

# **RADAR AND SONIC AS COMPLEMENTARY AND/OR ALTERNATIVE TESTS IN THE SURVEY OF STRUCTURES.**

A. SAISI<sup>1</sup>, S. VALLE<sup>2</sup>, L. ZANZI<sup>2</sup>, L. BINDA<sup>1</sup>

<sup>1</sup>Department of Structural Engineering, Politecnico of Milan, Italy, <sup>2</sup>Department of Electronics and Information, Politecnico of Milan, Italy

## **SUMMARY**

Following a long term experimental and theoretical research on the use of radar and sonic tests for the characterisation of historic masonries some case histories are presented, which show that radar and sonic tests are complementary rather than alternative tools for the diagnosis of historic masonries.

## **1. PREMISES**

The experience of these last decades consequent to several seismic events shows how difficult it is to choose preventive or repair techniques to be applied to historic stone masonry buildings. Their load bearing structure consists of walls, which are frequently highly inhomogeneous multiple leaf masonry. Physical or analytical modelling of these walls cannot appropriately assume any homogenisation if the real technique of construction of the wall is not known. In fact, the knowledge of the wall prospect is not enough to have information on how the inside is made [1]. Inside the wall there might be also cracks and voids and damages, which make it weaker. Two possible ways can be followed to reach this knowledge: (i) destructive survey through coring or local demolition, (ii) non destructive survey carried out by NDT (non destructive techniques) as thermography, sonic and EM or X-ray tests. The authors are applying sonic and radar tests since a rather long time ([2], [3], [4], [5], [6], [7]), proposing calibration methods and procedures in laboratory and on site. The differences, the advantages and the drawbacks in the use of sonic and electromagnetic (Ground Penetrating Radar, GPR) systems referred to on site applications are here outlined. In particular the tests carried out on 2 Italian monuments for different purposes will be reported. The investigations concern the control of the possibility of the technique to recognise defects. As well known the two techniques are based on different principles, and then are affected by different parameters. In fact, the emitted waves have

different origins: stress waves for sonic tests and EM waves in the case of radar. Furthermore the frequency content of the signals is very different. The fundamentals of wave propagation through solids allow to recognise the theoretical capabilities and limitations of the techniques. For sonic tests, the velocity of a stress wave passing through a solid, elastic, homogeneous and isotropic material depends on the density  $\rho$ , dynamic modulus  $E$ , and Poisson's ratio  $\nu$ . Instead, EM wave velocity in a homogeneous dielectric material is basically a function of the permittivity  $\epsilon$ . In the case of masonry only global variations in these three parameters can be indicated. Nevertheless, the data are certainly meaningful for the overall state of the wall. Furthermore, resolution in terms of the smallest recognisable features is related to the dominant wavelength of the incident wave and also to the size of the tested element. The wavelength,  $\lambda$ , is a function of velocity,  $v$  and frequency  $f$ :  $\lambda = v/f$ . For a given velocity, as the frequency increases the wavelength decreases, providing the possibility for greater resolution. However, as frequency increases the rate of energy absorption also increases limiting the size of the wall section that can be investigated. The optimal frequency, for both techniques, is chosen considering attenuation and resolution requirements to obtain a reasonable combination of the two limiting parameters. Concerning sonic tests, it is known that the input frequency changes with the characteristics of the superficial material. Due to the wall structure or to the presence of a thick plaster or a partially detached plaster, the high frequency components can be filtered. The output signals can have a rather low frequency content. The sonic test in this case do not have the resolution requested to detect in detail the wall morphology but it gives an overall description of the position of low velocity points. In such situation the radar tests show some advantages.

On the contrary radar has several problems in the presence of moisture because the conductivity  $\sigma$  and, as consequence, the absorption are proportional to the water content of the material. It is important draw back the limits of the technique in this situation. The sonic tests are a reliable technique to evaluate the effectiveness of grout injection. The investigations, repeated before and after the repair, allow the control of the distribution of the grout in the masonry. Radar tests, instead, being negatively influenced by the presence of moisture, could be inappropriate or even misleading.

## **2. RESEARCH ON THE RESPONSE OF BRICK AND STONE MASONRY**

The research on the limit and advantages of radar and sonic tests has been carried out for several years also within a BRITE/EURAM Contract. Two typical cases of applications are presented in the following.

### **2.1 Torrazzo of Cremona**

The Torrazzo, the Cathedral bell-tower, is the symbol of Cremona, a city which is situated 90 km south-east of Milan. With its height of 112.10 m, the Torrazzo is known as the highest masonry tower in Europe. The walls made with solid bricks appear to have been covered with a sort of veneer wall, one brick thick, which was made in a more regular way and covered the underneath rough surface. The presence of this veneer and its eventual detachment has to be detected for safety reasons. In fact instability phenomena could in long term take place causing the failure of the detached veneer wall. The tests interested the East side of the Torrazzo and were carried out at the level of the Bertazzola lodge (Fig. 1). A large difference between the stress values measured by flat jack tests in various points of the wall was detected. The stress value of  $1.76 \text{ N/mm}^2$  measured at this level of the tower dropped to  $0.4 \text{ N/mm}^2$  in one area, suggesting the presence of detachments of the external leaf of the wall. The

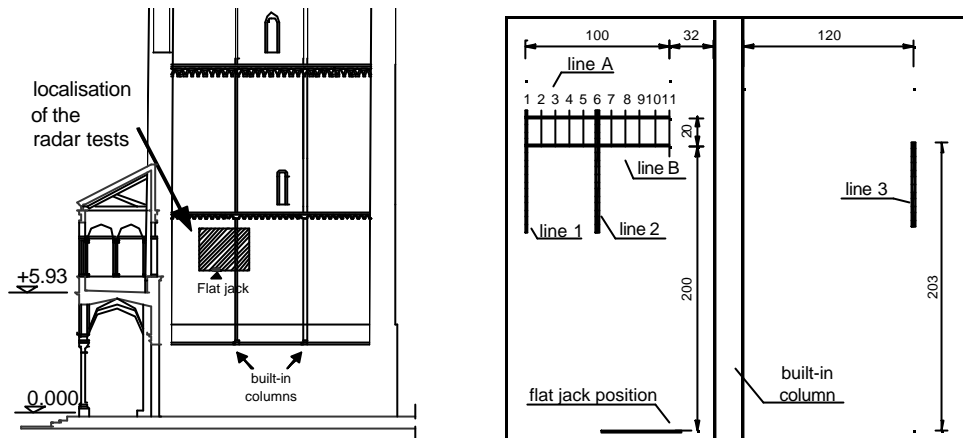


Figure 1: Localisation of the radar tests in the South side of the Tower.

fact appeared strange as in this area the wall of the tower was supposed to be solid; other flat jack tests revealed similar situations.

The radar tests were carried out by moving horizontally and vertically a 1.5 GHz antenna. The first examined profiles, concerning scan lines A and B, do not show any evidence. The second group of tests, acquired by vertically scan along lines 1, 2, 3 of Fig. 1, was initially limited to the upper part of the profiles, above line B. The data analysis enhanced a reflection parallel to the wall surface in the lower part of the profile (right hand side in Fig. 2). These deductions are also confirmed by the radar sections extended to the whole vertical scan lines 1 and 3 of Fig. 1; in fact, the sections show a very clear and continuous reflection, due to the media discontinuity. The effect can be explained by the presence of a void or a detachment in the lower part of the acquisition scans. All the acquisitions were, then, repeated scanning down from the line called B in Fig. 1, being evident a concentration of the discontinuity in that area. The group of acquired data, starting from line B (Fig. 3), shows again a coherent reflection just behind the wall surface. It is interesting to note the high energy of this reflection that indicates a sudden change in the dielectric characteristic of the media, as can be expected from a detachment of the external leaf. The supposed detachment is localised below the line B in Fig. 1, and extended in most of the wall area, from line scan 1 to line scan 3.

In this case sonic tests were not helpful. Due to the Tower geometry, acquisitions by transparency could not be carried out. Acquisitions by transparency could perhaps be sensible to the presence of the detachment in spite of the great thickness of the wall; nevertheless it was impossible to realise a perfect correspondence between the emission and receiving locations as required. Superficial acquisitions did not detect any variation because the elastic waves propagated only through the external leaf, rather homogeneous being composed by solid bricks and vertical mortar joints.

## 2.2 Noto Cathedral

The authors applied systematically sonic and radar tests and other diagnostic techniques on the remaining walls and piers of the Cathedral of Noto. The right aisle and most of the dome of the Cathedral collapsed in 1996. The aim of the research was to verify the state of damage and the possibility of preservation of the remaining walls and piers in view of the reconstruction of the

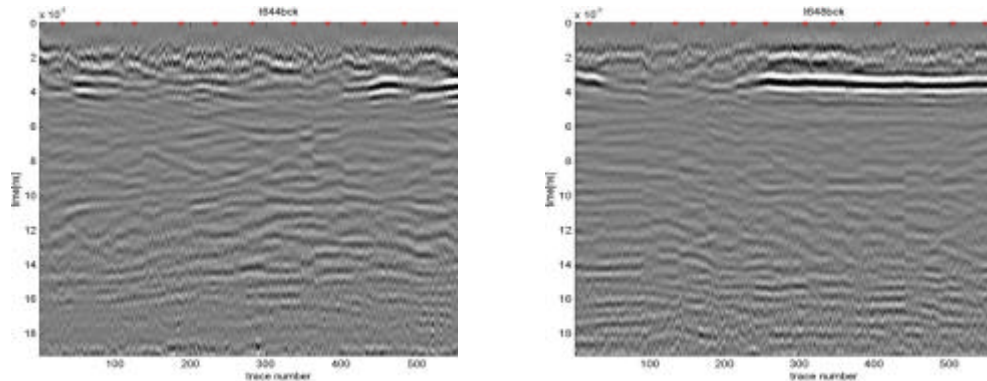


Figure 2: Upper segment of line 2 in Fig. 1. Left to right corresponds to the top to bottom direction. Figure 3: Lower segment of line 1 in Fig. 1. Left to right corresponds to the top to bottom direction.

damaged part of the Cathedral. Furthermore the sonic tests were used to control the effect of grout injection used as a possible technique for repair of the damaged masonry. The extensive campaign of sonic tests carried out on the piers shows recursive phenomena. The values of the sonic velocities are decreasing as the height of the piers increases (Fig. 4). The effect can be probably explained by the use of different type of stone, characterised by different sonic tests. In fact, a local calcareous sandstone was used in the lowest part of the pier up to about 1.0 m and travertine, with much lower density and strength, in the highest ones.

In order to know the response of the two stone to the elastic waves, the ultrasonic velocity was determined by transmission on stone blocks. In fact, in the case of the calcarenite the values are almost constant with an average of 3068 m/sec (Coeff. of Variation: 2.5%). The values of the travertine are more scattered, with a measured velocity between 1325 m/sec and 3548 m/sec, and an average of 1823 m/sec (Coeff. of Variation: 36.9%). The scattering of the data is due to the presence of large voids, randomly distributed in the material, and confirms the results of the mechanical tests, very scattered, as well, in the case of travertine. Furthermore the sonic tests allowed to detect that piers P1C and P1B were the most damaged as it could be detected also by the presence of a more diffused crack pattern. Radar tests were also carried out on the pier P1E. Fig. 5 shows the geometry of the pier P1E and the localisation of the sonic and radar tests.

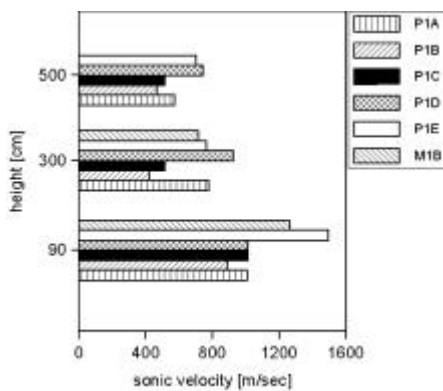


Figure 4: Vertical distribution of the sonic velocity measured on piers P1<sub>i</sub> and wall M1B.

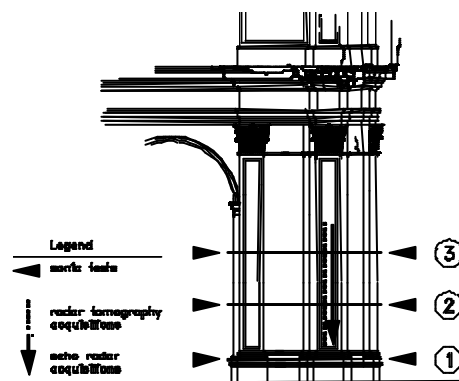


Figure 5: Geometry of the pier P1E and localisation of the sonic tests

Fig. 6 shows the sonic velocities evaluated on the pier P1E respectively at 0.90 and 5.0 m. The values are clearly decreasing with the height of the pier.

The radar data were acquired for a vertical section imaging. The equipment used was a GSSI SIR 10 with 500 and 900 MHz antennae. The first step of the test was the antenna frequency selection. The 900 MHz antenna did not ensure enough penetration to investigate all the pier section because of the pier dimensions and the high moisture content. Instead, with the 500 MHz antenna the SNR was sufficient to receive the signal even for longer paths; the interpretation was hard only for measures through the lower part of the pier, where the humidity was high. The data were collected both by reflections and tomographic mode. The high moisture level did not allow the study of the pier base, up to about 1.5 m on the floor level. Fig. 7a shows the results of the tomography. The data were processed with a software developed by Valle & Zanzi [8]. In the central part of the pier section high EM velocities are detected. This effect could be explained by the presence of inhomogeneities in the masonry (Fig. 8). In proximity of these areas the sonic tests localised lower quality masonry. Very low EM velocity (about 8 cm/ns) in the lower part of the pier confirms the high moisture content. Fig. 7b shows the echo radar section acquired by vertical continue scans. The complexity of the wall section did not allow a clear identification of the several local anomalies. The radar contribution in this case was limited only to a map the reflections from the external stone leaf (first strong reflection). In the lower part of the profile, the section presents a lower energy return due to high moisture content. In this case the sonic tests allowed an extensive and detailed investigation of the state of conservation of the remaining parts of the Church. The radar tests, instead, were affected by the relevant presence of moisture that imposed to use the 500 MHz antenna and by the general morphology of the rubble masonry, that obstacle the significativity of the tests

### 3. CONCLUSIONS

In the applications, the radar and the sonic tests gave reliable informations, confirmed by the use of other complementary diagnosis techniques. The following remarks can be drawn from the evaluation of the results of the experimental research carried on:

- ?? the sonic tests were able to detect the variation of materials in the piers and walls. The possibility of recognising different materials is very important to investigate large areas of walls, as in the case of the Noto Cathedral.
- ?? sonic velocity can be successfully used to qualify the state of an existing masonry. It can reveal and eventually locate states of damage in structural elements or portions of walls. The radar tests, instead, could be

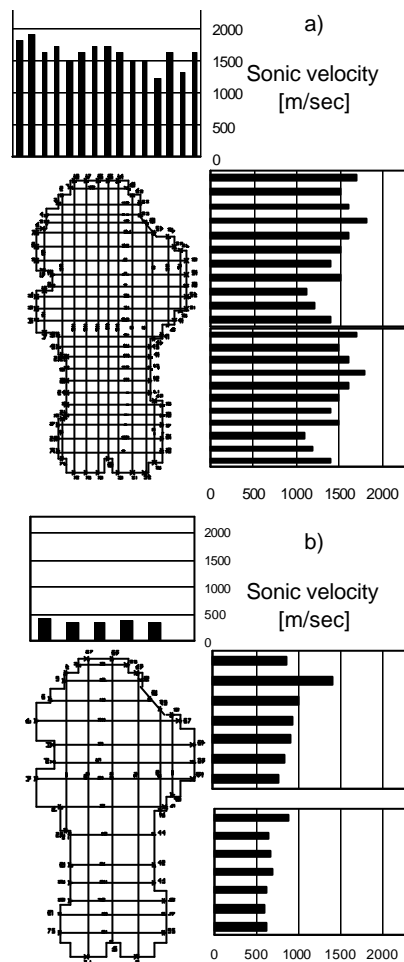
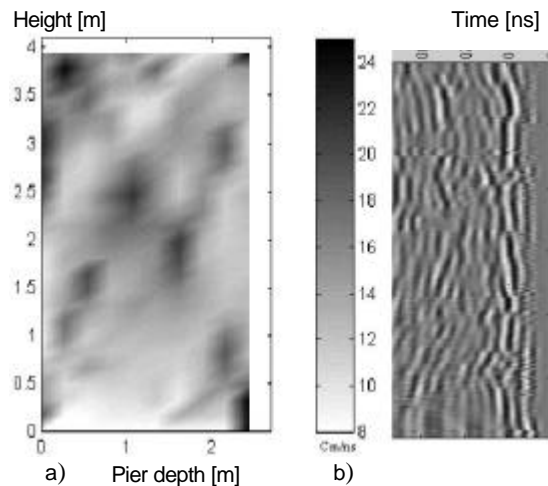


Figure 6a,b: Results of the sonic tests (m/sec) at 0.90 and 5.00 m respectively.

disturbed by the diffractions produced by large quantities of small scattering inhomogeneities, as in a rubble masonry.  
 ?? the radar and sonic tests can detect efficiently local defects inside the wall such as the presence of large voids  
 ?? the radar tests can recognise the presence of leaves in a wall, in the case of strong interfaces between the layers themselves, like in the case of detachment of veneers



#### 4. ACKNOWLEDGEMENTS

Authors wish to thank for their contribution on the site and laboratory tests, the technicians M. Antico, M. Cucchi, the Architect C. Tiraboschi and R. Tongini Folli, and L. Cattaneo. Special thanks go to Prof. M. Forde and to the Edinburgh University, UK, for the availability of the equipment, and to S. Oliver and E. Walsh, H. Rutledge and W. Chung, for the radar acquisitions. The investigations were carried out with the support of the Prefettura di Siracusa, by the Parish of Cremona, by Murst - Cofin 98 and by the project Giovani Ricercatori.

Figure 7a,b: Radar tomography and echo-profile on a pier of the Noto Cathedral. The echo-profile scale allows a direct comparison of the results (the time scale of the profile corresponds to about 2 m depth).



Figure 8: Detail of a pier section.

#### 5. REFERENCES

- [1] Hendry A.W. - "Aspects of stability and strength of stone masonry structures", in *Proc. 3<sup>rd</sup> Int. Masonry Conf., British Masonry Soc.*, 1994, n. 6
- [2] Berra, M. et al., "Ultrasonic pulse transmission: a proposal to evaluate the efficiency of masonry strengthening by grouting", in *Proc. of the 2<sup>nd</sup> Int. Conf. on Non-Destructive Testing*, 1988, Perugia, Vol. I, p. I/10.1-I/10.19.
- [3] Binda, L. et al., - "Identification of moisture capillarity in masonry using digital impulse radar", *Journal of Construction & Building Materials*, 1994, Vol. 8, No. 2, p. 101-107.
- [4] Binda, L. et al. - "NDE of masonry structures: use of radar test for the characterisation of stone masonries", *Non Destructive Testing and Evaluation Int. Jour.*, 1998, Vol. 31, N.6, p. 411-419
- [5] Schuller, M.P. et al - "Acoustic Tomography for Evaluation of Unreinforced Masonry", in *Proc. 6<sup>th</sup> Conf. on Structural Faults & Repair*, 1995, Vol. 3, p. 195-200.
- [6] Valle, S.; Zanzi L. - "Radar Tomography for Cavities Detection", in *Proc. SAGEEP'96*, 1996.
- [7] Valle, S.; Zanzi L. - "Resolution in radar tomography for wall or pillar inspection", in *Proc. 6<sup>th</sup> International Conference on Ground Penetrating Radar*, 1996, Sendai, Japan.
- [8] Valle, S.; Zanzi L. - "Traveltime radar tomography for NDT on masonry and concrete structures", *Europ. Journ. of Environmental and Eng. Geophysics*, 1998, Vol.2, n. 3, p. 229-246.