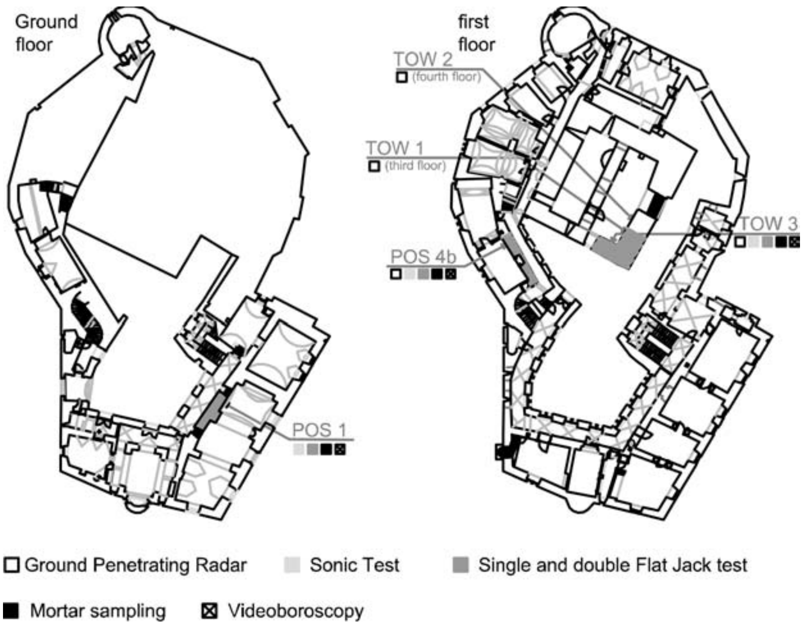

Figure 1 Plan of the Castle (courtesy of ZAG and IRMA) with the test localisation.

2 Diagnosis Strategies

A correct intervention on a historic structure should start from an accurate diagnosis of the building in order to minimise the interferences of the intervention with the historicity of the architectural document.
Furthermore, the study of the building rules and structural details, such as the wall sections, has a great importance in the mechanic behaviour of the structure.
The structural performance of a masonry can be understood provided the following factors are known: its geometry; the characteristics of its masonry texture, single or multiple leaf walls, connection between the leaves, joints empty or filled with mortar,

physical, chemical and mechanical characteristics of the components (stones, mortar); the characteristics of masonry as a composite material.
In order to fulfil these needs an experimental on site investigation is required and recommended also by Codes of Standards in several countries.
NDT can be helpful in finding hidden characteristics (internal voids and flaws and characteristics of the wall section) which cannot be known otherwise than through destructive tests. Up to now most of the ND procedure can give only qualitative results. The application to masonry of NDT, 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 but also the harmonisation of the results. Furthermore, most of the NDTs come from other research field 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 (Binda et al. 2003a,b). Therefore the designer is asked to interpret the results and use them at least as comparative values between different parts of the same masonry structure or by using different ND techniques.
To this purpose it is important the production of guidelines for the correct application of investigation techniques to diagnosis problems of different classes of masonries (Binda et al. 2000).
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.
Finally 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.
The crack pattern should be classified and accurately documented by pictures and on the geometrical survey.
The definition of the structural model can be carried out only on the base of the geometrical survey but also of the crack pattern.

3 The Pisece Castle: historical details

The Pisece castle in Slovenia (Fig. 1) was built in the first half of the 13th century as defence fortification against the Hungarian danger by the archbishop of Salzburg. The oldest parts belonging to this building phase are the romanic tower, the peripheral walls and the romanic chapel. It belonged to the knights of Pisece untill the 14th century. In the 1595 the castle was sold to Inocent Moscon, and his heirs were owner of the castle until the end of the Second World War, when it became property of state. Since the 1998 the castle stands empty.
Important interventions were introduced in the 16th century with the addition of the wide circular Tower in the South-West side. Successively, other architectural details were built, such as the small tower over the chapel in the baroque time and the neoromanic and neogothic decorations in 1867.

4 On site tests

Tests were carried out on site in order to control peculiar problems and situations. Flat jack-double and single, sonic, radar tests and videoboroscopy were applied.

The flat-jack tests were carried out to measure the value of the local vertical compressive stress and the stress-strain behaviour of the material.

4.1 Testing area: POS1

In this position the consistency of the wall section was unknown; furthermore it was necessary to find the state of stress in a position where the insertion of a brick masonry in a stone one was detected.

The results of a flat jack test show how in some cases preliminary application of sonic tests and radar is useful to control eventual anomalies like the presence of chimney flues or other voids.

This was the case of the test carried out at the position called POS1J3D (Fig. 2). Even if the masonry was compressed, the strain gauges measured vertical elongation (Fig. 2a). This fact is explicable by the wall characteristic, successively investigated, with the presence of a wide void, a fireplace, closed by a thin brick 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. 2b) The videoboroscopy inspection of Fig. 3a confirms this observation, revealing the presence of a real fireplace. The superficial brick masonry texture appears unregular (Fig. 3b).

4.2 Testing area: POS4

The wall of the tested area POS4 appeared very inhomogeneous with signs of past interventions but mechanical characterisation of the masonry was considered to be important also for the structural analysis.

The first inspection was made by radar profiles (Figs. 4 and 5) that clearly showed a position where the signal could not pass through the wall section although the thickness is not particularly large (about 90cm). Profile and time acquisitions were carried out with 1 GHz and 500 MHz antennas. The time acquisitions were performed in positions 5 to 10 placing a metal shield on the backside of the wall during the second

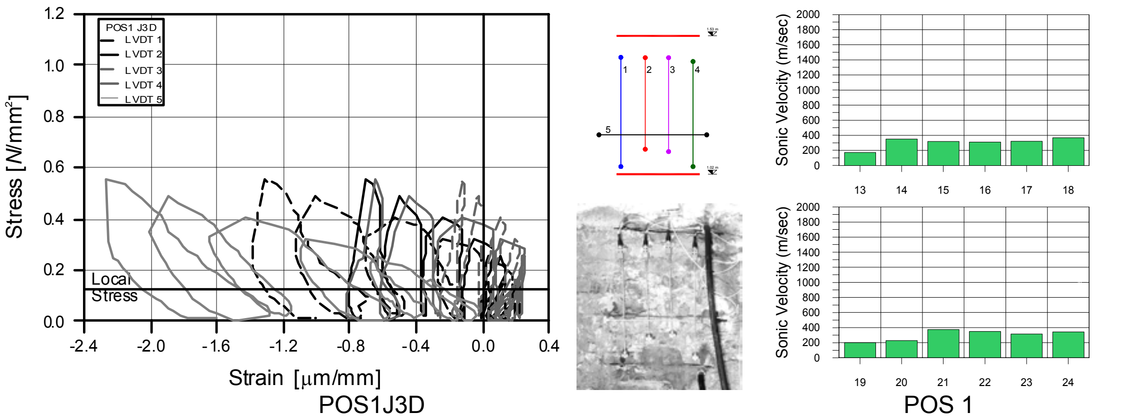

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Figure 2 Comparison of the double flat-jack with the sonic tests.

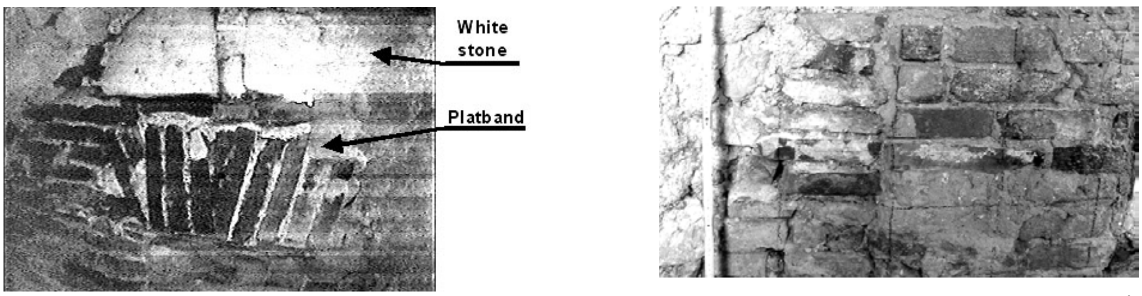

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Figure 3 Videoboroscopy and detail of the masonry in the position POS1.

half of the experiment. Moving from left to right positions, the shield reflection is absent (positions 5, 6, 7), then it appears as a weak signal (position 8) and finally as a good signal (positions 9 and 10). To show this transition, the radar data collected at positions 8, 9 and 10 are plotted in Fig. 4b. Where the radar signal could penetrate, an average velocity of 11cm/ns was measured which is a rather common value for a stone masonry.

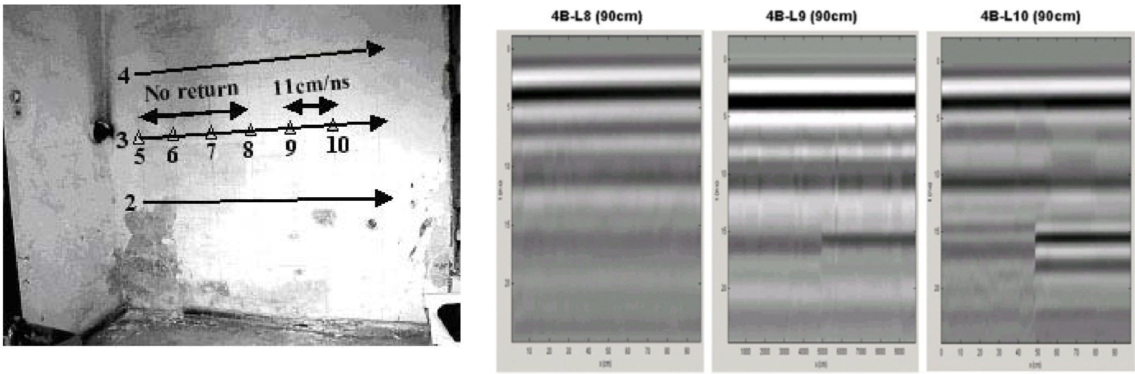

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Figure 4 Geometry of the radar survey a) and time radar data b) acquired at positions 8, 9 and 10. A metal shield was placed on the backside of the wall during the second half of the experiment to enhance the backside reflection.

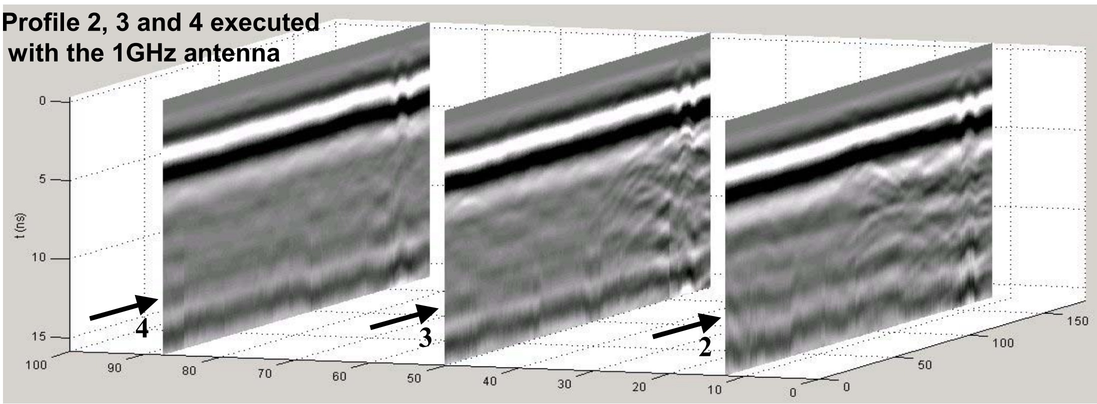

Figure 5 Results of the radar test along the profile 2,3,4 of Fig. 4a.

Fig. 6a shows the sonic velocity map compared to the no return area revealed by the radar test. The area where the radar was unable to reach the backside of the wall is associated with low sonic velocities. This indicates the presence of a void or a deteriorated masonry that results in a poor elastic response for the sonic test and in a high absorption effect for the radar test. The profiles acquired by high frequency radar (Fig. 5) confirm a low penetration on the left side where no reflections and/or diffractions appear after the background signal.
The no return positions were avoided for the flat jack tests that were instead located in the area of Fig. 7a. The flat jack results show a good behaviour of the masonry (Fig. 7b); also boroscopy shows a non homogeneous but rather solid masonry with an elastic modulus around 1490 N/mm^2 (Fig. 8).

4.3 Testing area: TOW1, TOW2 and TOW3

Positions TOW1, TOW2 and TOW3 are part of the Tower structure that seems to be made by regular stone blocks. It was expected that this masonry typology should provide different and better results compared to the others walls. However the tower is highly affected by deep and major cracks, also at the highest floors (Fig. 9).

The survey and drawing of the crack patterns is an important phase of the structural diagnosis. The interpretation of the crack pattern can be of great help in understanding the state of damage of the structure, its possible causes and the type of survey to be performed, provided that the development history of the building is already known.

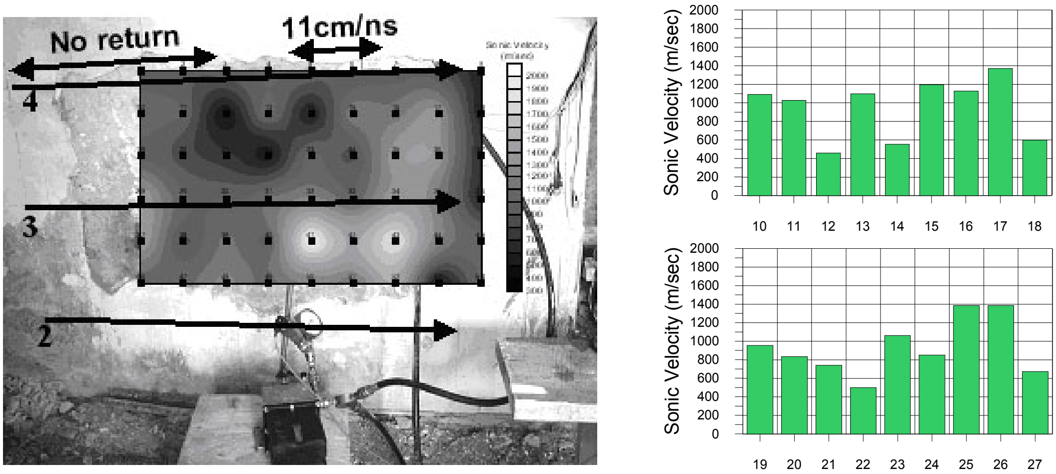

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Figure 6 Results of the sonic tests in the position POS 4b

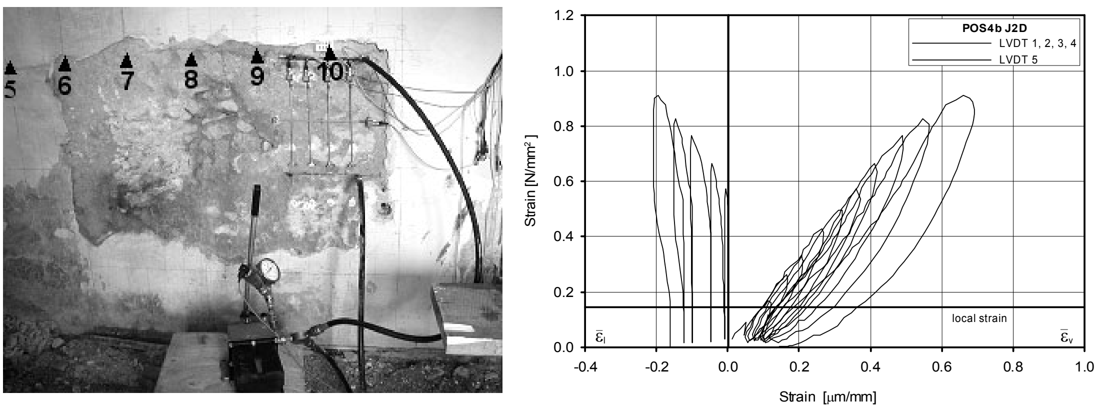

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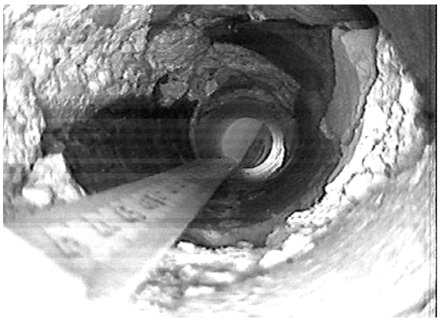
Figure 7 Localisation and result of the double flat jack test POS4b.

Thus, an accurate crack pattern survey was carried out on every side of the Tower (Fig. 9). At the highest levels (third and fourth floors) radar tests were also executed with medium and high frequency antennas to explore the morphology of the walls. In spite of the huge thickness of the wall (2.3m at the third floor and 2m at the fourth floor), even the 1GHz antenna could penetrate through the whole section and could show the signal reflected by the backside. Average velocities of 12cm/ns and 11cm/ns were measured at positions TOW1 and TOW2 respectively. From these values and from the horizontal profiles executed at these levels, as the one showed in Fig. 10, it can be excluded the presence of voids or slow material inside the wall section. The wall is rather homogeneous and the radar sections are only disturbed by some diffractions mainly correlated with the presence of large cracks already observed with the crack pattern survey.

More NDT experiments were performed at the ground floor were a flat jack test was planned.

The distribution of the sonic velocity is more homogeneous than in the other cases (Fig. 11a). The inspection by videoboroscopy showed a section made with regularly cut stones (Fig. 11b). At TOW3 stone blocks appear regular but the survey showed the



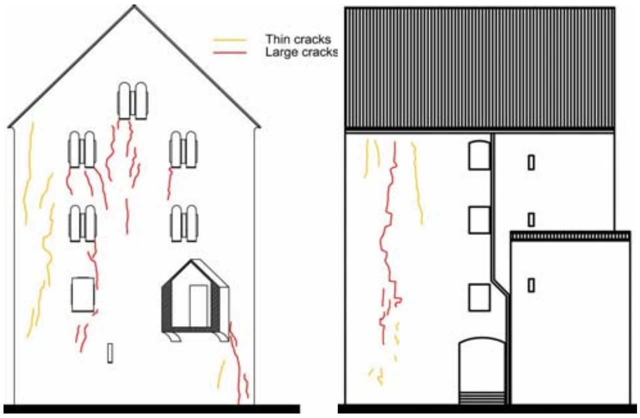


Figure 8 Videoboroscopy in the position POS 4b.

Figure 9 Crack pattern survey of the Tower in the South and East side

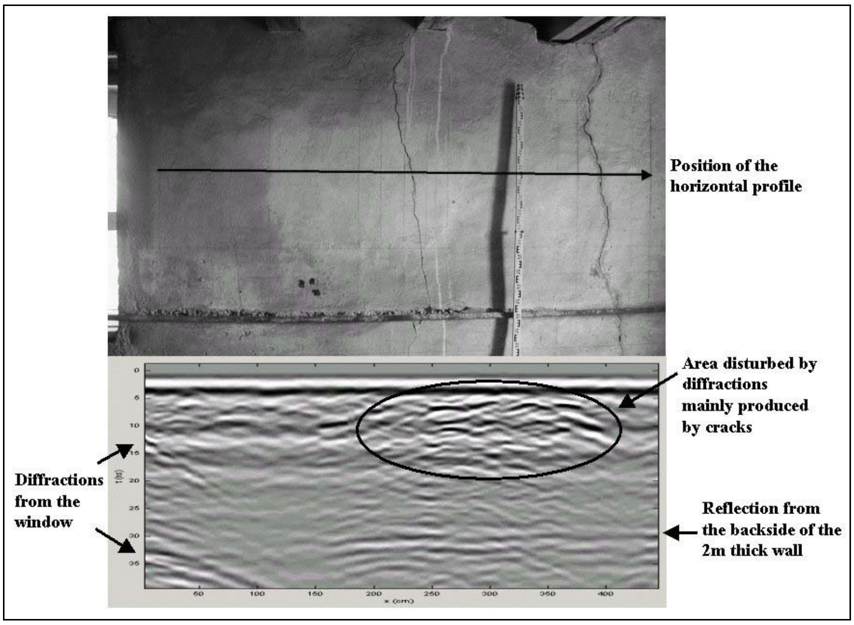


Figure 10 Position of one the horizontal radar profiles collected at the fourth floor of the tower (TOW1). The interpreted radar section is shown below. Some diffractions from main cracks and the reflection from the backside can be observed. The diffractions at the left side are lateral artefacts produced by the window at the left of the profile.

presence of some small voids near the joints that could be produced by the drilling operation.

Also the result of the double flat jack test shows a rather good behaviour (Fig. 12) with an average elastic modulus of 1700 N/mm^2, even if the state of stress is the highest.

Finally, a radar vertical profile was executed on the external side of the tower starting at an eight of 190cm from the base and moving upward (Fig. 13). The profile is parallel to the corner at a distance from the corner of 70cm. 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. 14).

The acquisition geometry has a great importance on the effectiveness of the test, for this type of application. In fact, the possibility to survey the wall from a surface that is nearly parallel to the cracks is essential. Fig. 14 shows the processed radar profile rotated vertically to facilitate the correlation with the picture of the adjacent side of the tower while Fig. 15 presents the interpretation of the main reflections and diffractions

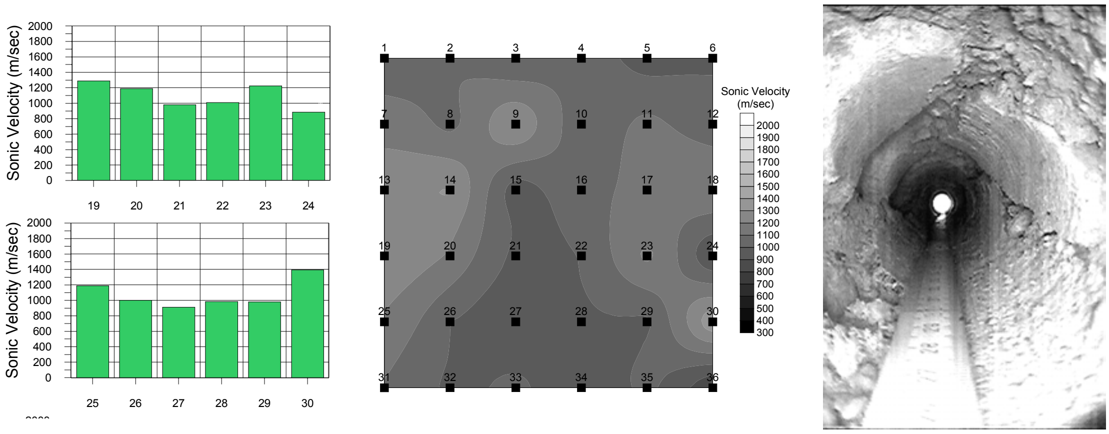


Figure 11 Sonic tests results and videoboroscoy carried out on position TOW3

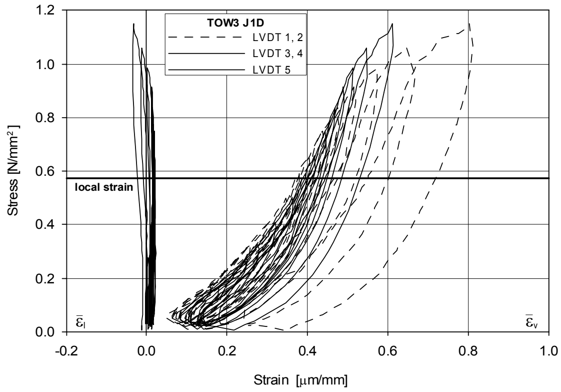


Figure 12 Results of the double flat jack in the position TOW3

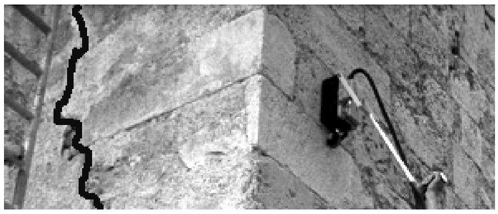


Figure 13 Position of the vertical radar profile collected with a 1GHz antenna to map some important cracks.

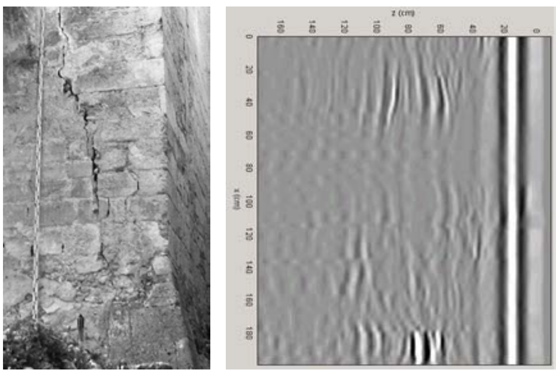


Figure 14 Cracks as observed on the adjacent wall and processed radar section.

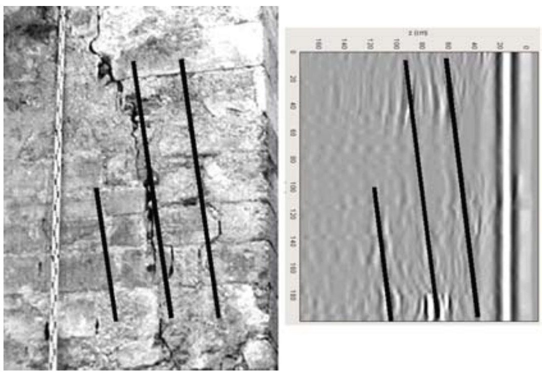


Figure 15 Interpretation of the vertical radar profile. A system of three main cracks seems to be detected by the radar profile at increasing depth from the surface.

apparently associated with three main cracks running at three different depths from the surface.

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

5 Masonry Typology and Materials

The inspection of the surface texture gives only a 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 seems characterised by 3 different masonry typologies, as reported in Fig. 16, regular in brick, 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.

Figure 16 Masonry typologies: regular in brick (POS1), irregular (POS4) and regular in stone (TOW3).

At present there are no standardised tests to define the composition and the chemical-physical and mechanical characteristics of mortars sampled from an existing building. Chemical and mineralogical-petrographical analyses are useful to determine: the type of binder and of aggregate, the binder/aggregate ratio, the extent of carbonation, the presence of chemical reaction, which produced new formations (pozzolanic reactions, binder-aggregate reactions, alkali-aggregate reactions). The grain size distribution of the aggregates can also be measured by separating the binder from the aggregates through chemical or thermic treatments (Baronio and Binda 1991).

The above-mentioned tests allow the determination of the composition of the existing mortars and permit the reproduction of mortars and grouts for repairing the masonry.

The results of the chemical analysis show very similar materials, as it is possible to deduct from Fig. 17. The low value of Soluble Silica reveals the binder as lime. The aggregate origin, instead, is in two cases calcareous and in a case mix calcareous/siliceous (even prevalently calcareous), as demonstrated by the value of the Insoluble residue.

In conclusions the mortars are very similar and made probably with local materials.

6 Conclusions

The on site investigation procedures should be calibrated and controlled in order to verify their effectiveness and particularly the possible application to each peculiar 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 test is usually self-sufficient to give the requested information, the complementarity of the different tests (sonic and radar tests, flat-jack, etc.) has also to be studied for the definition of the necessary physical and mechanical parameters of masonries.

The study carried out on the Pisece Castle has shown clearly that this complementarity allows a deep knowledge of materials, structures and special features of the masonry walls.

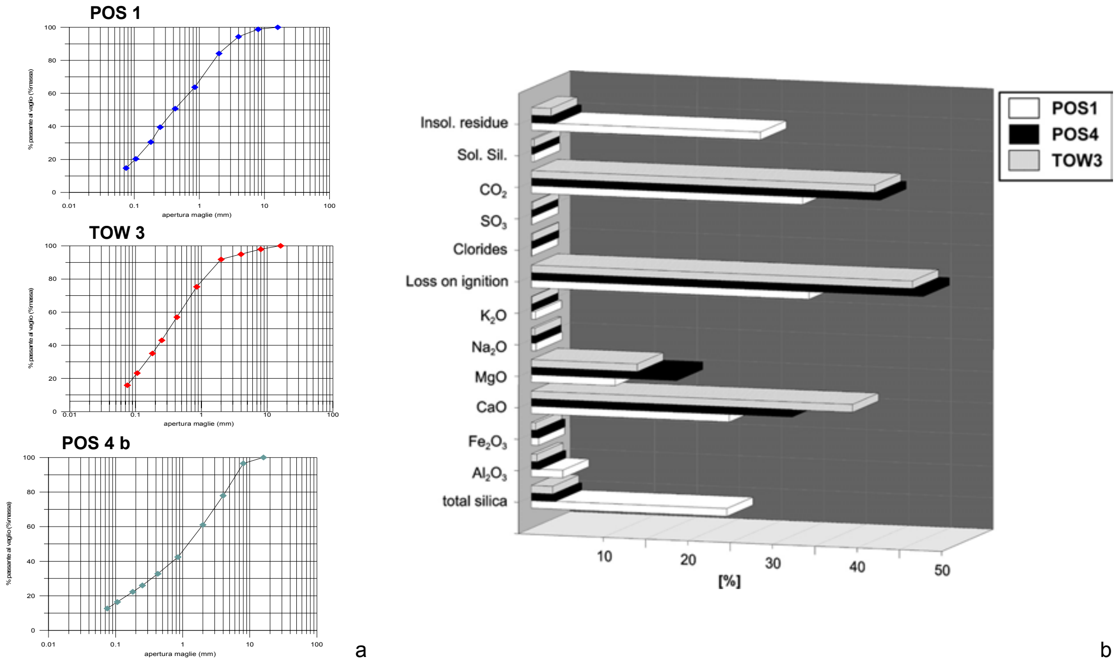


Figure 17 Grain size distribution and chemical analysis of the sampled mortars.

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