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The application of selected tomographic imaging methods in the inspection of concrete bridges

Abstract: Majority of non-destructive testing (NDT) methodologies necessitate access to only one side of the structure. Due to factors such as wave absorption or reflection by the test object, it is necessary to position the transmitter and receiver on different sides of the test surface. This particular investigative modality is designated as tomography. The article reviews the literature on the use of tomography for the inspection of concrete structures, and presents the results of research conducted on the use of GPR in tomographic mode on a bridge support. It is concluded that GPR in tomographic mode is well suited for mapping larger areas with varying concrete quality. Conversely, radiography is particularly well suited to point measurements and is not limited by the influence of dense reinforcement mesh. It has been determined that when employing a suitable radiation source, the risk to human health when utilising this method is negligible. The article examines X-ray tomography and ground-penetrating radar (GPR) techniques, both employing tomographic imaging and requiring access to at least two sides of the structure. It aims to compare the two methods in terms of accuracy and data acquisition, based on the author's experimental results and evidence from international literature.

Keywords: assessment, bridge, GPR, inspection, tomography, radiography.

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1. INTRODUCTION

In this article, the author focuses on a detailed description of X-ray tomography and ground-penetrating radar (GPR) techniques, both of which use tomographic imaging methods (applicable when access to at least two sides of the examined structure is required). The aim of the article is to compare X-ray tomography and GPR-based tomography as methods that differ in terms of accuracy and data acquisition, based on the author's own research results as well as findings from international literature. A more detailed description of concrete structure damages and the corresponding types of non-destructive testing methods can be found, among others, in [1-3]. During structural inspections, bridge inspectors typically rely on visual observation to identify any damage to the external surface of the structure. However, it is often necessary to obtain information about the condition of damage inside the structure. In such situations, various non-destructive testing (NDT) methods (Fig. 1) or drilling are typically employed to obtain information on the actual course of reinforcement or cable ducts utilised for the routing of prestressing tendons.

The majority of these testing methods are reliant upon access to a single side of the structure being tested. In this instance, the transmitter and receiver are situated on the same surface of the structure under evaluation. Each of these methods provides different type of data acquisition: point measurements or continuous measurements. Most of the mentioned methods provides rather point measurements, while georadar antennas give the possibility to perform each scan in the continuous mode, what gives this method particular advantage. This type of data acquisition is provided also by magnetic flux leakage method applied for the inspection of external plastic tendon ducts present in post-stressed bridges [5].

The utilisation of a dense measurement grid facilitates the generation of a pseudo-three-dimensional image of the interior of the structure under investigation (Fig. 2).

This test result is often mistakenly referred to as a tomogram, and the method itself is also often mistakenly called tomography. In Figs 3, 4 and 5 examples of the results of such a test on a reinforced concrete test block are shown.

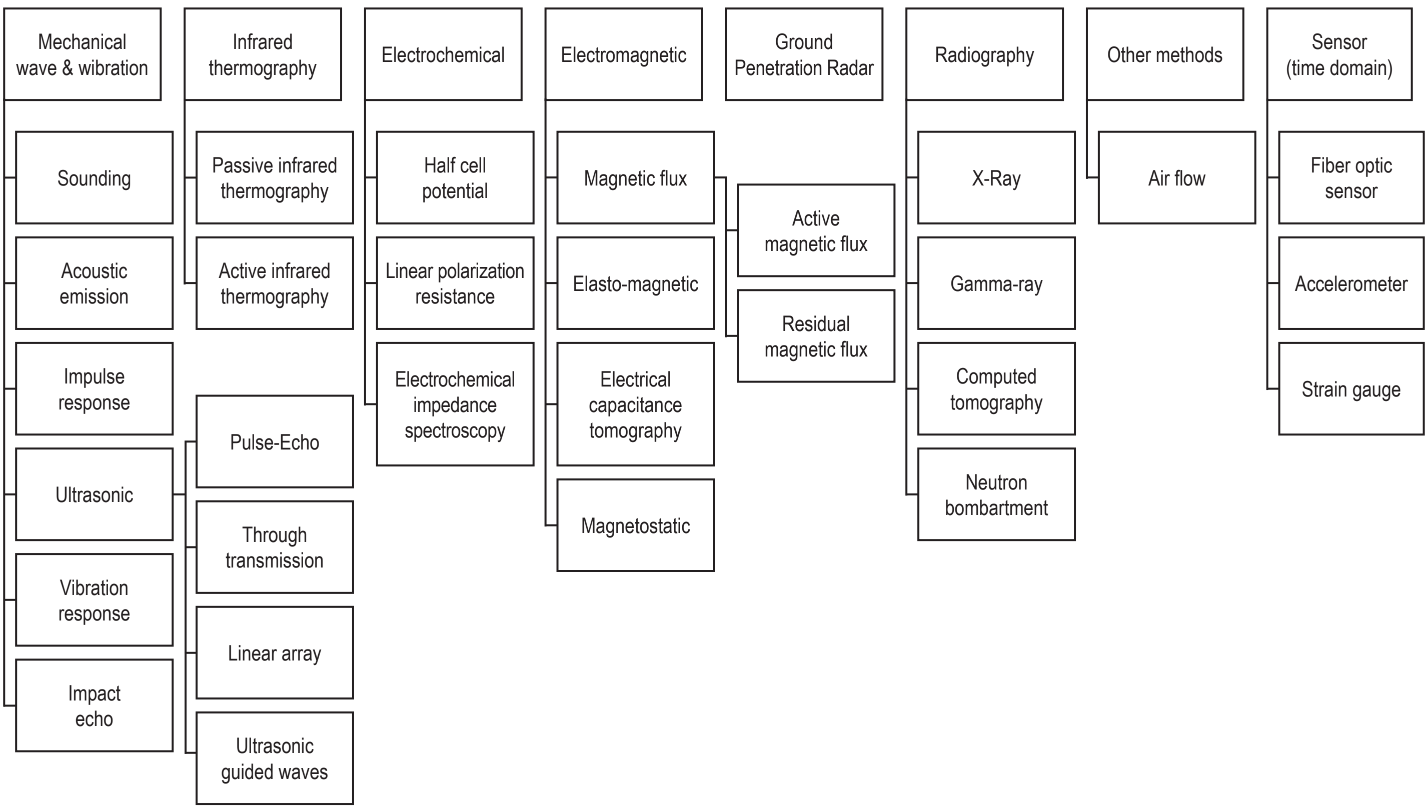


Fig. 1. Selected non-destructive testing methods [4]

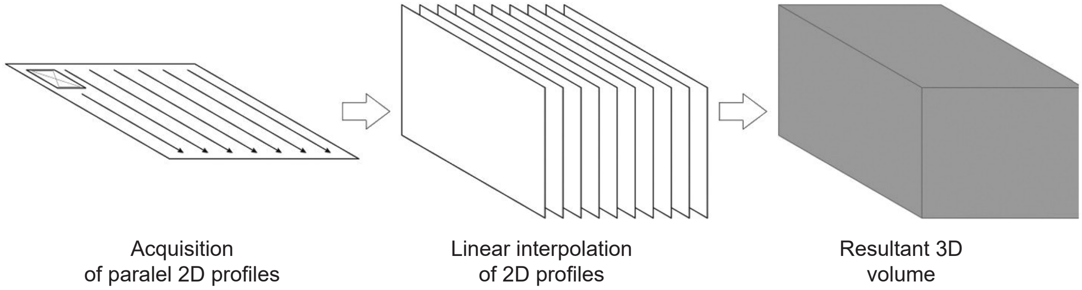


Fig. 2. Methodological framework for constructing 3D volumetric models from field-acquired reflection data [6]

a) b)

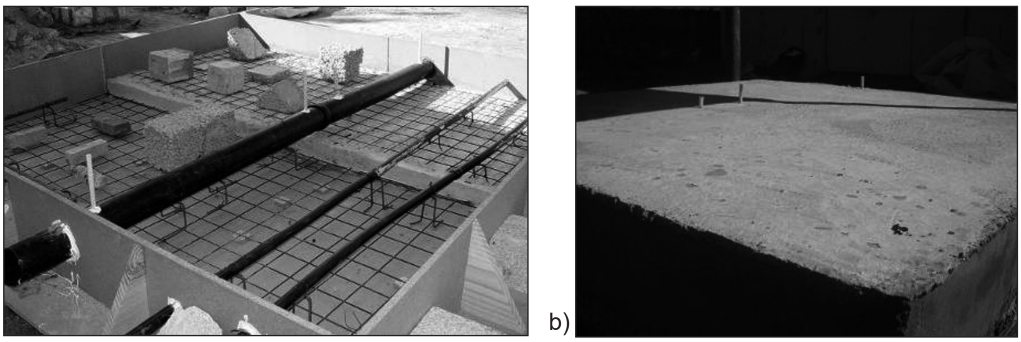


Fig. 3. Overall perspective of the concrete sample: a) a comprehensive view of the components and materials positioned within the specimen prior to pouring, b) the completed appearance of the slab post-casting [6]

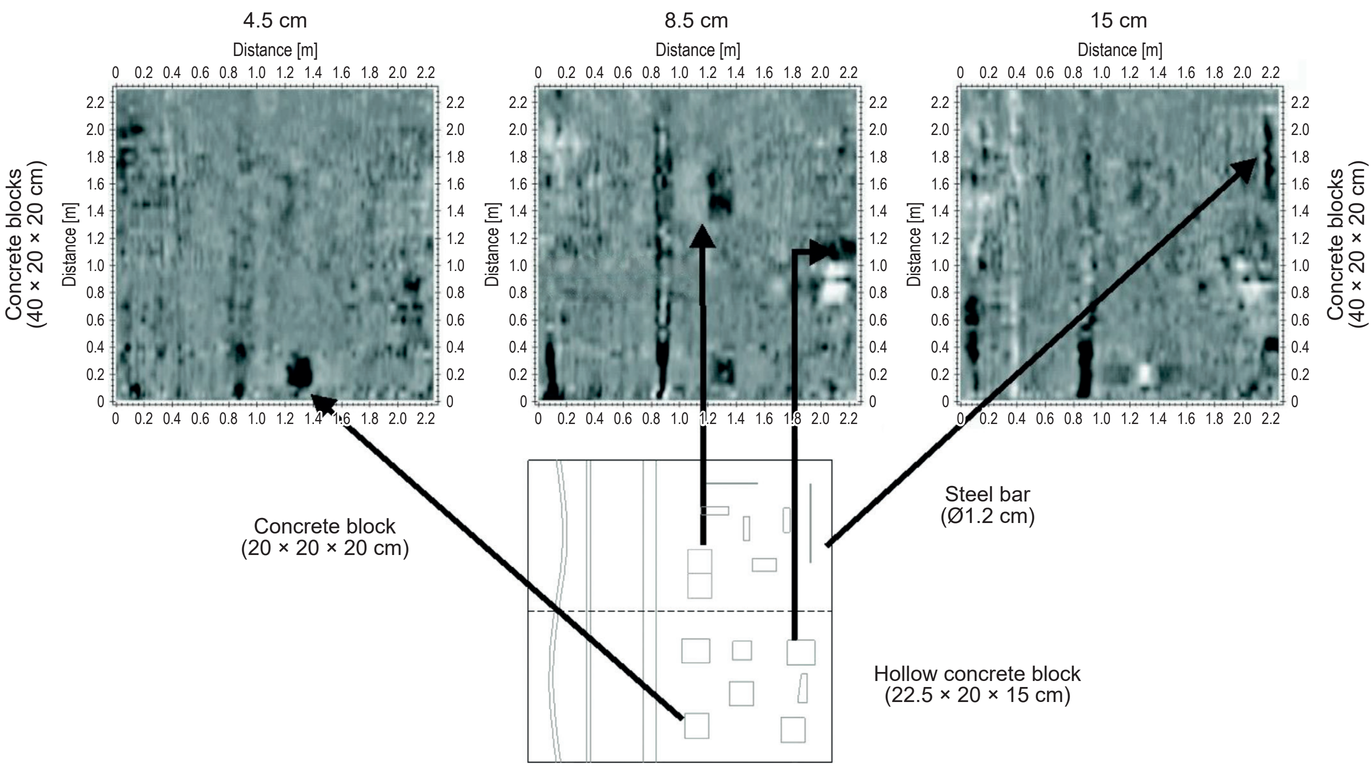


Fig. 4. Time slices generated after migration illustrate the spatial distribution of concrete blocks and a steel bar, with the latter oriented perpendicular to the direction of data acquisition [6]

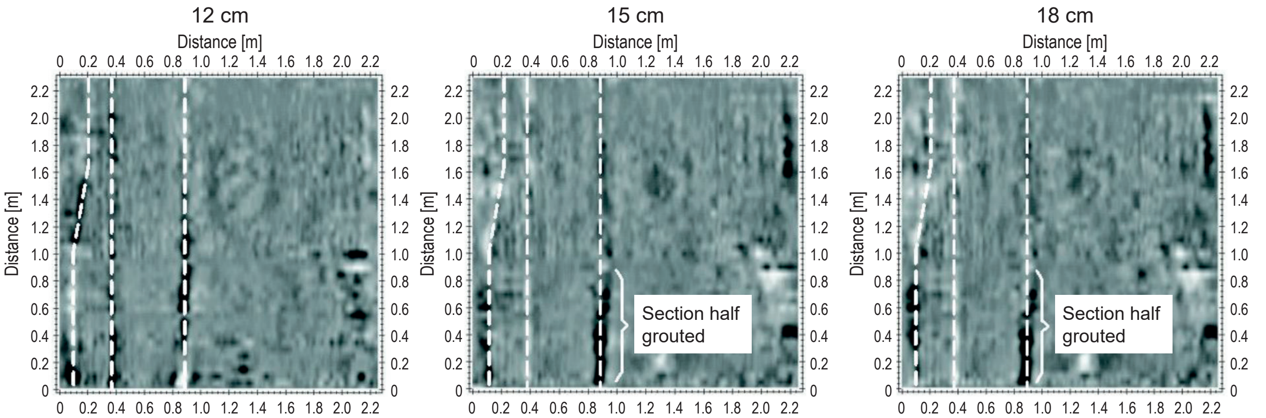


Fig. 5. Sequential time slices displaying the configuration of the three tendon ducts [6]

Despite the development of algorithms for the reconstruction of three-dimensional internal images of structures, it often happens that, due to wave absorption or reflection in the test object, the transmitter and receiver must be placed on different sides of the test surface, in particular on opposite edges. Consequently, the wave transmitted by the transmitter does not have to return to the receiver located on the same edge, but can penetrate deeper, thereby increasing the potential range of information obtained about the interior of the structure under test. This method of testing is referred to as tomography, and the resultant image is designated a tomogram.

Originally created for use in medical diagnostics and geophysical studies, tomography is a method that enables the visualization of an object's interior by analyzing data collected from its outer boundaries.

A selection of the work conducted for geophysical applications can be found in the following publications: [7-8] In the field of geotechnical engineering, borehole tomography is a widely employed technique for the detection of fractures in solid rock formations, in addition to the assessment of the technical integrity of foundation piles [9-11].

Depending on the type of waves utilised, it is possible to differentiate between acoustic tomography in different frequency ranges, radar tomography (employing georadar antennas) in different frequency ranges, and tomography using X-rays, gamma rays and synchrotron radiation. Furthermore, tomography, utilising electrical capacitance or resistance measurements within the examined structure, can be discerned [11].

It is important to acknowledge the simplicity of conducting tomography using X-rays or gamma-rays tests within a laboratory setting, provided that a sample is available for rotation within the scanner. The issue arises when dealing with a physical structure, where access to all sides for measurement is not possible.

The presentation of test results is dependent on the type of wave propagating in a given medium, with different scales being employed accordingly. In the case of acoustic or electromagnetic waves, the result of the test will most often be a velocity map or a map of the absorption of waves travelling in a given cross-section of the structure under investigation. In case of gamma-ray tomography result is presented usually in grey scale presenting the absorption rate within particular material.

The issue inherent in the extensive utilisation of acoustic or electromagnetic waves pertains to their propensity to be scattered, reflected or refracted within the medium under investigation (Fig. 6).

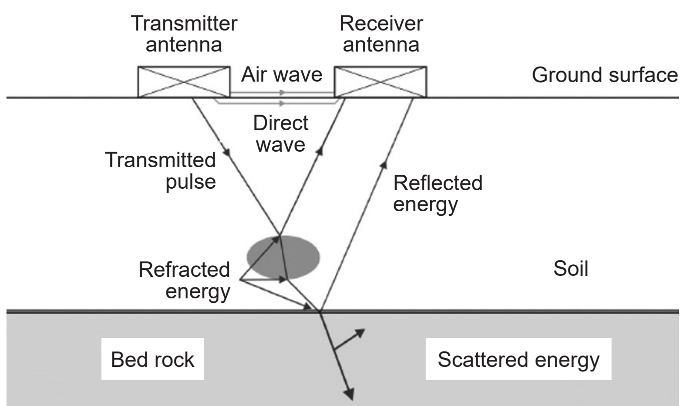


Fig. 6. Example of reflected, refracted and scattered electromagnetic waves [13]

The utilisation of ground-penetrating radar in tomographic mode offers several advantages. Primarily, it enables the coverage of the tested structural cross-section with a dense measurement grid in a relatively short timeframe. This can be achieved in various transmitter-receiver configurations. While the transmitter is generally static, the receiver is capable of movement along the opposite side of the structure under investigation, thereby facilitating dense coverage of a given structural cross-section with a dense measurement grid. It has been demonstrated that neither acoustic wave tomography nor X-ray or gamma ray tomography provide this advantage. These are methods for point measurements, especially in the context of tomography using X-rays or gamma rays.

The utilisation of radiography, as opposed to electromagnetic waves generated, for example, by ground-penetrating radar, offers distinct advantages. Specifically, X-rays or gamma rays propagate in a straight line through the structure under investigation (Fig. 7) without undergoing dispersion that is characteristic of acoustic or electromagnetic waves (Fig. 6). Furthermore, the wave energy is considerable, enabling the penetration of high-density media, such as reinforced concrete or steel.

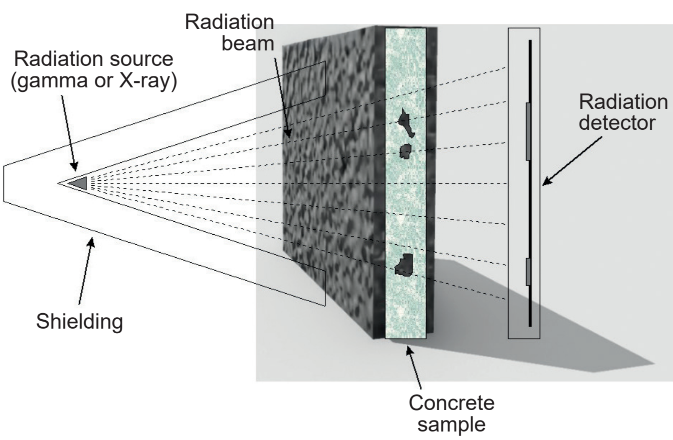


Fig. 7. Illustrative overview of the radiographic technique; developed by the author

The selection of the type of waves and their frequency in tomographic imaging should be made on the basis of the following factors:

- the required penetration depth,
- the type of material being tested,
- the size and type of object being searched for inside the structure (air void, reinforcement).

In general, it can be stated that ground-penetrating radar in tomographic mode is well suited to the mapping of larger areas with varying concrete quality (with measurement accuracy ranging from 3-10 cm, depending on the type of antenna used). Conversely, radiography is particularly well suited to point measurements with a required accuracy of less than 1 mm, and is not limited by the influence of dense reinforcement mesh.

In general terms, acoustic waves have the capacity to penetrate ferromagnetic media and travel slowly in air. In contrast, electromagnetic waves exhibit the inverse characteristics. These particles are known to be completely reflected from ferromagnetic surfaces and have been observed to propagate quickly in air. The accuracy of the test can be increased by using a higher frequency, which allows for the detection of smaller objects inside the structure. However, this also results in a decrease in penetration depth inside the structure.

2. TOMOGRAPHY USING X-RAYS, GAMMA-RAYS OR SYNCHROTRON RADIATION

A typical tomography system consists of a source that emits a beam of controlled intensity and a detector that captures the intensity of the transmitted beam (Fig. 7). A comprehensive review of various tomographic systems used for material testing is provided in [14]. It has been shown that steel absorbs more radiation than concrete, while air absorbs less. Internal structural variations within a sample are captured as photographic images. In X-radiography, X-rays are generated by an electron linear accelerator, whereas gamma radiation is emitted naturally by the decay of radioactive isotopes. Commonly used radioisotopes include cobalt-60 (60Co) and iridium-192 (192Ir), with iridium being more portable due to its lower radiation intensity and the reduced shielding required for safe handling. Radiographic methods are widely regarded as valuable diagnostic tools, capable of detecting issues such as grouting voids and, in some cases, identifying tendon corrosion and wire fractures [15].

The disadvantage of tomography using X-rays, gamma rays or synchrotron radiation is that when the receiver and transmitter are located on opposite sides of the structure being examined, a one-dimensional projection of what is present in the entire cross-section can only be obtained, without any information about the spatial location (Fig. 7).

In the context of tomography, employing X-rays, gamma rays or synchrotron radiation, the acquisition of a two-dimensional cross-section (located between the transmitter and receiver) necessitates access to more than two sides of the tested structure [15]. It is acknowledged that there are exceptions to this rule, as illustrated by the examples provided in the patents [17, 18].

Using a specially designed combination of hardware and software, we can determine the position of the key elements in the examined cross-section (Fig. 8).

Fig. 8 shows an example of how the positions of the post-tensioning tendons inside a concrete girder are analysed using film-based radiographic imaging. The examined girder contains two internal ducts for the tendons, and one of them shows a significant problem with incomplete grouting.

The analysis is based on measuring the radiographic density, marked as $D(x_0, z)$. The value x_0 represents the position indicated by the vertical dashed line on the radiograph. The graph on the right shows how the density changes along the *z* direction for this specific position.

In the corrected radiograph, the characteristic "bowl-shaped" patterns between points A-B and D-E indicate the locations of the tendons. A dark band above the upper duct can also be seen, which suggests the presence of an air void in that area.

The thin curve on the graph shows theoretical density values calculated using a forward model. The parameters highlighted in red were adjusted to make the model match the experimental data as closely as possible.

Geometric details, including the positions and diameters of the tendons and ducts, were obtained from direct measurements and tomographic reconstruction. The density value measured for the air void corresponds to an air-equivalent thickness of about 5 cm.

A small difference between the measured and modelled density profiles in the D-E region may indicate a local reduction in the tendon's diameter, estimated at around 0.7 cm [19].

As posited by several authors, the potential for elevated radiation doses to operators or bystanders is a matter of concern [20-21]. This risk can be mitigated by utilising Iridium (192Ir) as the radiation source [15]. However, the utilisation of this specific source imposes a limitation on the penetration of gamma waves in reinforced concrete, restricting it to a maximum of 30 centimetres. Nevertheless, through the implementation of appropriate hardware configuration or by conducting test holes in the structure, this range may be rendered sufficient for the majority of applications [16].

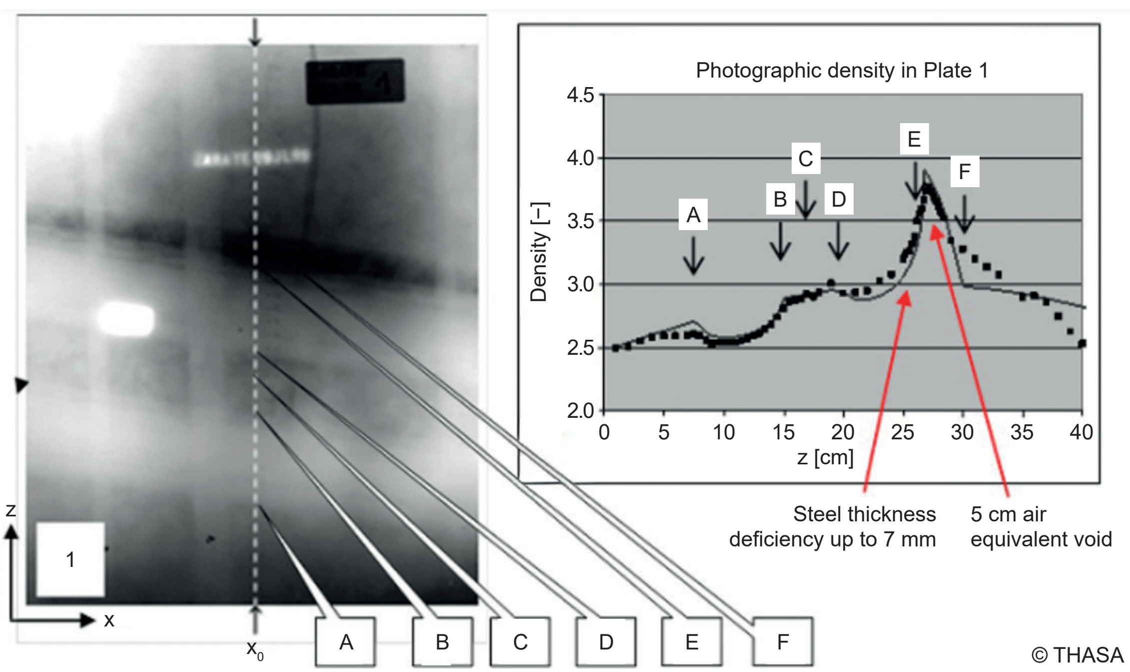


Fig. 8. Interpretation of Radiograph of the tendon duct [19-20]

3. AN INTRODUCTION TO TOMOGRAPHY USING GROUND-PENETRATING RADAR

In civil engineering, radar tomography, which is an advanced imaging technique utilizing ground-penetrating radar (GPR), has emerged as a powerful tool for non-invasive investigation of internal structural elements. This method is particularly effective for delineating the internal composition of components such as columns, walls, and other load-bearing elements that can be accessed from multiple orientations. Functioning as a distinct data acquisition modality, radar tomography involves spatially decoupled transmitting and receiving antennas, enabling multipath signal coverage and enhanced tomographic resolution.

In this configuration, electromagnetic waves are transmitted from a fixed source while the receiving antenna is systematically repositioned along the accessible boundaries of the target structure. As illustrated in Fig. 9, a representative case involves performing a tomographic scan of a column by fixing the transmitter at successive positions and translating the receiver along the remaining perimeter. This scanning strategy increases the angular diversity of ray paths, thereby improving the fidelity of the reconstructed image. With the known separation between transmitter and receiver, the average propagation velocity of radar signals along each path can be computed. The collected data, typically comprising either travel-time or amplitude measurements, serve as input to specialized inversion algorithms. These algorithms reconstruct spatial distributions of electromagnetic wave velocity or attenuation, allowing for the detailed imaging of internal features, material discontinuities, and potential defects within the structure's cross-section. This approach facilitates a high-resolution, non-destructive evaluation of structural components [22].

From a mathematical perspective, tomography involves solving an inverse problem to generate two- or three-dimensional images of velocity or attenuation distributions. These images are derived from measurements of transmitted first-arrival energy between boreholes (crosshole tomography) or across structural interfaces (crossmedium tomography). Specialized inversion methods are employed to reconstruct subsurface features, with travel-time and amplitude tomography being the most commonly used approaches in civil engineering applications [23-25]. Addressing the inherently non-linear nature of the inversion process requires the application of iterative reconstruction algorithms. These methods treat the cross-section of the object as a grid of unknown parameters, which are iteratively adjusted to match the observed projection data. However, a notable limitation of these algorithms is their neglect of diffraction phenomena, that is, wave interference effects which result in illumination beyond the bounds of geometric shadows. Despite this, such iterative techniques remain widely used due to their effectiveness in practical imaging scenarios.

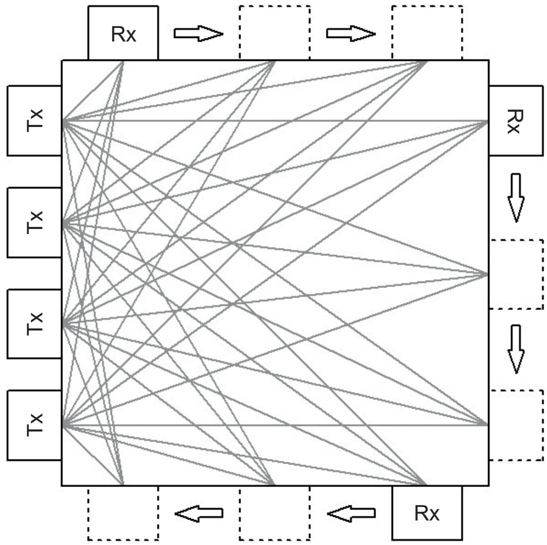


Fig. 9. Tomographic survey of a square column illustrating the arrangement of stationary transmitters (Tx) and the raversal path of mobile receivers (Rx) [13]

Commonly used iterative algorithms are [26-28]:

1. Algebraic Reconstruction Technique (ART).
2. Simultaneous Iterative Reconstructive Technique (SIRT).
3. Iterative matrix methods (e.g., Gauss-Seidel and Jacobi's method).
4. Conjugate direction/gradient methods.
5. Simple iteration.
6. A "neural network method".

These computational methods are predominantly utilized in travel-time tomography, where wave paths are modeled using ray-based approximations. Nonetheless, such approaches generally overlook diffraction phenomena, which become relevant when the dimensions of internal features are comparable to the wavelength of the probing signal, a condition frequently observed in microwave and ultrasonic non-destructive evaluation (NDE) of concrete structures [26]. In situations where wave transmission is the dominant mechanism and scattering effects are minimal, algebraic reconstruction techniques remain effective. These methods are particularly advantageous for detecting low-contrast anomalies such as air voids or non-metallic inclusions, which allow partial transmission of electromagnetic energy. A more comprehensive discussion of various image reconstruction strategies can be found in [30].

In radar tomography, standard tomograms are used to depict the spatial distribution of wave propagation velocity across a structural cross-section. When dealing with electromagnetic waves, regions exhibiting higher velocities typically correspond to materials with low dielectric permittivity, whereas slower velocities indicate materials with higher dielectric properties. For example, areas where wave speeds exceed 20 cm/ns often suggest the presence of air-filled voids, while near-zero velocities are generally indicative of metallic elements like steel or zones with significant moisture content.

In attenuation, or slowness, tomography, radar data can be used to differentiate between materials based on their electromagnetic energy absorption characteristics. High-attenuation materials, such as water, saline environments, substances with elevated chloride concentrations, or ferromagnetic components, can be clearly distinguished from low-attenuation materials like air pockets or dry wood.

Following data acquisition, the information must undergo a series of processing steps, including quality control and, most critically, inversion procedures that convert travel-time measurements into a velocity distribution map. Once the tomographic images are generated, they are analyzed and interpreted, with particular attention given to the identification and assessment of potential artefacts introduced during the inversion process. Accurate interpretation is only possible when travel-time data has been properly calibrated, spatial coordinates are precisely defined, and rigorous quality assurance has been performed. An overview of the entire processing workflow is presented in Fig. 10.

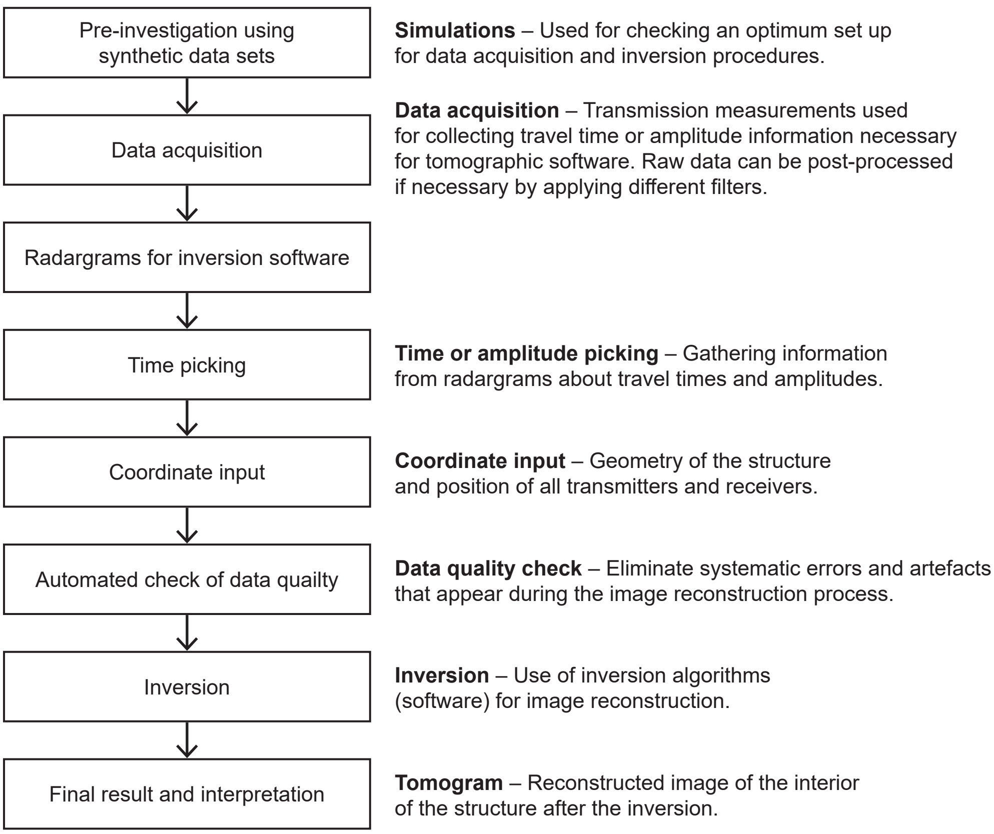


Fig. 10. Schematic representation illustrating the overall workflow for data acquisition and subsequent processing stages [6]

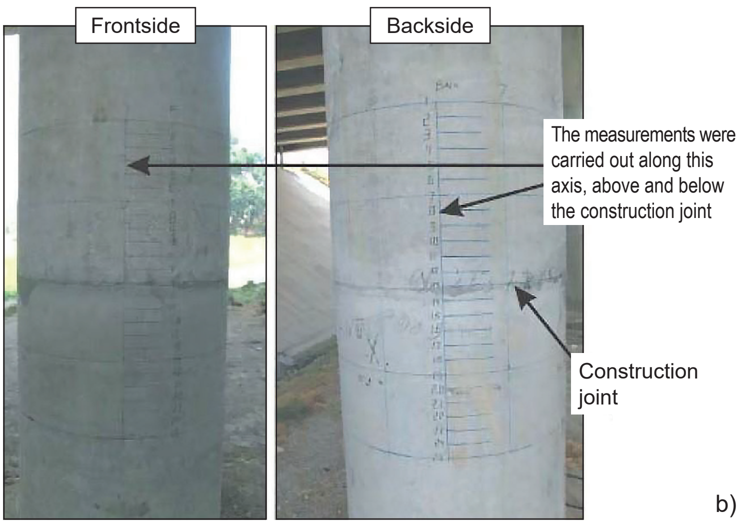
4. TEST RESULTS ON RIO AVE BRIDGE IN PORTUGAL

To evaluate the accuracy of radar tomography on a full-scale structure, transmission measurements were conducted on the Rio Ave Bridge [31], focusing on a construction joint within a bridge column measuring 100 cm in diameter (Fig. 11). Given the labor-intensive nature of the method, data collection was limited to column B, which was identified as a critical area based on corrosion sensor readings indicating abnormally high electrical resistance, a strong indicator of advanced steel corrosion. The aim of the investigation was to identify structural degradation that could account for these anomalous readings. Due to the insufficient penetration depth of the 1.6 GHz antenna, a lower-frequency 900 MHz antenna was employed to achieve better subsurface coverage.

Measurements were performed with the antennas aligned vertically. At each point along the column, spaced at 5 cm intervals, the transmitting antenna was fixed in place while the receiving antenna was moved vertically along the entire column height (Fig. 11), generating 25 profiles, each 120 cm long. To ensure measurement reliability, a second acquisition was performed using the same configuration but with the roles of the transmitter and receiver antennas reversed.

Data processing involved multiple stages. Initially, the lengths of the recorded profiles were standardized, and the input data were thoroughly validated. The processed data were then input into an inversion algorithm, yielding a series of tomographic images that map the electromagnetic wave velocity distribution across the examined cross-section. An example of such a velocity map is shown in Fig. 12.

The resulting tomogram clearly reveals two distinct zones above and below the construction joint, characterized by differing wave velocities. On average, the region above the joint exhibited velocities approximately 10% higher than those below, suggesting the use of dissimilar concrete mixes. Typically, higher wave velocities are associated with degraded concrete, potentially resulting from corrosion-induced changes or inadequate compaction during casting.



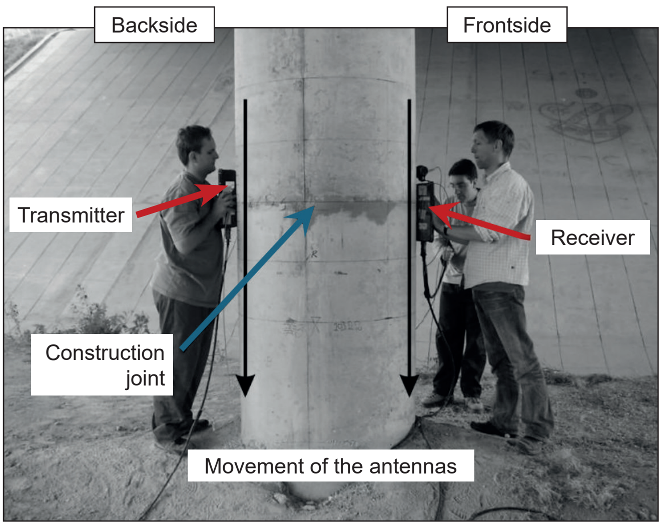


Fig. 11. Measurement set-up: a) Location of the transmitter antenna and the 120 cm receiver profile measured at column B. b) Transmission measurement configuration with the transmitter and receiver antennas positioned on opposite sides of column B; the transmitter location and the 120 cm receiver profile are indicated [6]

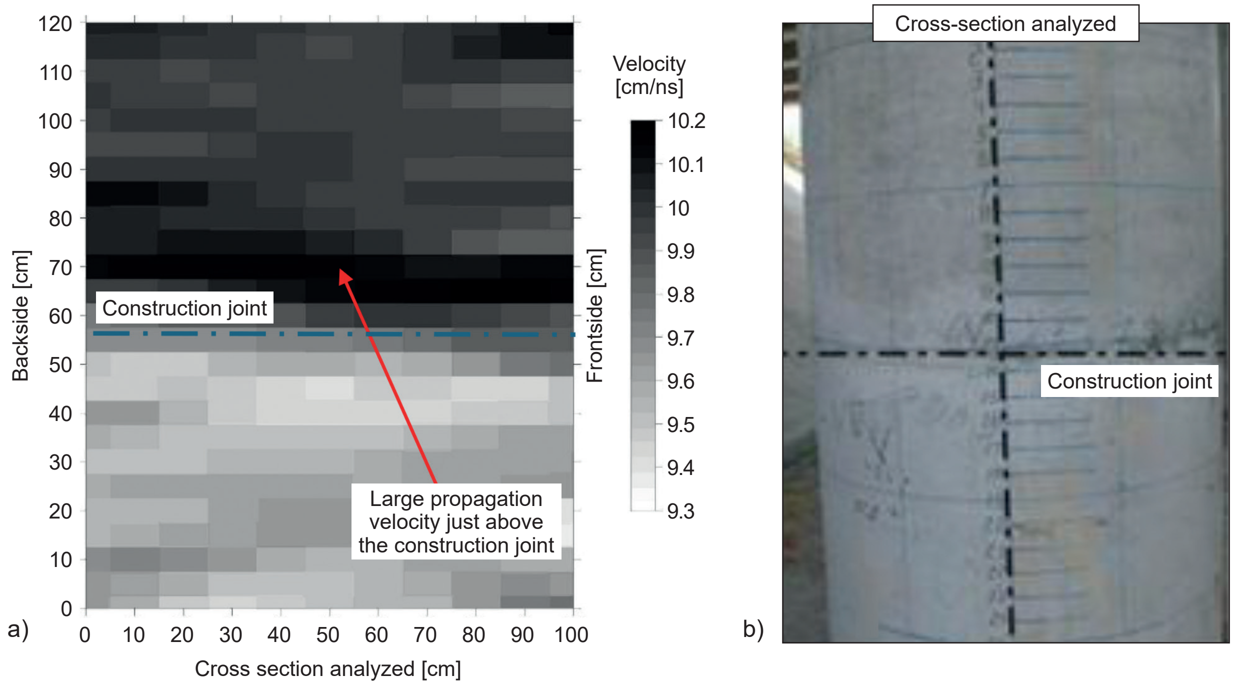


Fig. 12. Results from column B: a) a velocity distribution map illustrating the spatial variation of wave propagation speeds within the cross-sectional plane of column B, b) location of the analyzed cross-section – modified after [31]

5. CONCLUSIONS

The article provides a review of the extant literature concerning the utilisation of tomography for the examination of reinforced and prestressed concrete structures. The examination employs methodologies based on electromagnetic waves, acoustic waves, X-rays, gamma rays and synchrotron radiation. The results of tests using Gamma-rays and radar tomography on a real structure are then presented. It has been concluded that:

1. The experimental findings substantiate the feasibility of employing ground-penetrating radar in tomographic mode to identify larger areas comprising poorly vibrated concrete within a structure.
2. The advantage of this method is that it allows for the precise determination of the location of a given material heterogeneity within the tested structure.
3. Salient disadvantage of this method is the time-consuming nature of the processing and analysis of the measurement data. Also frequency of used antennas must be chosen carefully to achieve the desired wave propagation depth inside the tested structure.
4. It must be marked, that for depths more than 1 m antennas with 900 MHz must be used, what can severely reduce the resolution of the data.
5. It must be noted, that georadar antennas give the possibility to perform each scan in the continuous mode, what gives this method particular advantage.

The author also conducted a detailed analysis of the possibility of using tomography with X-rays, gamma rays and synchrotron radiation. This analysis concluded that:

1. With the use of an appropriate radiation source, the health risks associated with this method are minimal. This conclusion challenges the prevailing stereotype in this area.
2. The author concludes that no other method exists that is equally effective for testing cable ducts in cable-concrete structures.
3. The information obtained is usually a one-dimensional "projection" of a given structural cross-section, unless access is possible to more than two sides of the structure under test.

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Zastosowanie wybranych metod obrazowania tomograficznego w kontroli mostów betonowych

Streszczenie: Większość metod badań nieniszczących (NDT) wymaga dostępu tylko do jednej strony konstrukcji. Ze względu na takie czynniki, jak pochłanianie lub odbicie fal przez badany obiekt, konieczne jest umieszczenie nadajnika i odbiornika po różnych stronach badanej powierzchni. Ta szczególna metoda badawcza jest określana jako tomografia. W artykule dokonano przeglądu literatury dotyczącej wykorzystania tomografii do kontroli konstrukcji betonowych oraz przedstawiono wyniki badań przeprowadzonych nad wykorzystaniem GPR w trybie tomograficznym na podporze mostu. Stwierdzono, że GPR w trybie tomograficznym dobrze nadaje się do mapowania większych obszarów o zróżnicowanej jakości betonu. Natomiast radiografia nadaje się szczególnie dobrze do pomiarów punktowych i nie jest ograniczona wpływem gęstej siatki zbrojeniowej. Ustalono, że przy zastosowaniu odpowiedniego źródła promieniowania ryzyko dla zdrowia ludzkiego związane z wykorzystaniem tej metody jest znikome. W artykule przedstawiono także techniki tomografii rentgenowskiej i georadaru (GPR), które wykorzystują obrazowanie tomograficzne i wymagają dostępu do co najmniej dwóch stron konstrukcji. Celem pracy jest porównanie tych dwóch metod pod względem dokładności i pozyskiwania danych w oparciu o wyniki eksperymentów autora i dowody z międzynarodowej literatury.

Słowa kluczowe: GPR, inspekcja, most, ocena stanu technicznego, radiografia, tomografia.