Location of Voids in Masonry Structures by Using Radar and Ultrasonic Traveltime Tomography

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Abstract. For the location and quantification of voids and of larger deteriorated areas in masonry structures, radar and ultrasonic tomography were applied systematically as complementary methods. The impulses were mainly recorded in transmission configuration. The traveltime of the first time of arrival was picked manually as well as automatically and was used for tomographic data inversion. The results of the inversion of experimental data and of data obtained from numerical modelling are compared. By using different transducers and transducer configurations, the advantages and limits of radar and ultrasonic tomography are described.

1 Introduction

Although the internal structure of historic masonry is usually very inhomogeneous, the current approach normally used to assess structural safety and/or physical damages on historic masonry buildings mainly includes manual optical inspection, laboratory tests on cored samples and load carrying tests. For getting more information about the internal condition in order to preserve the building and to avoid disturbing the state of stress and strain of the structure, on-site applicable non-destructive procedures and investigation techniques are highly needed.

Recent results from the European Research Project *On-site investigation techniques for the structural evaluation of historic masonry buildings* (ONSITEFORMASONRY) have shown that radar (**G**round **P**enetrating **R**adar - GPR) as well as acoustic methods are very well suited to detecting structural inhomogeneities in brick and stone masonry [1]. The main objectives of this project were the development and improvement of methodologies for the evaluation of the structure of historic masonry, to enable owners and end-users of Cultural Heritages to recognise structural problems and to find appropriate solutions to solve them.

In the past, successful radar investigations have been carried out by executing 2D and 3D profiles in echo configuration (i. e. transmitter and receiver antenna were on the same side of the building structure) [2], [3], [4], [5], [6], [7]. All these investigations demonstrate that with the conventional impulse-echo configuration, information can be obtained about thickness, number of layers and the position of detachments, voids and metal inclusions. But in most cases, the quantification of moisture distribution as well as the determination of 3D dimension of larger voids failed due to missing information. Up to now, only in a few cases radar investigation on masonry structures were performed in tomographic configuration [8], [9]. Valle and Zanzi [10], [11] have explored the potential of the technique and the reliability of the possible inversion procedures. But still radar tomography cannot be considered as a standard method for non-destructive testing of historic buildings.

The difficulty of interpretation of **ultrasonic** results in the case of inhomogeneous materials like masonry was always known and the first results can be regarded as qualitative rather than quantitative values. Several efforts have been made in order to calibrate the test procedure and to interpreting the data gained from sonic and ultrasonic tests [13], [14], [15], [16], [17], [18]. The ultrasonic transmission- and echo-method in combination with tomographic evaluation is widely used for metals in the frequency range higher than 1 MHz [19]. In the low frequency range the application is more difficult because of the broad radiation characteristic of the transducers. Nevertheless tomographic calculations have already been successfully performed on masonry. One example is described in [20] for a historical bridge made from natural stone masonry, where deteriorated areas were localised (ultrasonic frequency: 20 kHz). In marble elements the localisation of horizontal cracks and cavities is possible with only a few number of transducer locations [21] (ultrasonic frequency: 70 kHz).

The aim of the presented study was a systematic investigation at different test specimen for optimising measurement configurations and for the determination of the limits of radar and ultrasonic tomography. Efficient tools for data pre-processing and tomographic data reconstruction were tested. Numerical data, radar data and ultrasonic data were compared and the advantages of merging radar and ultrasonic data were analysed.

2 Equipment and Test Specimen

The results presented here were recorded with radar antennas and ultrasonic transducers by manual positioning of the sensors. For the future, it is planned to apply an automated **scanner system** using numerous transducers controlled by an electronic switch. Automatic scanners were already successfully applied for the investigation of concrete bridges [22]. This will significantly shorten the measuring time and will make measurements easier for the operator. An open question is still the adapted fixing of transducer arrays at surfaces of historical buildings and architectural monuments

2.1 Radar Equipment

For the radar investigations presented here, the commercial SIR 10A and SIR 20 radar systems from GSSI (USA) were used. The bow tie antennas from the same manufacturer having nominal frequencies of 900 MHz and 1.5 GHz were applied. For the recording of the antenna position, a survey wheel or a marker were used. In the European research Project ONSITEFORMASONRY, some results were compared with the commercial RAMAC system from MALA (Sweden) with a new developed high frequency antenna working at 1.7 GHz and a prototype positioning system based upon the principle of a retractable string and an angular encoder.

2.2 Ultrasonic Equipment

At present the laboratory system for ultrasonic tomography consists mainly of commercially available system components [24]. These are combined for the experiments to meet the given requirements. The main components are:

- Transducers SO202 from the Russian Manufacturer ACSYS within a frequency of 25 kHz

- waveform generator as trigger and a rectangular or programmable waveform generator including an amplifier for excitation of the transducers. Here, a rectangular pulse form with a duration of 40 µs and a repetition frequency of 20 Hz was applied
- pre-amplifier at the receiver side
- processing and measuring computer

2.3 Test Specimen

For systematic investigations of the influence of larger voids, first specimens made of solid brickwork with completely filled joints were needed. Although it is well known that real masonry structures do not consist of completely filled joints, it was tried to construct masonry specimens as homogeneous as possible consisting of filled joints, full brick an defined large air voids to reconstruct and comprehend the propagation of acoustic and electromagnetic waves under optimum defined conditions. Therefore the already existing large masonry test specimen "W2" and a newly constructed specimen "Asterix I" were chosen.

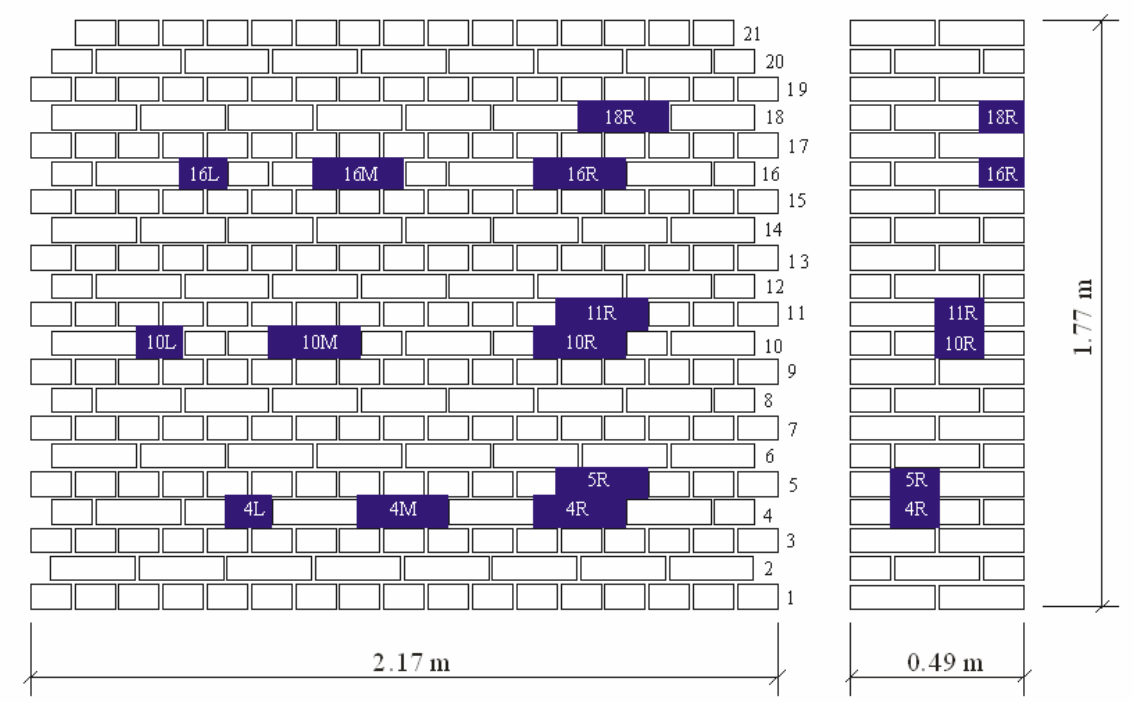

Figure 1: Front view and cross section of the masonry test specimen W2 showing the position and size of voids (missing bricks).

The specimen "W2" was chosen as representing a large wall which is only accessible from two opposite sides. This specimen has a height of 2.0 m, a length of 2.25 m and a thickness of 0.49 m and was constructed from solid brickwork with completely filled joints. During construction, larger air voids were simulated by skipping bricks or part of it at three different depths. These air voids have sizes of 6 cm x 11 cm x 12 cm (half of a brick), 6 cm x 11 cm x 24 cm (one full brick) and 12 cm x 11 cm x 24 cm (two full bricks). The voids of W2 are located in depths of 12 cm (line 4 and 5), 24 cm (line 10 and 11) and 36 cm (line 16 and 18) from the testing surface. **Figure 1** shows the exact position of the voids.

“Asterix I” is a result of learning from testing problems. The testing issues consists of four different sizes of air voids to find out the limits of ultrasonic and radar tomography. “Asterix I” is build like a column. That means that measurements can be carried out from four sides providing more information on the internal section. The specimen “Asterix I” (**Figure 2**) has a height of 1.5 m, a length of 1.01 m and a thickness of 0.76 m. The solid brickwork with completely filled joints was constructed containing three different sized air voids. The dimension of the largest void is 27 cm x 27 cm x 62 cm, of the middle sized void 14 cm x 14 cm x 28 cm and the smallest void has a size of 6 cm x 6 cm x 28 cm.

The comparison of the results from W2 and Asterix I enables to find out the lack of information by measuring only from two sides instead of four.

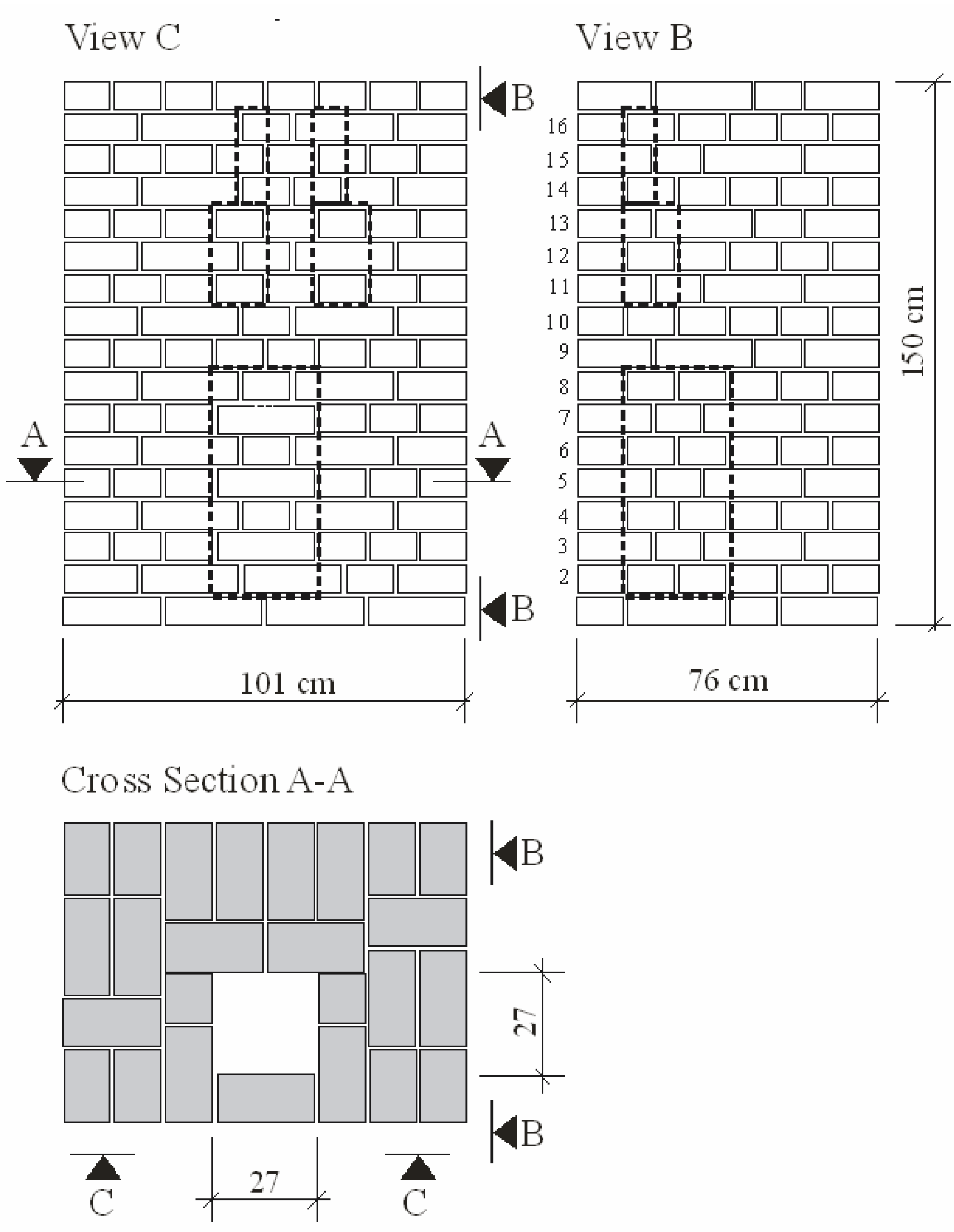

Figure 2: View B and C and cross section A-A of the masonry test specimen “Asterix I” showing the position and size of voids

3 Recording of theoretical and experimental data

3.1 Numerical Simulation

For testing the reliability of experimental data, numerical simulations with acoustic and electromagnetic waves were performed along selected cross sections of the test specimens by using the simulation tool of REFLEX [32].

a)

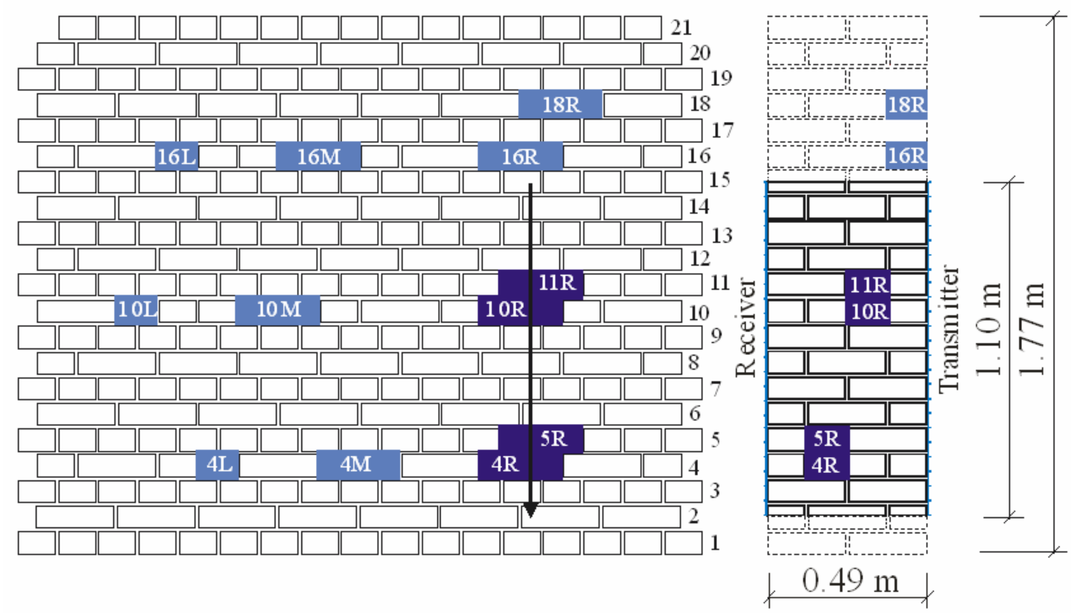

Figure 3: Front view and cross section of investigated area in test specimen W2

In **Figure 3** the section selected from test specimen W2 is shown, which was used for simulating the propagation of acoustic and electromagnetic waves. 23 transmitters and receiver positions with a distance of 5 cm on each side were simulated. The surrounding material was described as homogeneous (without considering single bricks and joints). The tomographic reconstruction [25] - [30] of this section was performed with GeoTom [33].

a) b) c)

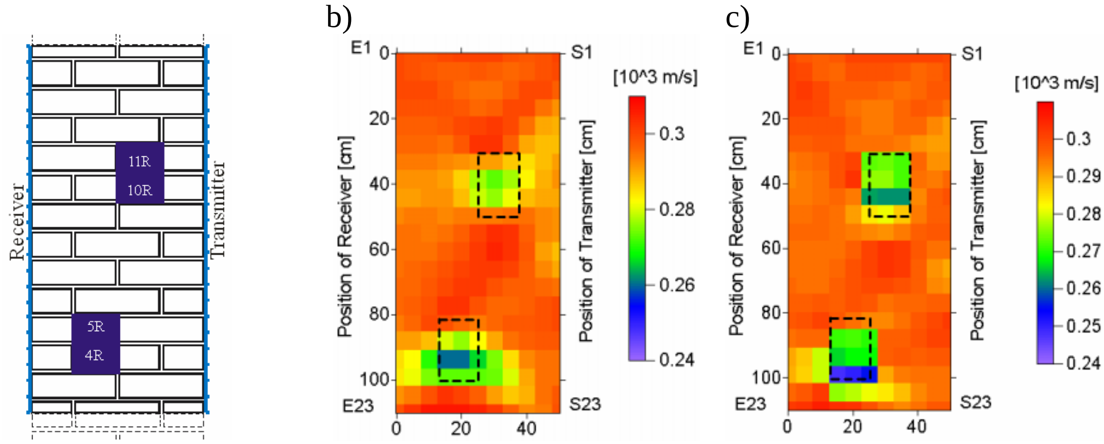

Figure 4: Tomograms of simulated acoustic data at W2, a) cross section of investigated area; b) tomogram after using homogeneous starting model, c) tomogram after using adapted starting model

a) b) c)

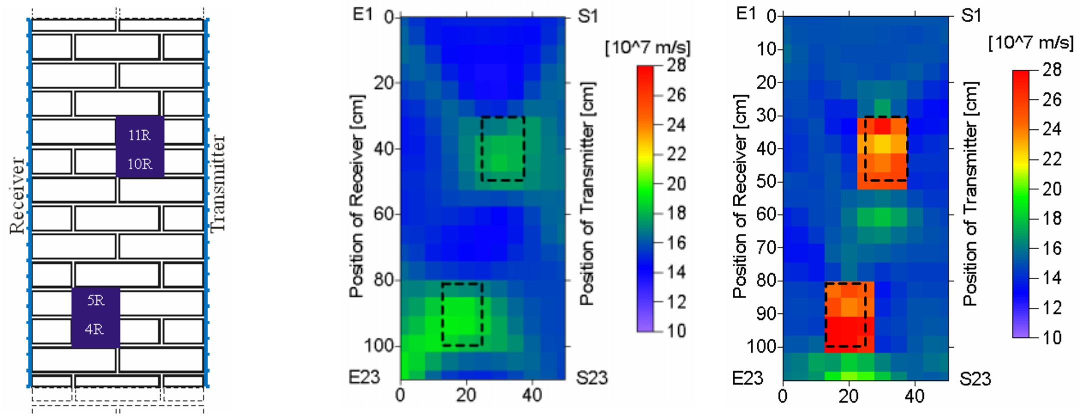

Figure 5: Tomograms of simulated electromagnetic data at W2, a) cross section of investigated area; b) tomogram after using homogeneous starting model, c) tomogram after using adapted starting model

The results showing the velocity distribution along the section of the acoustic and electromagnetic waves are presented in **Figure 4** and **Figure 5**, respectively. The reconstruction started with a homogeneous starting model (**Figure 4b, Figure 5b**) that got adapted after each inversion step. **Figure 4c** and **Figure 5c** indicate the result of the tomographic reconstruction with an adapted starting model. These tomograms represent the best possible results that were expected under optimum conditions, e. g. no air gaps, no layers and no interfaces. As expected, the voids can be recognised as zones with lower velocities for the acoustic waves and with higher velocities for the electromagnetic waves compared to the surrounding area with similar resolutions.

a) b)

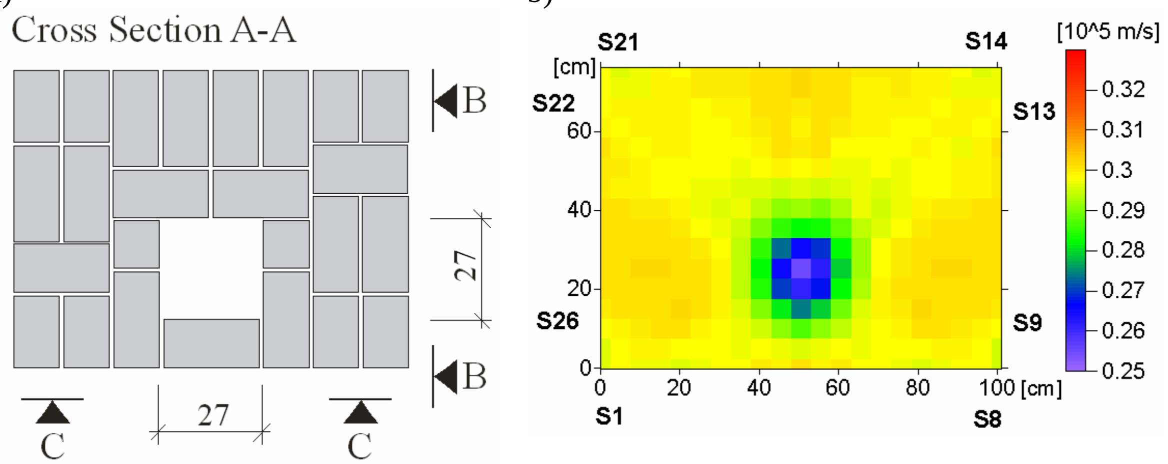

Figure 6: a) cross section of “Asterix I”, b) tomogram of simulated acoustic data at “Asterix I”

Figure 6b displays the result of the tomographic reconstruction of simulated acoustic wave propagation for the cross section shown in **Figure 6a**. Here, only a homogeneous starting model was used. 26 transmitters and receiver positions with a distance of 13 cm to each other were simulated along the whole circumference of the section. Again, the void is represented by a lower velocity similar to **Figure 4b**.

3.3 Measurements

At the test specimen W2, ultrasonic as well as radar transmission measurements were performed along the line marked in **Figure 3** to detect voids with sizes of (H x D x L) 18 x 14 x 26 cm.

The ultrasonic transmission measurements were performed two times by using different pairs of transducers emitting longitudinal waves: for the first run, two G0.2gc transducers from GE-Krautkrämer with a nominal frequency of 85 kHz were used and for the second run, two SO202 transducers from ACSYS with a nominal frequency of 25 kHz were applied. By fixing the transmitter on one side, the position of the receiver at the opposite of the specimen was changed. The total length of the line was 110 cm, the distance of the transducers on each side was 5 cm.

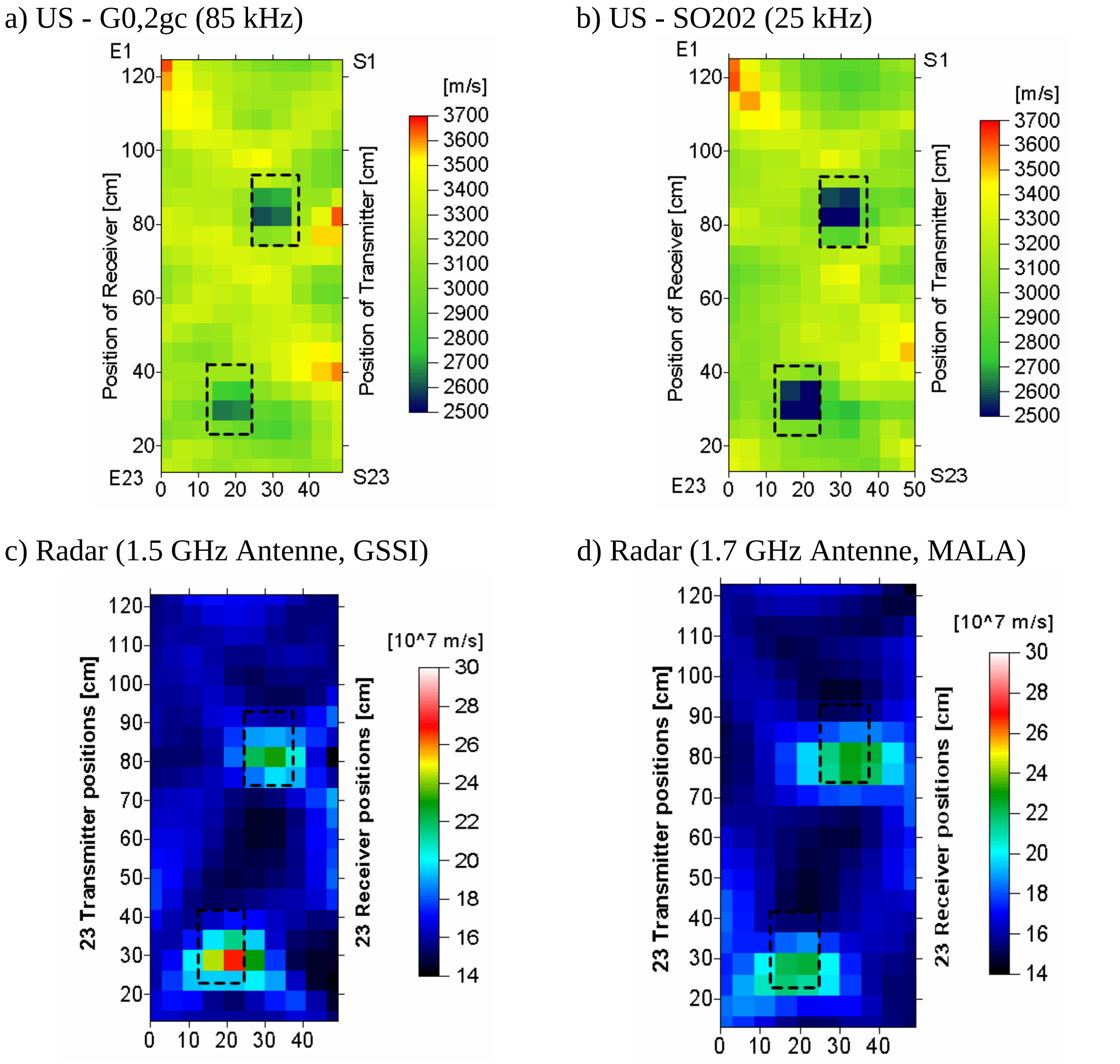

Figure 7: Tomograms of the investigated area at W2; a) and b) results of ultrasonic measurements with different transducers and frequencies; c) and d) results of radar measurements with different equipment and antennas (location of voids is marked with dashed lines)

The radar measurements were performed with two 1.5 GHz antennas from GSSI and were repeated with two 1.7 GHz antenna from Mala, which were developed in the EC project ONSITEFORMASONRY. While the transmitting antenna was fixed on one side, the receiving antenna was moved along the opposite side and a high amount of transmission measurements were recorded. Again, the length of the total line was 110 cm, while the distance of the transmitter positions was 5 cm.

As input for the tomographic reconstruction program GeoTom, the traveltime of the transmitted impulses was picked manually.

Figure 7 shows the results of the tomographic reconstruction of ultrasonic and radar measurements at W2 with adapted starting models. Although the results are similar to those of the simulation, the voids appear a bit smaller than expected. The tomograms of the ultrasonic investigations show two significant zones of lower velocities. These two zones fit almost perfectly to the real position of the voids. In this application, the different transducers show nearly the same results. In the radar tomograms, there are two zones of higher velocities that fit to the location of the voids.

The tomograms in Figure 7 show a clear and sharp separation of the anomalies with weak artefacts. This kind of quality can only be achieved with a lot of previous data checks, an adapted starting model and a pre- and post processing of the data as it is published in [30] and [31].

At the specimen "Asterix I" transmission measurements have been carried out with ultrasonic to detect voids with sizes of (H x D x L) 27 x 27 x 62 cm along the cross section shown in **Figure 6a** by using SO202 transducers from ACSYS with a frequency of 25 kHz. The same procedure of data analyse to the above described example was performed. It was very difficult to pick the right time of first arrival of the transmitted wave because the phase was skipping. The numerical simulation of the wave propagation with REFLEX could answer the phase skipping. The huge void compared to the dimension of the column caused a loss of wave energy, multiple reflections and sometimes very acute angles lead to that complication.

The traveltimes were picked manually and for the tomographic reconstruction the program GeoTom was used. The results are quite similar to those of the simulation. The tomogram of the ultrasonic investigation show one significant zone of lower velocity. This zone fit almost perfectly to the position of the void.

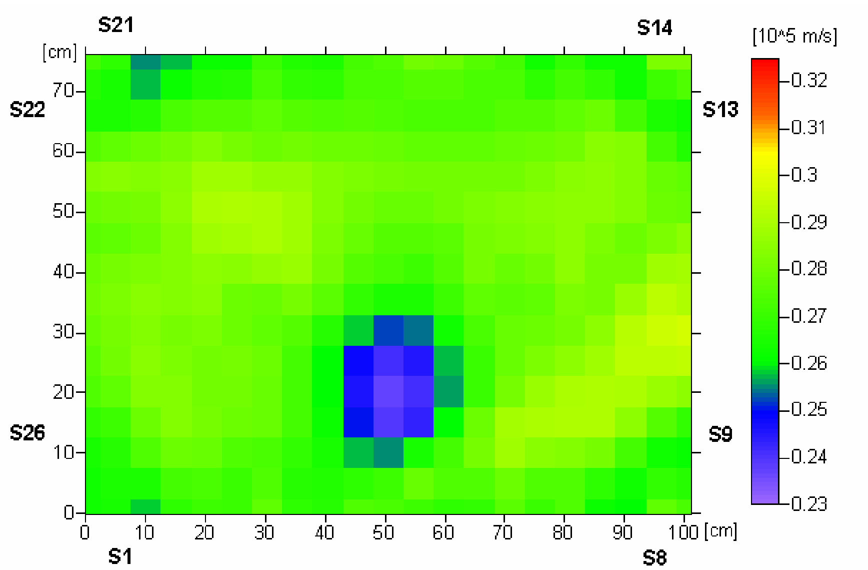

Figure 8: Tomogram of the investigated area at "Asterix I" by applying ultrasonics

4 Conclusions and Perspectives

The tomograms in **Figure 7** and **Figure 8** show that for homogeneous single leave masonry the recognition of voids having minimum sizes of 12 cm x 11 cm x 24 cm is possible with radar and ultrasonic traveltime tomography. The results of the measurements and the simulated data are in a good accordance.

The comparison between measurements from two and four sides show an increase of artefacts at the edges of the reconstructed section in case of only two side accessibility of the structure. But except for the investigation of pillars and columns, in most cases only the opposite sides of a wall are accessible.

By combining the results of radar and ultrasonic investigations, the content of information about of the detected anomalies increases. Because both methods complement each other, the detection of voids (reduced velocity and high reflectivity for ultrasonic, enhanced velocity and low reflectivity for radar) or metal inclusions (enhanced velocity and less reflectivity for ultrasonic, total reflection for radar) is improved.

In the presented laboratory investigations, the result of the acoustic method shows areas with lower velocity compared to the surrounding material and the result of radar shows areas with higher velocity. This specific behaviour leads to the expected conclusion that the anomaly is air or an air filled material.

In the ongoing research, different types of masonry, various anomalies (wood, steel, natural stones) and their sizes in proportion to the investigated cross section will be investigated. The aim is to determine the limits of detection and, by using the combination of acoustic and electromagnetic methods, to identify the type of anomaly.

Acknowledgement

Parts of this work were funded by the European Commission within the 5th Framework Project ONSITEFORMASONR (www.onsiteformansory.bam.de). We gratefully acknowledge the help of Anne Dobat for doing the ultrasonic measurements.

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