DIAGNOSTIC INVESTIGATION OF THE STONE PILLARS OF S. NICOLO' L'ARENA, CATANIA

A. Saisi [1], L. Binda [1], L. Zanzi [2]

ABSTRACT

The church of S. Nicolò L'Arena in Catania built in the 17th century has been subjected to various important damages due to earthquakes and the Etna volcano eruption. It has a large dome and vaults supported by very massive stone pillars. The church was partially rebuilt after the above mentioned damages. 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 pillar have a highly inhomogeneous section with a mixture of large irregularly cut stones and rubble material. The other pillars 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 restoration actions.

Very interesting information were expected by stratigraphy of the section by coring, flat jack tests and sonic tomography; also radar tests were applied. Sonic tomography is a powerful method to obtain information on the conditions of a structural element. In general, the velocity distribution is an indication of the elastic properties of the element.

The results obtained from sonic tests were compared to the results of the other type of tests in order to set up an investigation procedure useful for these cases. The paper presents and discusses the preliminary results of the research carried out by the authors.

Key words: diagnosis, non destructive testing, sonic test, tomography, flat jack

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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 material; in a homogeneous solid, velocity variation indicates variation in elastic properties of the element.

When a structural element can be accessed from all the sides as in the case of the pillars of churches, the indication can be more precise 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 (Valle, 1996), (Valle, 1998b), (Binda, 2001), (Saisi, 2001). In the following an experience is presented of the application of sonic tomography on the pillars of a Church in Sicily, S. Nicolò l'Arena in Catania, damaged by the last earthquake.

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.

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. 1 and 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

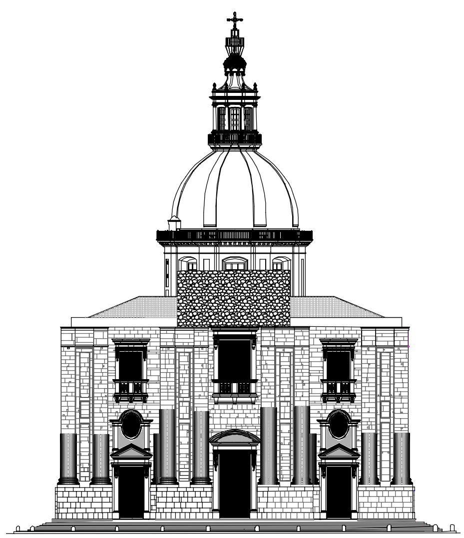


Figure 1. S. Nicolò Church. View of the facade.

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 has been recently planned to design the preservation and restoration actions.

Very interesting information were expected by stratigraphy of the pillar section by coring, material characterisation, flat jack tests and sonic tomography.

The masonry texture appears characterised by two different typologies: (i) a solid stonework built by large and regular blocks and filled with rubble masonry made with rather strong mortar; (ii) a highly inhomogeneous stone masonry surrounded by a cover more than 300 mm thick, made with tile fragments, stones and rather weak mortar, locally called "incoccio" (Figs. 3a and 3b). Often the two typologies are present in the same structural element (Fig. 4). Apparently the second one was used as repair technique (Fig. 5).

Fig. 6 shows a segment of core drilled from pillar 2. As it is possible to observe, the mortar inside the pillar 2, at the height of 6.40 m, is very compact. As known, the coring inside the masonry usually does not allow the extraction of consisting samples, especially of mortar, being the operation very invasive due to the fact that the sample is drilled wet.

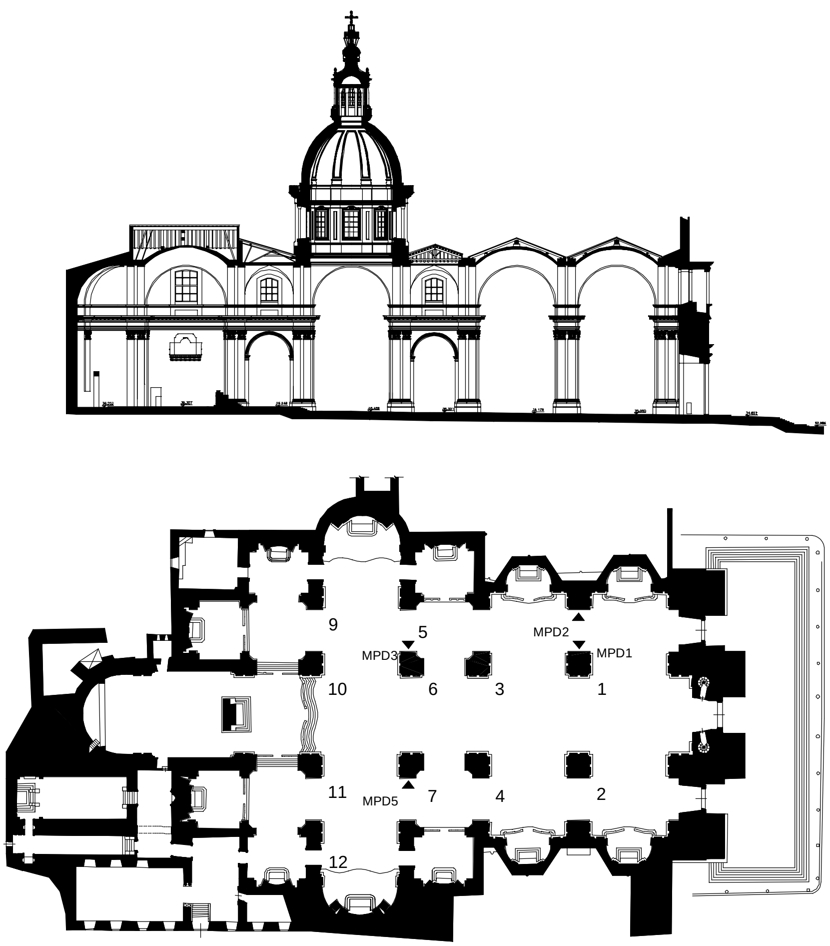
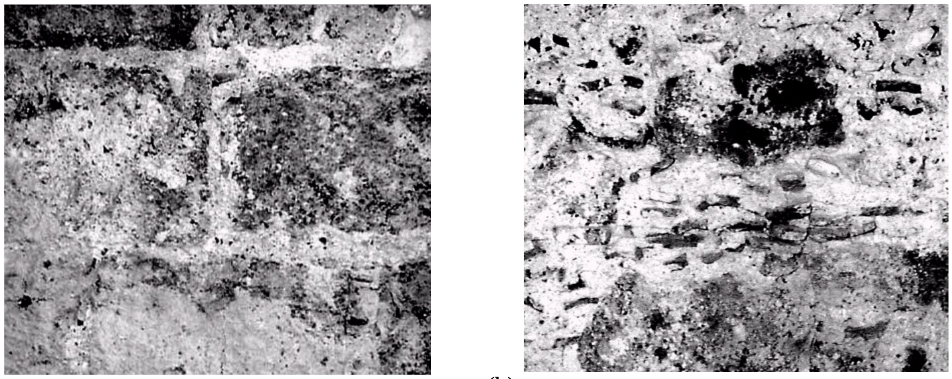


Figure 2. Localisation of the tested piers.



(a) (b)

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

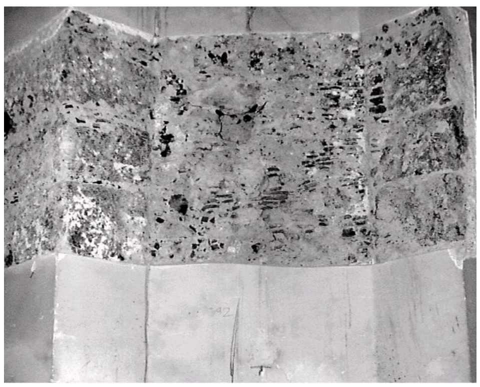


Figure 4. Regular stones and "incoccio".

Figure 5. "Incoccio" probably used to widen the section of the pillars.

Even if the core drilling is usually intended to be slightly destructive and therefore used in numerous points, the limit of drilling is due to the fact that it spoils the materials (especially mortars). It gives only a stratigraphy of the wall interior and therefore it does not allow the reconstruction of the wall section.

In this case, the optimal mechanic characteristic of the mortar enabled the extraction of a coherent core of the masonry.

The mortar sampled from the "incoccio" of the pillar 1 is exemplified in Fig.7. The material, completely different on respect to the ones sampled inside the pillars, appears very weak and incoherent.

Chemical and petrographic analyses carried out on the two mortars show that the "incoccio" mortar is an air lime mortar, while the other can be defined hydraulic. The hydraulicity of the mortars sampled by coring inside the pillars 3, 4 and 6, is revealed, in fact, examining the high levels of soluble silica find in the chemical analysis. They can be caused by the presence of pozzolanic aggregates chemically reacting with the hydrated lime.

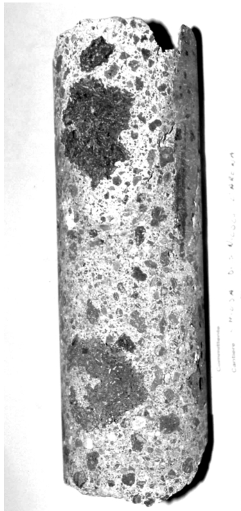


Figure 6. Core drilled inside pillar 2 at 6.40 m of height

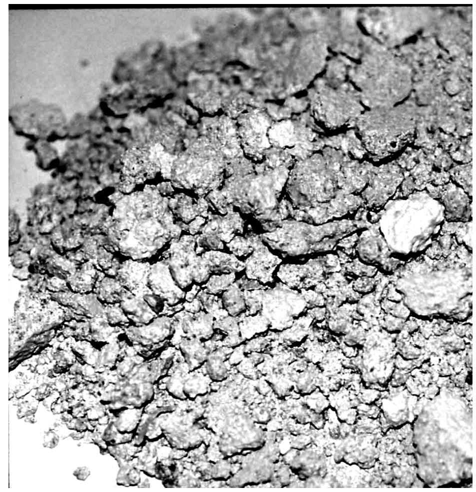


Figure 7. Consistence of the mortar sampled from "incoccio" in pillar 1.

PRINCIPLES OF THE PULSE SONIC TEST

Among the ND investigation methods, the sonic methods are with no doubt, the most widely used. The testing technique is based on the generation of sonic or ultrasonic impulses at a point of the structure. A signal is generated by a percussion 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 (Aerojet, 1967). 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 (Abbaneo, 1995), (Abbaneo, 1996).
The limitation given by ultrasonic tests in the case of highly inhomogeneous material, as irregular stone masonry, made the sonic pulse velocity tests more appealing for masonry. 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. The frequency and energy content of the input pulse are governed by the characteristics of the hammer (Suprenant, 1996). Signals are stored by a waveform analyser coupled with a computer for further processing.

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 plaster layering). 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.

SONIC TOMOGRAPHY

Among the ND applications the tomographic technique is quite attractive for the high resolution that can be obtained (Schuller, 1997), (Valle, 1997), (Valle, 1998b).

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 can 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.
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 (Valle, 1998a), (Valle, 1998b).
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 (Valle, 1998c).

ON SITE INVESTIGATION

After the 1990 earthquake, apart form the previously mentioned damage to arches and vaults, the most dangerous situation seemed to interest pillars 1 and 2, which were showing vertical cracks.
They were therefore provisionally confined with thick steel tie beams and then subjected to on site and laboratory investigation, then extended to all the pillars.
Geometrical and crack-pattern surveys were carried out (Fig. 8 and 9), followed by several drilling of core in order to study the stratigraphy of the masonry and see, through the use of boroscopy, the presence of cracks and voids.
Unfortunately drilling of core is a very local investigation and boroscopy does not allow to see so much.
So flat jack tests, in order to measure the state of stress and the stress-strain behaviour, were also carried out. Finally, in order to have a more general view of the state of damage sonic tomography was performed.

Flat jack results

Flat-jack tests are carried out to measure the value of the local vertical compressive stress and the stress-strain behaviour of the material.

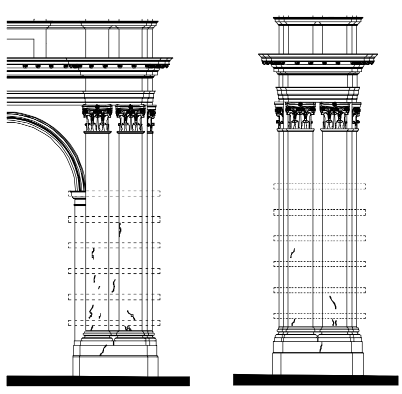


Figure 8. Crack pattern of pillar 1.

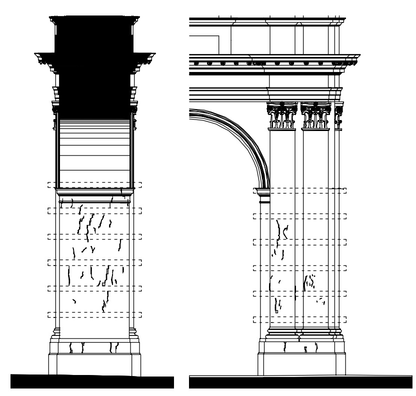


Figure 9. Crack pattern of pillar 2.

Several single flat-jack tests were carried out on the pillars and the detected values seem to show an irregular distribution of stresses.
The highest values seemed to be particularly dangerous, taking into account the strength values detected by double flat jack. As known, (Rossi, 1982), (Binda, 1999) double flat-jack tests are carried out in order to check the mechanical behaviour of the masonry under compression.
Pillars 1, 6, 7 and a portion of the perimeter wall (Fig. 2), which is structurally a built-in pillar, were investigated. The used flat jacks have the unusual dimension of 625x255x4 mm. This was suggested by the characteristic masonry texture, observed after the plaster removal. The strains were measured by 8 LVDT, 6 placed vertically and 2 horizontally.
The tests carried out on the pillars 6 and 7 gave similar results. The pillars, in fact, were supposed to be built with the same construction technique and, then, to have similar mechanic properties.
Fig. 10 and 11 show the masonry texture, the flat jacks position, the measurements tools and the stress-strain plots from double flat-jack test. The stress strain diagrams (Fig. 12 and 13) demonstrate the good characteristics of the pillars in terms of compressive strength and elastic properties.
The texture of the pillar 1 is shown in Fig. 14, where the incoccio presence is clearly recognisable. Such masonry, built by tiles, small stone and weak mortar, is present in the tested portion of the perimeter pillar, as well as probably in larger surface (Fig. 15).

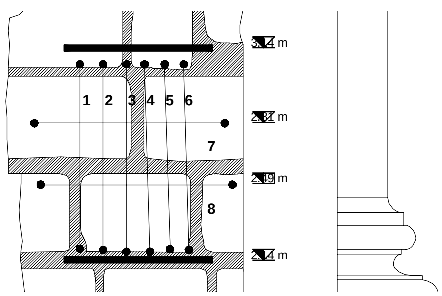


Figure 10. Masonry texture and localisation of the test MPD5 on pillar (Fig. 2).

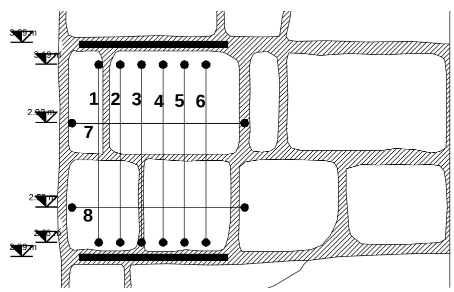


Figure 11. Masonry texture and localisation of the test MPD3 on pillar (Fig. 2).

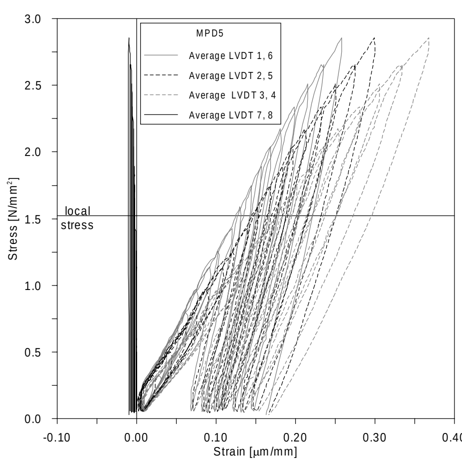


Figure 12. Stress strain curve of test MPD5.

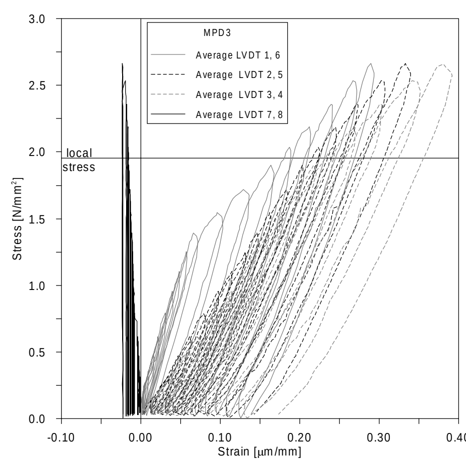
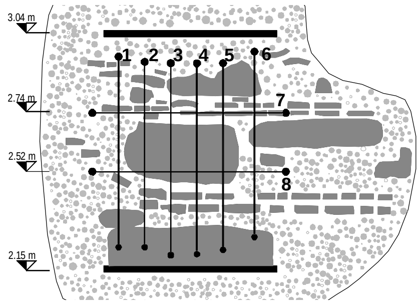


Figure 13. Stress strain curve of test MPD3.



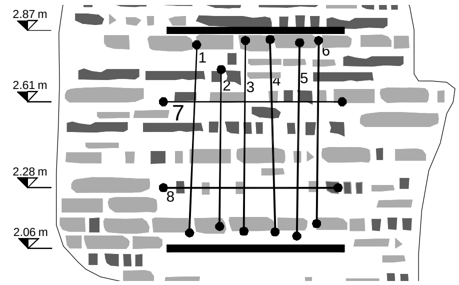
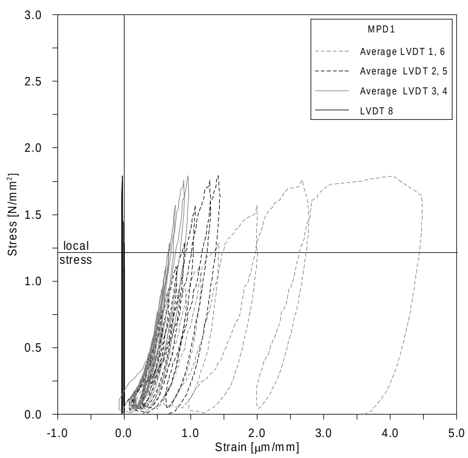


Figure 14. Masonry texture and localisation of the test MPD1 on pillar 1 (Fig. 2).

Figure 15. Masonry texture and localisation of the test MPD2 (Fig. 2).



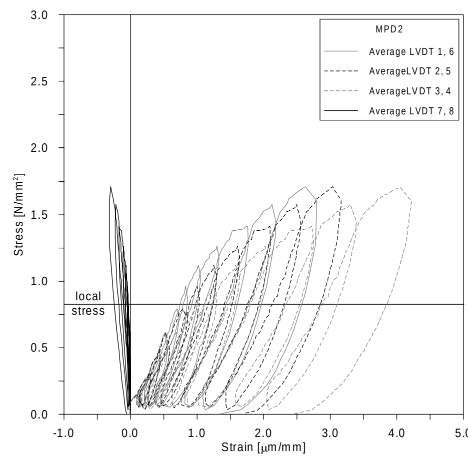


Figure 16. Stress strain curve of test MPD1

Figure 17. Stress strain curve of test MPD2

The double flat jack results seem very different from the ones obtained previously (Fig. 16 and 17). First of all, the deformation is about 10 times the one of the other tested pillar for much lower stress values. Furthermore Fig. 14 shows clearly why the measured values are so much different. This is due to the high inhomogeneity of the masonry.

This comparison between the two series of data enhances the different mechanical behaviour of the two characteristic masonries of the Church.

Nevertheless these data cannot give information of the behaviour of the internal leaves of the pillars. Nevertheless, they can be considered an important further information on the pillars situation and behaviour.

<u>Experimental results and elaboration of the sonic tomography</u>

The sonic tests carried out on the S. Nicolò pillars produced 28 tomographic sections (18 horizontal and 10 vertical). They 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. 18 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 relatively high at the base and at the top of the pillars and very low velocities in the middle. This situation 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. 19 and Fig. 20.
The very low velocities that have been found in the pillars 1 and 2 and the fact that these pillars show a dangerous crack pattern (Fig. 8 and 9), confirm the need of urgent preservation actions. From an external observation, the masonry texture seems, in fact,

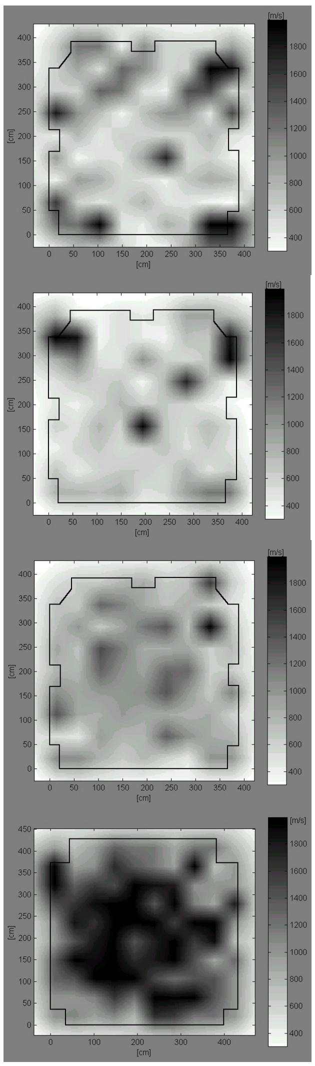


Figure 18. Horizontal tomographies of the pillar 2, at 8.9, 7.6, 4.9, 3.8, 1.8 m.

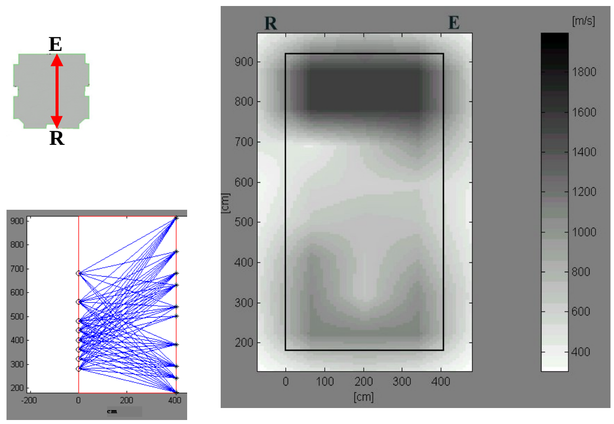


Figure 19. Vertical tomography of the pillar 1

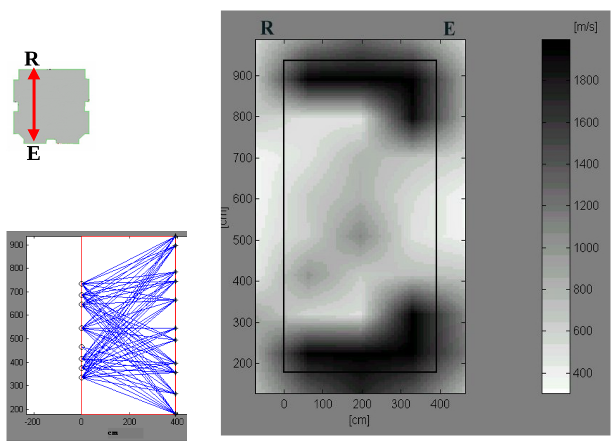


Figure 20. Vertical tomography of the pillar 2

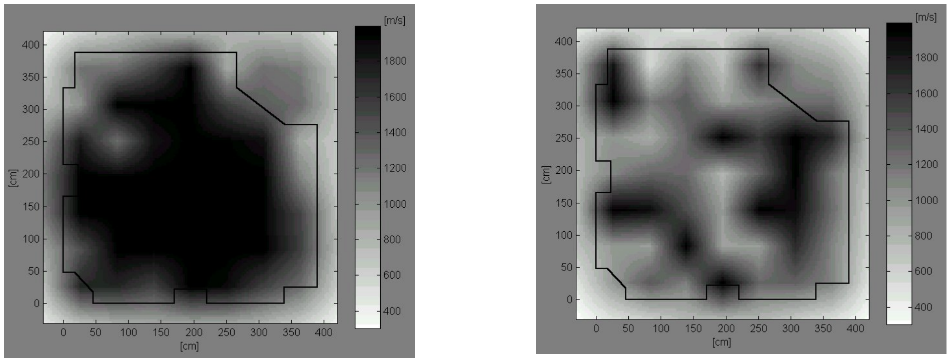


Figure 21. Horizontal sections of pillar 6 and pillar 10 at 5.8 m.

very poor, characterised by the presence of the so called "incoccio".
From coring of the pillars it was also clear that the internal mortar is very weak.
The other pillars that have been investigated generally present much higher velocities indicating a less alarming state of conservation (Fig. 21).
In particular the pillar 6 seems characterised by a better quality material. The observation of the masonry texture reveals a large block stonework, rather regular, as external leaf.

CONCLUSIONS

The investigations carried out on the S. Nicolò Church allowed understanding the behaviour of the materials and the structures of the masonry, by recognising the presence of different building techniques.
The characteristic of the two masonry typologies was controlled by double flat jack tests, which clearly revealed the completely different mechanical behaviour. This parameter is of primary importance in the numerical structure modelling for the safety control.
Furthermore, the results obtained from traveltime tomographies are very interesting and basically consistent with the external observations of the pillars.
Anyway, being the problem very complex due to the numerous parameters which can affect the velocity (voids, cracks, filling, etc.), these results will be compared to the ones of other investigations applied to the pillars.
In fact, the experience shows that the difficulty of data interpretation can be partially overcome by complementary tests as flat-jack, coring and boroscopy, radar, etc.
From a methodological point of view, this intensive application of the sonic tomographic method on 8 pillars of the same church (an approximate number of 12000 point-to-point measurements are available) represents a very interesting dataset that will be further studied to explore some promising methods based on spectral analysis aimed to derive the absorbing properties of these masonries.

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