Radar tests were carried out on a stone masonry pier of a damaged Cathedral in Noto, Southern Italy. Radar data were collected and processed to obtain a tomographic image of a section of the pier. The aim was to obtain information regarding the material conditions. From the data plot followed also an interpretation of the moisture distribution in this structural element with rubble core. Modalities for a correct planning of the tomographic data collection procedure, and an accurate data analysis and interpretation are also discussed.

Einleitung

On 13th March 1996 the piers of the right hand side of the central nave of the Cathedral of Noto, in Sicily, Italy, failed causing the collapse of the roof and vaults and of most of the dome. On the remains of the Cathedral, a diagnostic study was carried out prior to undertaking the project of repair and strengthening of this historical masonry structure. The study was aimed at defining the state of damage of the building materials and structure. The diagnosis should be the result of a structural analysis based on appropriate mathematical models, and of experimental investigations on site and in the laboratory. The investigations on site must be non destructive to the possible extent but give precise information.

Non-Destructive Testing (NDT) techniques can assume an important role in the diagnosis process but when dealing with historic structures their employ has to be particularly careful. In these structures the definition of “masonry wall” can include many types of wall (brick, stone, multiple-leaf, cavity wall, etc.). and it should not be forgotten that all techniques need to be calibrated on the specific structure they are being applied to. Furthermore, preliminary investigations have to be carried out in order to characterise the different materials and to formulate preliminary hypotheses on the structural behaviour. At the present state of use, NDT techniques are
complementary, therefore they should be used together if possible, not as alternatives. Nevertheless research and development in this field is progressing fast and confidence in their use is gradually increasing.

On this specific structure a number of diagnostic techniques have been applied, including sub-surface radar on load bearing structural elements. In the following it is presented an experience of use of radar tomographic tests on one of the main piers (pier P1E) of the Cathedral, which was damaged during the partial collapse of the building and remained since exposed to the weather conditions (Fig. 1). The pier tested was one of the four supporting the dome and the transept vaults; the right one (PE) collapsed almost totally.

Abb. 1: Map view of the cathedral with location of the tested pier.

The aim of the diagnosis research was to verify the state of damage and/or conservation of the walls and piers in view of the reconstruction of the missing parts of the Cathedral. Radar tests were applied to detect the wall type and possibly its conditions. The piers, built according to a typical technique of Noto, are characterised by an external leaf 30 to 40 cm thick and made of regular calcarenite blocks. The internal leaf consists of rubble masonry characterised by irregular courses of round river stones at the base and smaller pieces of calcarenite and travertine up to the top, alternated with weak mortars (Figure 2). Because of their characteristics and of the overall dimensions of the building, the piers have considerable mass and in plan they reach nearly 6 m length by over 3 m width.

Abb. 2: Detail of excavated pier section.

Radar Tomography

Radar tomography measurements aim to localise the presence of inner defects or inhomogeneities in the element under investigation from measurements points located on the outside surface. This is done by indirectly mapping the variation of
material dielectric properties: variations in signal behaviour are due to the dielectric properties of the materials crossed and the number of interfaces encountered. By plotting the distribution of EM wave velocity or the amplitude of the received signal, a travel time or an attenuation tomographic image is obtained.

The tomographic technique involves the use of (at least) a transmitter and a receiver positioned on opposite sides of the structure and moved in a series of possible combinations to obtain partial maps of the same cross section of the structure. From the elaboration of these partially overlapping scans, one property of the signal – for example the wave velocity – is plotted across the section. Local variations of dielectric constant or material characteristics may so be identified and related to engineering features/defects of the structure.

Figure 3 shows the section coverage obtainable with a single tomographic scanning of the structure. The situation depicted in (a) is the most widely used in radar tomography and the most recommendable since the angle of the paths connecting transmitter and receiver gives rise to better location and resolution of anomalies at the inversion imaging stage. Usually the survey with this antennae configuration is repeated a number of times with the receiver moving in discrete steps along the same direction of movement as the transmitter. The survey stops when a satisfactory coverage of the section area has been achieved. Ideally a combination of surveys (a) and (b) should be performed. Case (b) gives a complete cover of the section area but because of the direction of direct propagation of the ‘first arriving’ signal the data obtained will locate the presence of the anomaly but will not resolve its time/depth position. The consequence of this, is poor vertical resolution. The problem is made more grave by the shifting of the zero position of the radar signal along the time axis when the antenna is coupled to the material (and because of imperfect radar systems). This instability of the zero time will affect tomography readings especially and parallel readings as in situation (b) in particular. Better results are obtained when combinations of case (b) with (a) or (c) are used.

Another aspect to be considered is the density and regularity of the reading stations on the outside of the element: it is advisable to have simmetrical number and position of stations on the transmitting and receiving sides of the element. Nevertheless the spacing between the stations on each side of the section is not required to be constant: it is preferable to select a station spacing that will produce in the inside of the section a homogeneous density of ideal straight ray paths connecting transmitting and receiving antenna positions. The advantage would be a considerable reduction in „edge“ and „corner“ effects in the tomographic image, with a more realistic resolution of the section characteristics.

Furthermore, the angular orientation of the path between transmitter and receiver has to be considered: this needs to be not excessive or the resolution of the received waveform will be affected. In fact the signal propagating laterally from the cone of emission of the antenna is characterised by lower energy. Therefore it will lose quickly high frequency components resulting in a longer wavelength.

In travel time tomography a series of partial time domain maps of the section are obtained. It is so possible to measure the time taken by an impulse to transmit through the structure. The radar signal velocity will be higher when travelling across highly porous dry material, with the highest velocity registered when travelling in air (0.3 m/ns). The radar plots will register shorter arrival times of the received signal when the wave has travelled at higher speed (fig. 4). Time variations must be sudden but variations > 10 or 20 % may indicate scattering or clutter problems. In the
tomographic inversion an image is built up by an iterative process, where velocity through the various materials is mapped in a cross-sectional representation related to material properties (primarily dielectric constant and conductivity). Voids, defects and other features are so located. One of the advantages of using radar for tomography is the possibility of continuous data reading which makes the survey much faster than when performing stepped tomography like in the case of sonic tomography.

Abb. 3: Section coverage obtainable with a single tomographic scanning of the structure: a) transmitting antenna (T) scans while receiver (R) is stationary; b) both antennae move in parallel; c) stationary transmitter and mobile receiver.

Abb. 4: In a) sketch of section with air void; b) representation of signal arrival time: shorter time in correspondence of the air void.

Data collection planning

The location of the test lines that will define the tomographic section should be selected to be representative of the masonry and of the problems to investigate. Subsequently the spacing between the tomographic reading stations has to keep into account the overall dimensions of the section (depth and height) and the resolution expected.

The first step is to carry out some measures in transmission to verify if the emitted signal is powerful enough to reach the opposite side of the wall (from the received signal it will then be possible to calculate the travel time through the section). From these calibrations on the structure, it will follow the choice of antenna frequency to be used. This will be a compromise between the accuracy of the measurements and the penetration depth to be achieved (the lower the frequency, the better is the penetration but the poorer the resolution and vice versa). This relationship is not constant and depends on the material characteristics and the presence of humidity.
In fact, moisture affects the conductivity of the materials and this may decrease the wave velocity besides increasing its attenuation.

**Experimentals**

After several reflection trials with 500 MHz antenna failed in providing data from the core of the pier - the signal lacked the penetration energy required to cross twice the thick pier sections -, transmission mode data collection for tomographic elaboration was considered. The aim of this radar work was to build up some kind of picture about the internal geometry of the pier and/or to investigate the amount of moisture content that may have penetrated the structure. These factors may have had an influence on the collapse mechanism of the piers and on its present state of conservation.

As regarding the tomographic work, the first action was to choose an appropriate antenna frequency. High frequency offers more accurate resolution, in terms of calculated travel time between transmitter and receiver. In the case of the vertical section through the standing pier, the 900 MHz antennae did not have enough penetration energy to pass through the pier section along the longest wave paths. This was caused by the pier dimensions and by the dielectric properties of its materials. Several vertical sections were considered for tomography and the wave propagation tested at various levels of height on the pier. A section running from East to West on the pier's longest axis would have been desirable, because it would have provided the largest cross section and therefore a more representative one.

Preliminary scans on the pier determined that this would not be possible as the 500 MHz antenna signal was not capable of penetrating that thickness. Various shorter sections running North to South through the pier were then considered. Finally, because of heavy metal scaffolding present for static reasons around the pier, the longest section in this direction was chosen (3.125-m thick). Transmitting and receiving stations were then carefully marked on the pier. Thirty eight stations at 0.1 m intervals on each side were decided upon, ranging from 4.5 m up the pier down to a level of 0.8 m above the floor of the cathedral. Below this point, through the thicker base of the pier, the receiving antenna could not detect the radar signal.

For measurement collection, the transmitter was first placed on the North face of the pier at the highest position (station 45) 4.5 m above the floor. With the receiver on the South wall moving downwards, measurements were taken from every receiving position from 45 to 8. This process was then repeated with the transmitter in station 44, and then again at every other transmitting station. (Fig. 5). The rays coverage through the vertical section of the pier is shown in fig. 6. The data were acquired with a GSSI SIR10 system, using 500 MHz antennae along the vertical section depicted on the pier in figure 7.

**Data elaboration and interpretation**

The wave travel times from the complete set of data collected along the section on the pier was inputted in a tomographic program using a SIRT algorithm. These, together with the spatial coordinates of transmitting and receiving stations, were elaborated to obtain the tomographic output plots.

From a first elaboration of the data (fig. 8) it is already possible to note the general trend of velocities in the structure, which are increasing with vertical distance up the pier. Also noticeable is that on the left and right of the image the velocities are generally different from the core of the pier. What is known from the collapsed pier is
that the external masonry leaf is made of regular stones and these will present a density different from the material used for the core. Visible on the plot is also a faint cross of lower velocity departing from the corners of the image and meeting in its centre. These "corner effects" are partially due to the density of the ray coverage (fig. 6) which leaves the top and bottom sides of the section relatively badly covered by the rays in the middle. This reduces the information accuracy for those regions and exaggerates the visible difference of areas of high and low velocity.

Abb. 5: The radar tomography method employed on the standing pier for the vertical section.

Abb. 6: Ray coverage obtained.

Abb. 7: Front view of the pier from South direction (from the main nave) and location of the vertical tomographic section.

By reducing the aperture of the fan between transmitter and receiving positions, the very angulated readings are discarded and the image shown in figure 9 is obtained. The advantage of this process is also that the ray density is more homogeneous and
the corner effects are greatly removed. The areas with velocity distinction are better defined with the highest velocity in the top 2/3 of the section and areas of constant velocity down the left and right hand side where the sandstone layer is. Overall this portion of the pier appears homogeneous, with only local anomalies of slightly higher velocity on the right side.

A further distinction in the velocity distribution is running approximately horizontally at 1.6 m level, with considerably lower velocities below this line. This was attributed to the moisture content in the materials and was investigated further.

Abb. 8: EM wave velocity in the pier. Abb. 9: Corrected EM velocity

Once the wave travel time had been calculated for each transmitter/receiver combination, the time for each ray path connecting horizontally transmitting and receiving antenna was extrapolated to obtain an averaged velocity profile across the pier. The graph in figure 10 clearly shows a significant difference in travel times between the top and bottom stations, which can be caused by the distribution of moisture within the pier. In particular, for heights up to approximately 1.7 m, the greater time values denote a distinct variation in wave velocity. The lower velocities can be explained by high conductivity in the materials when a high water content is present.

Abb. 10: Horizontal Travel Time variation with pier height.

The combination of high material conductivity and low frequency signal, such as in this case, would cause the wave velocity to drop significantly. The moisture in the lower part of the pier would be due to capillary suction from the foundations. Other variations in the travel time in higher sections of the pier can be attributed to small
inhomogeneities in the pier (for example areas where the materials present variations in density) other than to moisture content variations. These considerations were confirmed by reflection plots acquired along the same survey lines used for the tomography: the echo data consistently show a greater attenuation of the signal in the lower part of the masonry element, with weak reflections from the local interfaces.

Conclusions

Because of the costs due to acquisition time and data elaboration, a tomographic survey needs good understanding of which results can be achieved and how. The accuracy of resolution of radar tomography is heavily influenced by many parameters including the source used (antenna frequency), the number and the position of the reading stations and the reconstruction algorithm, besides the complexity of the element tested (geometry and materials).

It is important to stress that the outcome of tomographic elaborations also depends on the experience of the user in data collection and preparation (i.e. in recognising and eliminating spurious data or observations with excessive angular distribution, in recognising edge or corner effects on the plots, in the kind and number of elaborations performed) and in a careful interpretation of the results.

From this study it was concluded that radar is a useful tool to qualify the internal section of a structure and to detect the moisture capillary rise level within a structure.

Acknowledgements

Authors wish to thank Prof. Michael Forde, Edinburgh University, UK, for the availability of the equipment, and exchange students, S. Oliver and E. Walsh for the radar acquisitions. Acknowledgements go also to the colleagues and students in Milan who have contributed to this work.

References


