Transactions on the Built Environment vol 55, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

Sonic tomography of the stone pillars of a 17th century church

L. Zanzi[1], A. Saisi[2], L. Binda[2] & E. Cardarelli[3]
[1]*Dip. di Elettronica e Informazione, Politecnico di Milano, Italy*
[2]*Dip. di Ingegneria Strutturale, Politecnico di Milano, Italy*
[3]*Dip. di Idraulica, Trasporti e Strade, Università "La Sapienza", Roma, Italy*

Abstract

Pulse sonic tests were applied to 8 massive stone pillars of a 17th century church (S.Nicolò all'Arena at Catania, Italy). The data were processed to obtain 28 tomographic sections showing the distribution of the elastic wave velocity within the tested pillars. The results of the tests are compared in order to check the morphology and the state of damage of the pillars. A preliminary frequency analysis of the data seems to indicate that these experiments can be used to extract the energy absorption distribution.

1. Introduction

Sonic tomography is a powerful method to obtain information on the hidden conditions and morphology of structural elements. In general, the velocity distribution is an indication of the elastic properties of the element.

When the elements can be accessed from all the sides as in the case of the pillars of churches, the results can be more reliable because the acquisition can be designed to ensure a dense and regular distribution of rays within the horizontal sections.

The authors have developed a broad experience on the subject, on several historic monuments [1], [2], [3], [4]. In the following an experience is presented of the application of sonic tomography on the pillars of a Church in Sicily, S. Nicolò all'Arena at Catania, damaged by the last earthquake.

Transactions on the Built Environment vol 55, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

The investigations are part of a more extensive diagnostic programme finalised to verify the state of damage of the building in view of repair intervention.

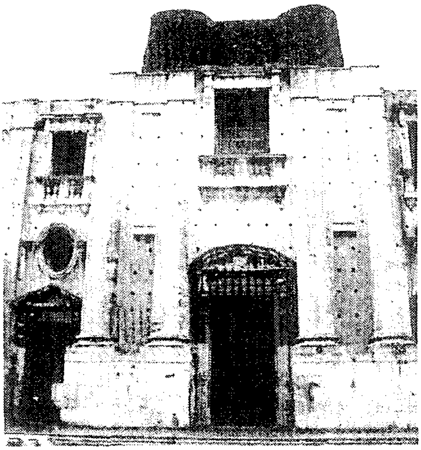


Fig. 1. S. Nicolò Church. View of the facade.

2. Problem description

The investigated Church, S. Nicolò all'Arena, was built in the 17th century in Sicily, Italy (Fig. 1). It has a large dome and vaults supported by very massive stone pillars with a typical section of about 16 m^2 (Fig. 2). During an earthquake and eruption of the Etna volcano the monument was invaded by the lava and partially collapsed; so it was partially rebuilt. The original pillars, which remained at the entrance and at the first arcade, were built with a different construction technique than the reconstructed pillars. All are made with volcanic stones and lime mortar. Nevertheless the original ones have a highly inhomogeneous section with a mixture of large irregularly cut stones and rubble material. The others have a multiple leaf section with large regularly cut stones and rubble filling.

After an earthquake, which struck the Eastern part of Sicily in 1990, the structural elements of the church as the dome and the vaults were damaged and the appearance of vertical cracks on the original pillars were detected. It is not clear whether those cracks were already visible and were simply propagating during the earthquake. An investigation programme (including sonic, radar, flat jack, coring, boroscopy, etc.) has been recently planned to design the preservation and

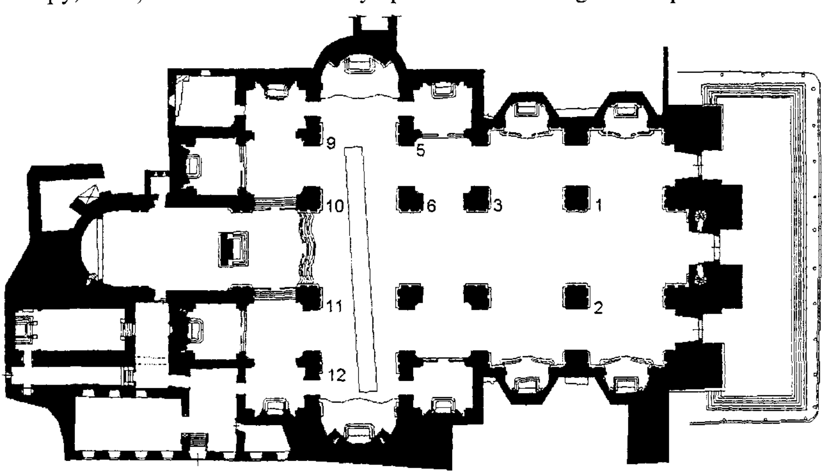
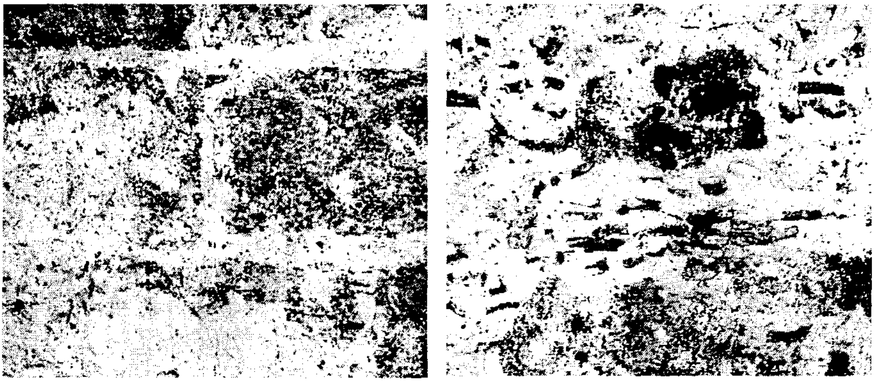


Fig. 2. Localisation of the tested pillars.

Transactions on the Built Environment vol 55, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509



(a) (b)

Fig. 3. Main masonry typologies of the Church. Regular block masonry (a) and 'incoccio" (b).

:storation actions.

'he masonry appears characterised by two different typologies: (i) a solid :onework built by large and regular blocks and filled with rubble masonry made 'ith rather strong mortar; (ii) a highly inhomogeneous stone masonry surrounded y a thick cover made with tile fragments, stones and rather weak mortar, locally alled "incoccio" (Figs. 3a and 3b). Often the two typologies are present in the ame structural element (Fig. 4). Apparently the second one was used as repair :chnique (Fig. 5).

. Principles of the pulse sonic test

.mong the ND investigation methods, the sonic methods are with no doubt, the lost widely used. The testing technique is based on the generation of sonic or ltrasonic impulses at a point of the structure. A signal is generated by a percussion

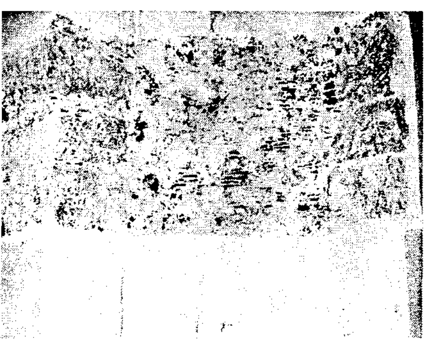


Fig. 4. Regular stones and "incoccio".

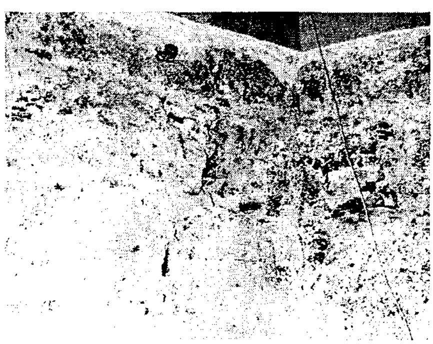


Fig. 5. "Incoccio" 30 cm thick, probably used to widen the section of the pillars.

or by an electrodynamics or pneumatic device (transmitter) and collected through a receiver which can be placed in various positions.

The elaboration of the data consists in measuring the time the impulse takes to cover the distance between the transmitter and the receiver. The use of sonic tests for the evaluation of masonry structures has the following aims:

- to qualify masonry through the morphology of the wall section, to detect the presence of voids and flaws and to find crack and damage patterns;
- to control the effectiveness of repair by injection technique.

The first applications of sonic tests to the evaluation of masonry materials and structures have been carried out long time ago in the sixties [5]. The difficulty of interpretation of the results in the case of inhomogeneous materials like masonry was always known and the first results were clearly interpreted as qualifying rather than quantifying values. Several efforts have been put in the tentative of interpretation of the data from sonic and ultrasonic tests [6].

The limitation given by ultrasonic tests in the case of highly inhomogeneous material made the sonic pulse velocity tests more appealing for masonry. Nevertheless in the case of low porosity units and mortar used in solid or cavity walls, ultrasonic tests can also be successfully used.

Limits of sonic tests to masonry can be defined as follows:

- cost of the operations due to the high number of measurements which has to be carried out;
- difficult elaboration of the results due to the difficulties created by the inhomogeneity of the material;
- need for the calibration of the values to the different types of masonry.

The fundaments of wave propagation through solids allow to recognise the theoretical capabilities and limitations of the technique. The velocity of a stress wave passing through a solid material depends on the density ρ, dynamic modulus E, and Poisson's ratio ν of the material. Resolution in terms of the smallest recognisable features is related to λ, the dominant wave-length of the incident wave, which is given by $\lambda = v/f$, where v is the velocity and f the dominant frequency.

Hence, for a given velocity, as the frequency increases the wave length decreases, providing the possibility for greater resolution in the final velocity reconstruction. It is beneficial, therefore to use a high frequency to provide for the highest possible resolution. However there is also a relationship between frequency and attenuation of waveform energy. As frequency increases the rate of waveform attenuation also increases limiting the size of the wall section which can be investigated. The optimal frequency is chosen considering attenuation and resolution requirements to obtain a reasonable combination of the two limiting parameters.

Mechanical pulse velocity equipment can be used to acquire pulse velocity data. The input signals are generated by a hammer, often instrumented, and the transmitted pulse is received by an accelerometer positioned on the masonry surface. Some other instruments generate impulses by means of a pendulum apparatus, which permits repeatable input waves. In this last case the hammers provide a mass falling down from the same distances [7]. The frequency and energy

Transactions on the Built Environment vol 55, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

content of the input pulse are governed by the characteristics of the hammer [8]. Signals are stored by a waveform analyser coupled with a computer for further processing.

Three types of tests can be conducted: (1) direct (or through-wall) tests in which the hammer and accelerometers are placed in line on opposite sides of the masonry element, (2) semi-direct tests in which the hammer and accelerometers are placed at a certain angle to each other, and (3) indirect tests in which the hammer and accelerometer are both located on the same face of the wall in a vertical or horizontal line.

The velocity and waveform of stress waves generated by mechanical impacts can be affected by:

- Input frequency generated by different types of instrumented hammers and transducers;
- Number of mortar joints crossed from the source to the receiver location; the velocity tends to decrease with the number of joints.
- Local and overall influence of cracks.
- Variation of the input frequency with the characteristics of the superficial material (e.g. presence of thick plaster or cracks). The sonic test in this case shows a very important limit. Due to the wall structure or to the presence of a thick plaster (with fresco) the high frequency components might be filtered. As a result, the output signals will have a rather low frequency content. Since the wavelength is equal to the ratio between wave velocity and frequency, this effect leads to an output signal that contains only very long wavelengths. The sonic test in this case does not have a resolution able to detect in detail the wall morphology but it gives an overall description of the position of low velocity points.

4. Sonic tomography

Among the ND applications the tomographic technique is quite attractive for the high resolution that can be obtained [1], [9], [10].

Tomographic imaging is a computational technique that utilises an iterative method for processing a large quantity of data collected on the external surface to reproduce the internal structure of an object. Standard pulse velocity data could be used to reconstruct a velocity distribution within a solid material, thus providing an "image" of the masonry interior.

The technique gives a map of the velocity distribution on a plane section of the structure under investigation. The input to the method consists of the traveltimes taken by the elastic wave to cross the structure along several directions which uniformly cover the section under investigation. The section of the masonry is marked by a mesh grid whose dimension is related to the expected resolution and to the distance between two subsequent transmission or receiving points. The calculation is carried out, in the case of sonic tests, under the hypothesis that in a non-uniform velocity field sonic impulses do not necessarily propagate along straight lines but can follow curved lines according to Snell's law.

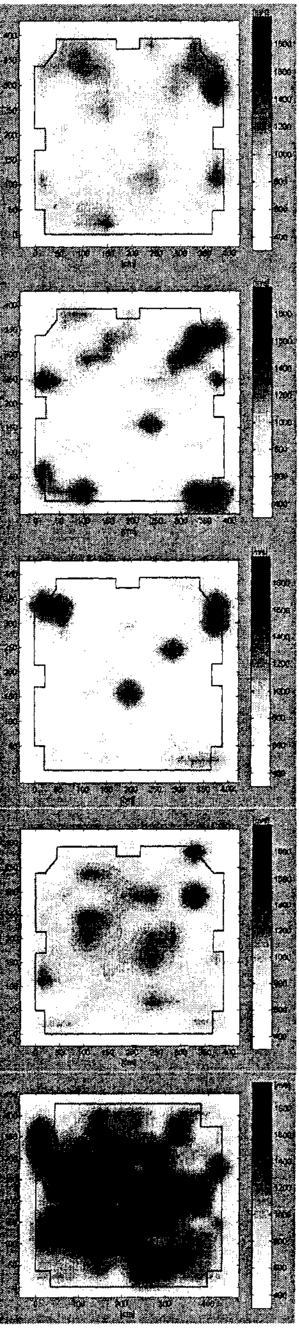
Transactions on the Built Environment vol 55, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

Because of the cost due to the acquisition time and processing complexity, a tomographic survey needs good understanding of which results can be achieved and how. In fact, the accuracy of tomography depends on many parameters: the source (sonic or electromagnetic), the number and the position of measurements, the equipment settings, the reconstruction algorithms [1], [11].
It is essential to stress that the resolution capabilities of tomography can be evaluated only taking into account the measurement locations (i.e., the angular distribution of the observations and their spatial sampling) and the physical limits related to the wavelength [12].
The result of the tomographic inversion is a map of a property of the materials. In case of travel time tomography (TT) the measured quantity is the traveltime of the signal and the map is the distribution of the propagation velocity within the object. For other types of test (e.g. radar tomography) different parameters can also be extracted, as in the case of amplitude tomography (AT) where the measured quantity is the amplitude of the signal and the resulting map is related to the distribution of the absorption coefficient [11]. Unfortunately, the extension of this technique to sonic experiment is not straightforward because the signal amplitudes are strongly influenced by the variability of the source and receiver coupling efficiency. Nevertheless, there are alternative methods that ignore the amplitudes and that are based on the frequency analysis of the data; they were experimented on different applications of seismic and ground penetrating radar [13], [14] and they are also promising for these sonic investigations.

5. Experimental and elaboration of the results

The sonic tests carried out on the S. Nicolò pillars consist of 28 tomographic sections (18 horizontal and 10 vertical) that show the velocity distribution of the elastic wave generated by an instrumented hammer in the sonic frequency band. The receiving sensors are low-cost accelerometers appropriately fixed on the walls and connected to a 24 channel digital seismograph.
The data were processed by using a dedicated software developed by the authors.
The two most damaged pillars at the entrance of the church (pillars 1 and 2 of Fig. 2) have been investigated with much care: five horizontal sections at different heights plus vertical sections have been executed on each pillar.
In Fig. 6 the sequence of the horizontal tomographies of pillar 2 are represented.
A typical distribution of the velocity on the pillars 1 and 2 shows average velocities at the base and at the top of the pillars and very low velocities in the middle. This is very clear in the vertical tomography of both pillars even if the vertical sections have a lower density of ray as shown in Fig. 7 and Fig. 8.
The very low velocities that have been found in the pillars 1 and 2 confirm the need of urgent preservation actions. From an external observation, the masonry texture seems, in fact, very poor, characterised by the presence of the so called "incoccio".
It is also worth remembering that these pillars show a dangerous crack pattern (Fig. 9). From coring of the pillars it was also clear that the internal mortar was very weak.

Transactions on the Built Environment vol 55, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509



ig. 6. Horizontal tomographies
f the pillar 2, at respectively
.9, 7.6, 4.9, 3.8, 1.8 m.

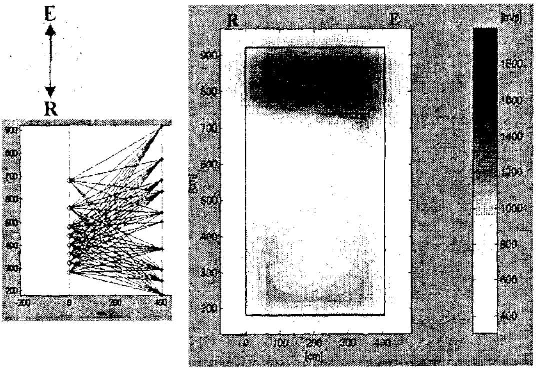


Fig. 7. Vertical tomography of the pillar 1

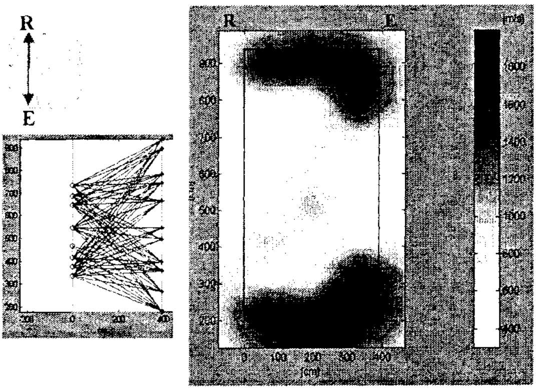


Fig. 8. Vertical tomography of the pillar 2

The other pillars that have been investigated generally present much higher velocities indicating a less alarming state of conservation (Fig. 10).

In particular the pillar 6 seems characterised by the better quality material. The observation of the masonry texture reveals a large block stonework, rather regular.

Some results on two very large pillars characterised by a complex geometry are worth of attention (pillars 9 and 12). They show higher velocities on the narrow side of the pillar and lower velocity on the large side (Fig. 11).

This trend is symmetrically observed on both the pillars and might be related to a specific construction design or to a non homogeneous state of degradation of these elements.

Transactions on the Built Environment vol 55, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

6. Feasibility study for absorption tomography

As already mentioned, amplitudes do not represent a useful information with the present acquisition technology because they are influenced by too many factors besides absorption. Instead, a different approach can be applied to extract an indication of the absorption distribution based on the frequency downshift effect. This approach has been tested on different geophysical exploration fields as borehole seismic tomography [13] and radar tomography [14]. Fig. 12 shows a selection of a few sonic traces indicating that this effect is also observed in our experiments: moving from data collected near the source to data collected far from the source the dominant components of the signal move towards lower frequencies. However, this type of data collected around a pier needs a careful pre-processing to exclude from the spectral analysis the contributions of high frequency components given by energy travelling in air.

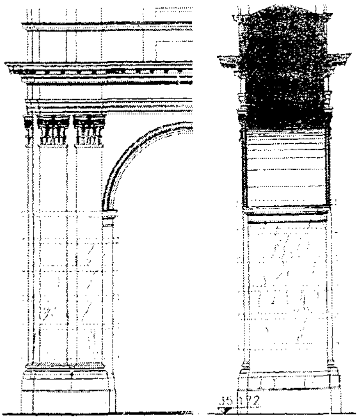


Fig. 9. Crack pattern of pillar 2.

The parameter that is normally used to measure the frequency downshift effect is the spectrum centroid. Some analysis has been done to test whether this parameter is expected to be sensitive enough to extract the downshift effect from our data. As an example, Fig. 13 shows some average spectra

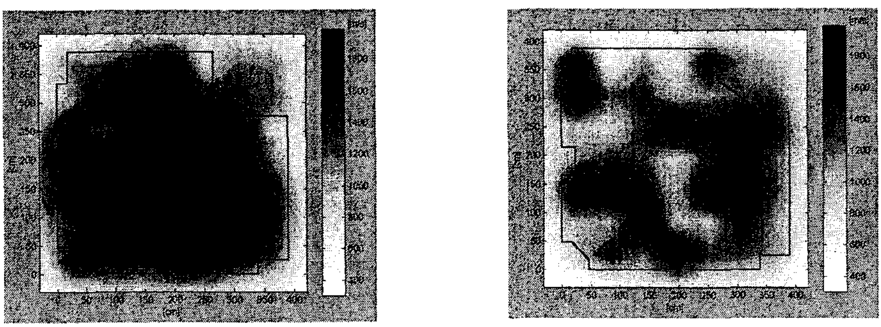


Fig. 10. Horizontal sections of pillar 6 and pillar 10 at 5.8 m.

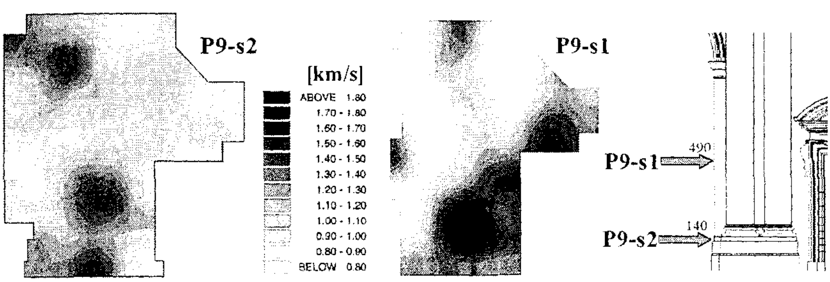


Fig. 11. Horizontal sections of pillar 9 at 1.40 and 4.90 m.

Transactions on the Built Environment vol 55, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

btained on different clusters of lata grouped according to the ange of the source-receiver listance. The data belong to a omographic experiment on a ection that was found to be quite omogeneous by the velocity nalysis and by other inspection nethods; thus, we might also xpect that the absorption roperties do not vary so much nd that the down-shift effect will e consistent with the raypath ength.

This is actually the case as the pectra and their centroids, narked by solid lines, clearly ndicate. As a consequence, the bsorption tomographies roduced by backprojecting the entroid measurements are xpected to be reliable and can e considered for the final nterpretation of all the nvestigations.

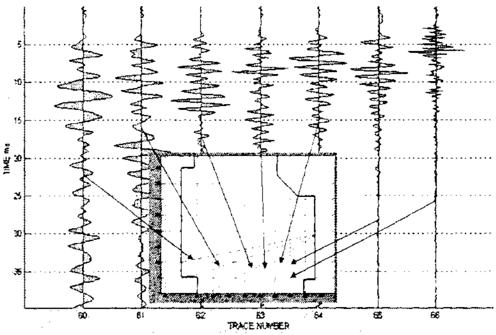


Fig. 12. Example of sonic traces.

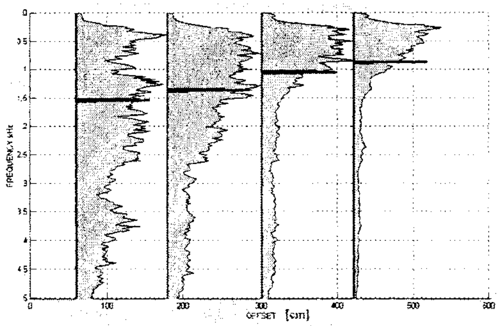


Fig. 13. Average spectra.

7. Conclusions

The results obtained from traveltime tomographies are very interesting and asically consistent with the external observations of the pillars. Anyway, being the roblem very complex due to the numerous parameters which can affect the elocity (voids, cracks, filling, etc.), these results will be compared to the ones of ther investigations applied to the pillars. In fact, the experience shows that the lifficulty of data interpretation can be partially overcome by complementary tests s flat-jack, coring and boroscopy, radar, etc. From a methodological point of view, his intensive application of the sonic tomographic method on 8 pillars of the same hurch (an approximate number of 12000 point-to-point measurements are vailable) represents a very interesting dataset that will be further studied to xplore the promising frequency down-shift methods aimed to derive the absorbing roperties of these masonries.

Acknowledgements

Authors wish to thank Arch. L. Cantini and Eng. C. Marrone, for their contribution in the xperimental work in-situ and the students S. Fraticelli, M. Perroni, S. Pirotta. Special thanks for their collaboration go to Eng. S. Cocina of the Genio Civile of Catania, and to Eng. V. Venturi of Sidercem. The research was supported by Murst - Cofin 98.

References

[1] Valle, S., Zanzi, Saisi, A., Binda, L., &. Lenzi, G. Tomography for NDT applied to masonry structures: sonic and/or EM methods, *Proc. of the Second International Arch Bridge Conference*, 6-9 October 1998, Venezia, Balkema, pp. 244-253, 1998.

[2] Valle, S., & Zanzi, L. Resolution in Radar Tomography for Wall or Pillar Inspection, *Proc. of the 6th Internat. Conf. On Ground Penetrating Radar*, Sendai, Japan, 1996.

[3] Binda, L., Saisi, A., & Tiraboschi, C. Application of sonic tests to the diagnosis of damaged and repaired structures, *Non Destructive Testing and Evaluation Int.*, Elsevier Science Ltd., Vol. 34, n. 2, Jan. 2001, pp. 123-138.

[4] Saisi, A., Valle, S., Zanzi, L., & Binda, L. Radar and Sonic as Complementary and/or Alternative Tests in the Survey of Structures, *Int. Cong. "More than Two Thousand Years in the History of Architecture Safeguarding the Structure of our Architectural Heritage Bethlehem*, (Palestine), 2001, Vol. 1, Section 1b, pp. 1-6.

[5] Aerojet General Corporation, *Investigation on sonic testing of masonry walls*, Final Report to the Dept. of General Services of Architecture and Construction, State of California, 1967.

[6] Abbaneo, S., Berra, M., Binda, L., & Fatticcioni, A. Non destructive evaluation of bricks-masonry structures: calibration of sonic wave propagation procedures, *Int. Symposium Non Destructive Testing in Civil Engineering (NDT-CE)*, Berlin, Germany, Vol. 1, 1995, pp. 253-260.

[7] Abbaneo, S., Berra, M., & Binda, L. Pulse velocity test to qualify existing masonry walls: usefullness of waveform analyses, *3rd Conf. Non Destructive Evaluation of Civil Structures and Materials*, Boulder, USA, 1996, pp.81-95.

[8] Suprenant, B., & Schuller, M. Non destructive evaluation & testing of masonry structures, reviewed and recommended by TMS, *The Aberdeen Group*, 1994, USA.

[9] Schuller, M.P., Berra, M., Atkinson, R., & Binda, L. Acoustic Tomography for Evaluation of Unreinforced Masonry, *Construction and Building Materials*, Vol. 11, N.3, pp. 199-204, 1997.

[10] Valle, S., Zanzi, L., Lenzi, G., & Bettolo, G. Structure Inspection with Radar Tomography, *Proc. of the International Colloquium "Inspection and Monitoring of the Architectural Heritage"*, IABSE-ISMES, pp. 223-230, 1997.

[11] Valle, S., Zanzi, L., & Rocca, F. Toward high resolution radar tomography, *Proc. of the 7th Int. Conf. on Ground Penetrating Radar (GPR '98)*, May 27-30, Lawrence, Kansas, USA, 1998.

[12] Valle, S. & Zanzi, L., Traveltime radar tomography for NDT on masonry and concrete structures, *European Journal of Environmental and Engineering Geophysics*, vol.2, n. 3, pp. 229-246, 1998.

[13] Quan, Y., & Harris, J.M. Seismic attenuation tomography using the frequency shift method, *Geophysics*, 62, 895-905, 1997.

[14] Liu, L., Lane, J.W., & Quan, Y. Radar attenuation tomography using the centroid frequency downshift method, *Jour. of Applied Geophysics*, 40, pp. 105-116, 1998.