Investigation on structures and materials of the Castle of Avio (Trento, Italy)

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Abstract

This paper presents and discusses the preliminary results of the investigations carried out by the authors on a Castle, considered as case histories within a project financed by the EC (project EVK4-2001-00091 ONSITEFORMASONRY), coordinated by C. Maierhofer of BAM. An extensive investigation programme (including sonic, radar, thermovision, flat jack, coring, boroscopy, etc.) has been planned to support the preservation and restoration actions of the Castles. The experience shows the importance of a project for the investigation in order to select the most relevant strategies and tests for each specific problem.
Keywords: NDT, masonry, diagnosis, on site tests.

1 Introduction

An extensive investigation programme was set up and applied to the Castle of Avio near Trento, Italy (Fig. 1), in order to arrive at a reliable diagnosis of the damages, which affect the complex construction.

The research was also part of a project financed by the EC (project EVK4-2001-00091 ONSITEFORMASONRY coordinated by C. Maierhofer of BAM) and finalised to the evaluation of the perfomance of on-site investigation techniques for the structural evaluation of historic masonry buildings.

The tests were finalised to study specific problems individuated by the responsible of the restoration design. In general, the objective of the investigation was the evaluation of the structural problems, which affect the Castle, i.e. passing through cracks, bulging and out of plumb of load bearing walls. The investigation was extended to the characterisation of the masonry and the control of the local state of stress and of the stress-strain behaviour [1].

An important and diffused crack pattern is visible on the main walls of the Towers and many rooms are characterised by remarkable cracks. 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 evaluation of the structural state of conservation of the building structure.

Georadar, sonic pulse velocity test, flat jack tests and other diagnostic techniques were applied to solve specific problems as the damages to the masonry structures, the state of conservation of the load bearing walls and their connections and to detect the presence of voids and other inhomogeneities [1, 2, 3, 4].

Laboratory tests on materials sampled on site gave information about the characteristics of stones and mortar [1]. Chemical analyses on mortar samples have been carried out in the nearest possible point of the cut joints where flat jack tests were performed, in order to characterise the masonry and its components [6].

2 Castles description

At present the Castle is owned by FAI, a private organization for the care of monuments. The building complex of the Castle of Avio nestles around the Main Tower (called "Mastio") and is surrounded by large circle of defensive walls (Fig. 1).

Figure 1: The Castle of Avio.

The Castle structures are mainly in stonework masonry, with local repairs in brick masonry. The constructions have timber floors.

It was probably founded in the 11th century but considerably extended in the 13th. A feud of the Castelbarco, over the centuries the Castle passed through various hands: the Venetians, the Emperor of Austria, the bishop Bernardo Cles, the family Madruzzo and only in the 17th back to the noble family of the Castelbarco. New parts were built in the 19th century. The Baron Palace is at present open in the west side, due to the collapse, in the 1893, of the Tower symmetric of the existing one.

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. Every 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 of an absolute dating. Critical connections between blocks need to be investigated, so 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 be then 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.

Figure 2: Avio Castle Crack pattern survey of the south wall.

C. Campanella and M. Tessoni – Associated Architects in Crema, carried out the geometrical survey (Fig. 2) 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 detailing reported in [5].

Extended crack patterns are visible on the main walls of the Palace Tower and many rooms are characterised by remarkable vertical cracks crossing the wall section (Figs. 1, 2). 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.

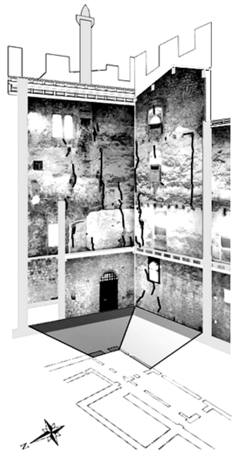
In general, the objectives of the investigation are the evaluation of the structural problems, which affect the Castle, starting from the crack pattern survey (Fig. 3), to the monitoring of the main cracks and deformations (Fig. 4), to the characterisation of the masonry and the control of the local 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 individuated by the responsibilities of the restoration design.

3 Crack pattern survey and monitoring

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, 3), and around the keystones of the upper arch windows.

This seems to indicate a lack of connection of the bearing walls in the corner, peculiarly in the upper part of the Tower where the timber floors are missed. Furthermore, cracks repaired with a dark grey mortar are visible, showing the long term existence of the structural problem.



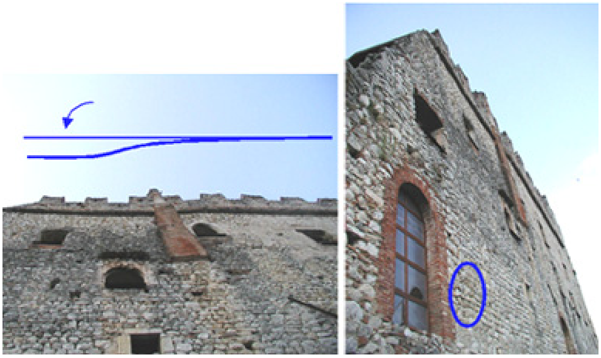


Figure 3: Crack pattern of the Tower.

Figure 4: Deformation of the South facade toward the valley.

A relevant deformation of the western upper corner of the south wall (Fig. 4a) is visible. This inflection did not produce wide cracks and could date back to the collapse of the closer Tower, opposite to the Palace Tower, at the end of the 19th century since there floors where missing and the corner did not have any connection and protection.

Fig. 4b shows a wide out of plumb of the outside wall with stone expulsion, which produces a relevant crack pattern in the internal room. The cracks have similar slope. The damage probably is not connected with a 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 cracks could be connected to the presence of chimney flues.

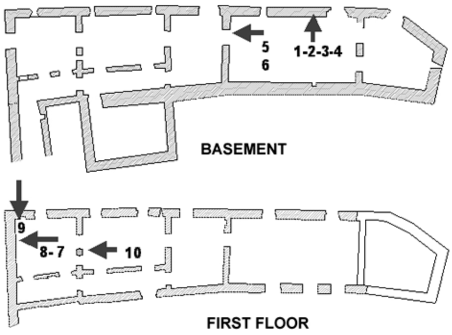


Figure 5: Localisation of the monitored cracks.

Figure 6: Measurement.

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 in a second time (19th century). This masonry is inhomogeneous, with brick insertion and poor mortar with wide voids. This poor workmanship could have affected the structural behaviour of the masonry. The room at the base of the Tower is the most damaged.

In order to evaluate the differential movement of the Castle, the most serious cracks are being monitored since December 2002 (Figs. 5-8). The deformations are measured by removable extensometer (Fig. 6) every 3 months. It is important to stress that the monitoring should be continued for four to five year, being the minimum significant period at least 18 months, in order to calculate the influence of the thermal deformation. Fig. 7 shows the localisation of some monitored cracks. Peculiarly, the position 1-4 corresponds to the buckling wall in Fig. 4. Fig. 8 shows the displacements measured up to now. The results of the monitoring show that some position like 3 and 4, 6, 7, 8 and 10 tend to extra movements which do not follow the temperature variation as they should do in a stable situation of the cracks.

The trend is confirmed by the out of plumb measurements reported in Fig. 9. It was therefore important to collect also data on the morphology of the deformed walls.

Another relevant crack pattern is easily recognised on the Mastio Tower (the oldest and tallest one), at the moment not yet monitored (Fig. 10). A remarkable crack pattern is visible on the Tower.

4 Study of the masonry components and morphology

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.

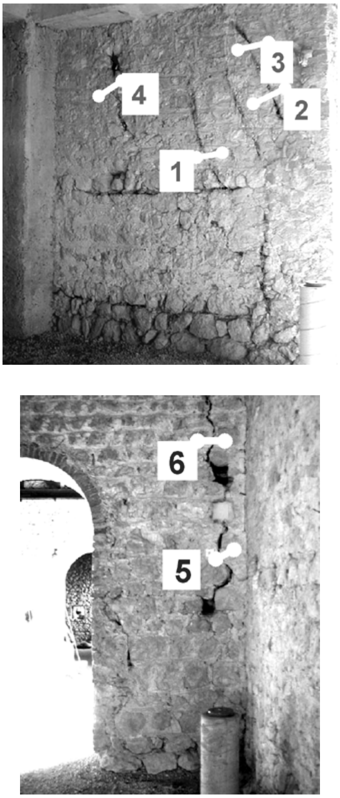


Figure 7: Localisation of some monitored cracks.

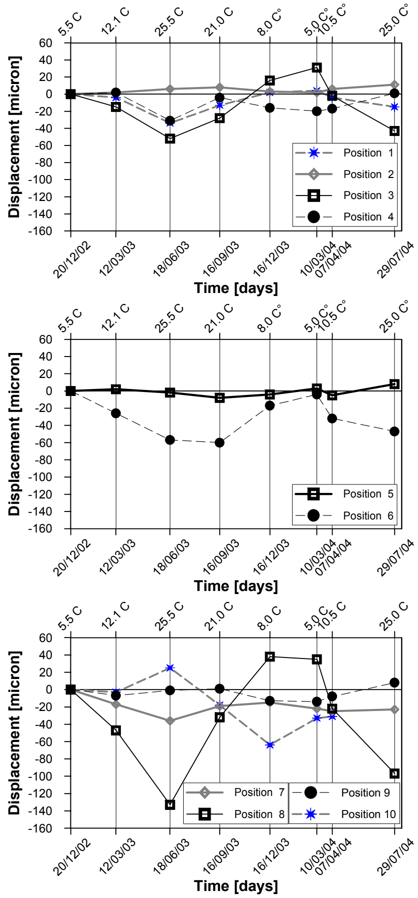


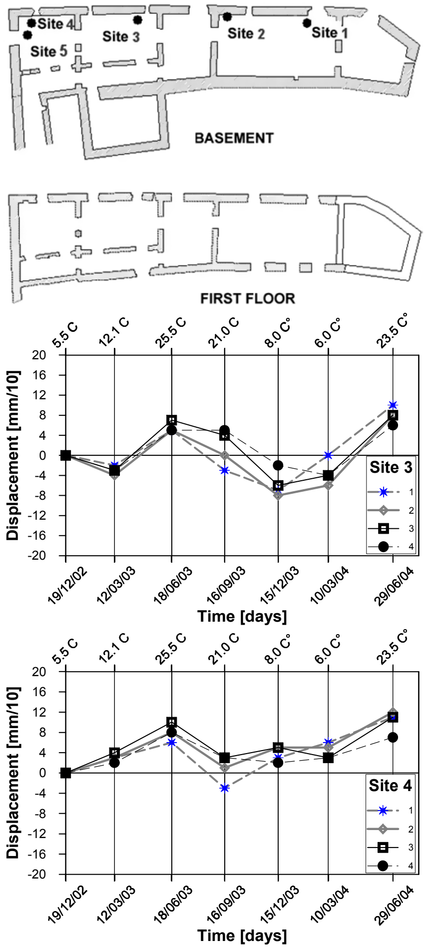
Figure 8: Monitoring of the cracks.

The Castle of Avio seems characterised by different masonry typologies. Fig. 10 shows the main masonry typologies of the Avio Castle. Two 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.

4.1 Characterization of mortar and stones

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



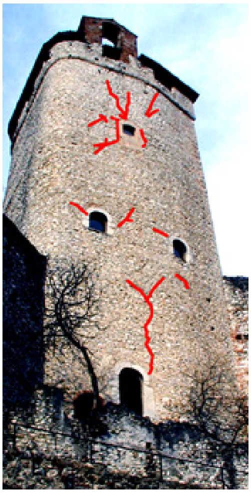


Figure 9: Out of plumb measurements.

Figure 10: Crack pattern of the Mastio.

The results of the chemical analysis show similar materials, as it is possible to deduct from Fig. 12. The low value of Soluble Silica reveals the binder as lime. The aggregate origin is mainly calcareous, as revealed by the different percentage of calcium carbonate variable between 17% and 49%.

The tests also allowed one to conclude that the mortars are rather similar and made probably with local materials.

Figure 11: Masonry textures of the external walls, of the partition walls and of the Mastio.

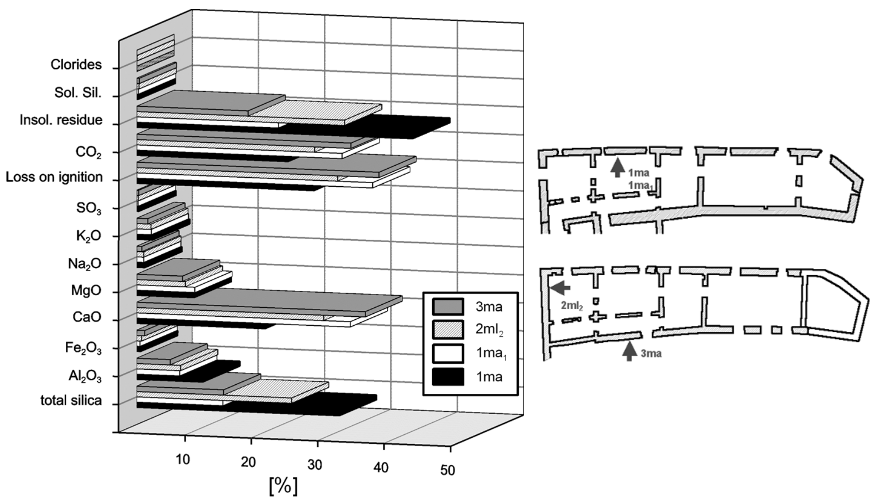


Figure 12: Chemical analysis of the mortars and localisation of the sampling.

4.2 Sonic tests and double flat jack tests

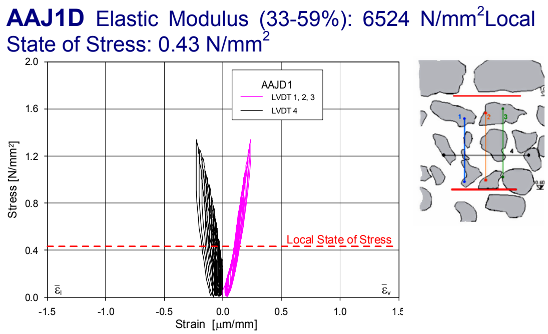
The complementary use of sonic and double flat jack test allows the masonry characteristics to be qualified.

Preliminary application of sonic tests and radar was useful to control eventual anomalies like the presence of chimney flues or other voids. In fact, the unknown masonry morphology can affect the results.

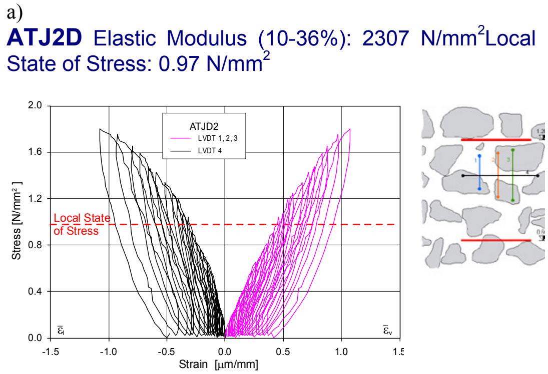
Fig. 13 shows the results of the single and double flat jack tests applied to the Avio Castle. The tests demonstrate that a classification of the masonry quality is possible.

Unexpectedly it seems that the “Mastio” walls are more deformable than the other walls. Due to the fact that the flat jack test is very local this results should be check by other tests.

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 seem to be aligned with the other data.



a)



b)

Figure 13: Characterisation of the masonries typologies by double flat jack.

4.3 Use of georadar for the detection of local defects and flows

The wall of the Avio Castle at the basement level (Fig. 4), 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 in several areas less compact materials (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 in correspondence of the leaves interface. This conclusion was confirmed also by direct visual inspection. The material found is very poor with weak or even locally missing mortar (Fig. 17). This can explain the appearance of bulging only on the outer surface as a detachment of the two leaves of the walls.

5 Conclusions

The research carried out within the frame of an EC Contract allowed a strict 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 other applications (Altes Museum in Berlin, Avio Castle in Italy, Pisece Castle in Slovenia, etc.).

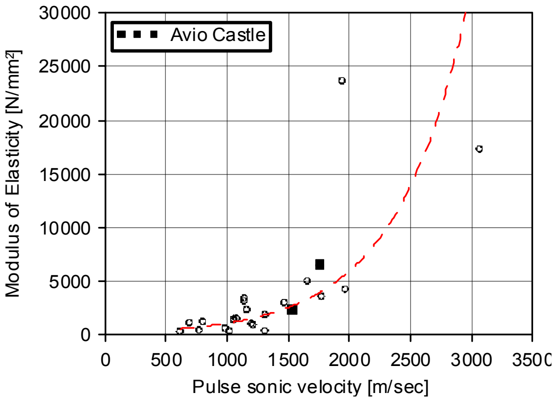


Figure 14: Correlation between pulse sonic tests and Modulus of Elasticity.

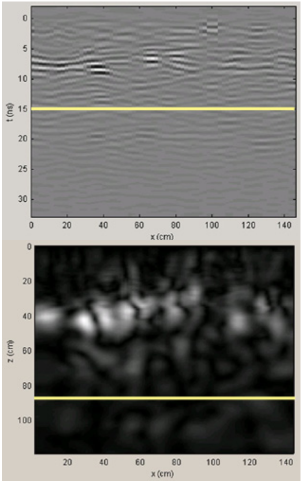


Figure 15: Radar profiles indicating the presence of a two leaves section.

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.

Specifically for the Avio Castle, the multidisciplinary approach and complementary use of investigation procedures (monitoring survey, NDT etc.) allowed the following conclusion:

- The Palace structures were badly damaged by the XIX century collapse.
- The missing floors and connections the longitudinal bearing walls are causing long term damages, deformation, out of plumb to them.
- This poorly stable situation has also caused the separation between the masonry leaves.
- The presence of chimney voids is also causing progressing damages.

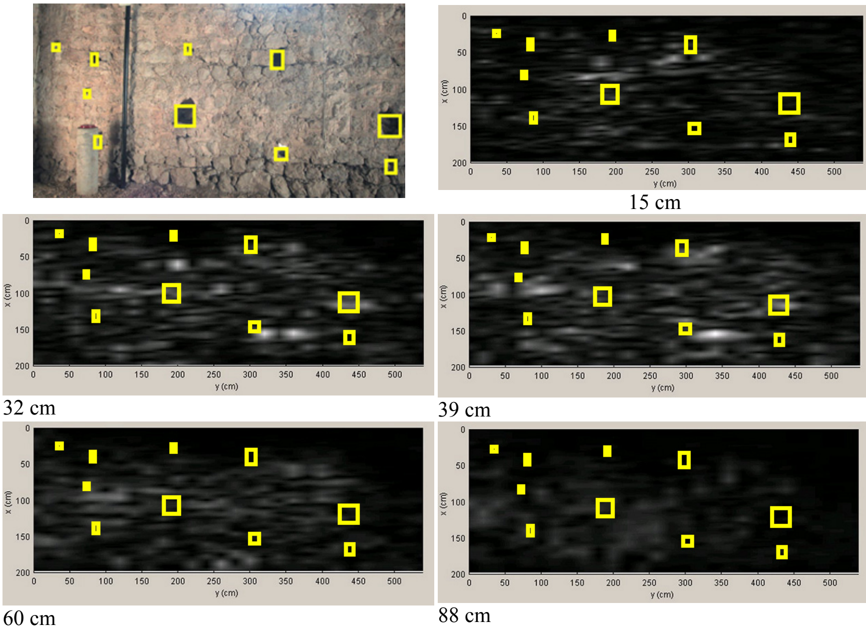


Figure 16: Reconstruction of the radargrams respectively at the depth of: 15, 32, 39, 60 and 88 cm. The elaboration enhances the presence of internal voids (white spots). White boxes identify the positions of surface cavities and missing stones.

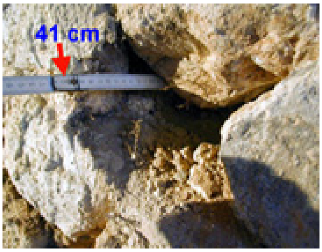


Figure 17: Inspection, which indicates the presence of a void.

- The “Mastio” Tower, due to additional dead loads (e.g. a bell support and additional floors), the lack of connection and a probably multiple leaf badly connected masonry, should be also monitored and better studied.

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. Concerning the paper objective 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 respectively flat jack tests and by sonic and/or georadar tests;
- sonic and flat jack test seem to have a possible correlation. This can help the application of flat jack, which gives a very local information;
- hidden voids, inclusions and flows can be detected by the use of georadar and/or sonic tests.

Acknowledgements

Authors wish to thank for their contribution to M. Ciano, the technicians M. Antico, M. Cucchi, M. Iscandri and to C. Arcadi. Special thanks go to Prof. Campanella and Dr. Bortolotto of the Politecnico of Milan, the FAI, Dr. Rodrigues (Geocisa), Prof. Modena (Univ. of Padova), Prof. Marchisio (Univ. of Pisa). The research activity was performed within the framework of the ONSITEFORMASONRY research project, coordinated by Dr. C. Maierhofer of BAM, funded by the European Commission. Support was also given by MIUR – Cofin, 2002.

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