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Imaging of concrete structures

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Demand for the development of non-destructive testing (NDT) techniques for concrete structures has increased with the growing concern about the deteriorating condition of the World's infrastructure. Efficient and accurate imaging techniques are needed for a reliable evaluation of safety and serviceability of concrete structures. Although, presently, imaging is routinely used in various fields, implementation of these technologies in NDT of civil engineering systems, especially of concrete structures, offers many challenges and requires additional development due to the composite nature of the concrete material and the complexities of reinforced or prestressed concrete systems.

This paper presents the basic principles of various imaging techniques associated with several NDT methods applicable to concrete structures. The techniques considered are radiography, radioactive computerized tomography, infrared thermography, radar imaging and acoustic imaging. Special considerations regarding the applicability and accuracy of these techniques for the condition assessment of concrete structures are discussed, and examples of imaging applications are given. © 1998 Published by Elsevier Science Ltd.

Introduction

There is growing concern about the deteriorating nature of the World's concrete infrastructure. Several Non-destructive Evaluation (NDT) techniques which are known in medical diagnostics, aerospace and geophysical applications, and in NDT of metals have been adopted, and further developed for use in the condition assessment of concrete systems. In recent years, numerous studies have been reported, giving application examples of NDT techniques in detecting and locating anomalies in concrete. Recent advances in speed and memory of computers combined with efficient imaging algorithms have led to the processing of measured responses from NDT to determine the spatial extent of the anomalies in two or three dimensions, as well as the nature of such anomalies.

Imaging of concrete structures for non-destructive testing purposes can be defined in a broad sense as obtaining a representation of certain physical properties of the concrete material and characteristics of the physical system by indirect or remote sensing methods which will not damage the structure, or permanently impair its serviceability. Imaging concrete is a challenging task, since concrete is a highly non-homogeneous material. It is generally produced in the field with limited quality control. Grain size distribution is highly variable and the properties of the constituent materials are greatly varied making it difficult to obtain accurate images. Other sources of difficulties in imaging concrete structures include the generally complex physical geometry, existence of inclusions, restricted accessibility of the object, and the problems related to the sensitivity of the method used to the inhomogeneities in concrete.

In this paper, imaging of concrete structures using appropriate NDT techniques is discussed. These include radiography, computerized radioactive tomography, infrared thermography, radar and acoustic techniques. Principles and application considerations of imaging using these techniques are discussed, and examples given.

Need for NDT

NDT of concrete structures is becoming increasingly important due to the aging and deterioration of infrastructures, e.g. bridges, roadways, water and sewer systems, ports, harbors, airports and buildings [1]. Scarcity of funds needed for repair or replacement of all structurally deficient or functionally obsolete concrete structures forces the state agencies to search for advanced NDT techniques which will facilitate rapid, cost efficient and reliable condition assessment of existing infrastructure to ensure public safety.

Incorporation of the quantitative results of standardized NDT techniques in infrastructure management systems is expected to provide the needed feedback in monitoring for detection and identification of deficiencies, and setting up priorities for repair, retrofitting or replacement actions.

Deterioration of concrete is a time-dependent process which severely affects the service lives, safety and maintenance costs of concrete structures. Various environmental effects cause concrete to deteriorate. Cracking in concrete is one of the major factors contributing to its deterioration. Cracks which exist in concrete at early stages later expand and widen during service conditions through various mechanisms, including mechanical and environmental effects leading to excessive damage, and even to a breakdown of the concrete structure. Corrosion of steel reinforcement and reinforcing bar (rebar) is another major deterioration mechanism of concrete. Corrosion process of the reinforcement doubles the volume of the original steel and applies pressure to the surrounding material, resulting in stress levels greater than the tensile strength of concrete. As a result, concrete fractures and rebar separation takes place [2].

The primary goal of any non-destructive evaluation technique is to detect and locate the anomalies within an optically opaque medium through appropriate imaging techniques. In the case of reinforced concrete, such techniques are expected to provide information about thickness variations as well as the inclusions such as the reinforcing bars, cracks, voids and delaminations, deteriorated zones and moisture.

NDT techniques

General NDT methods include X-ray and gamma-ray radiography, computerized radioactive tomography based on X-rays and gamma-rays, infrared thermography, radar (microwave) and acoustic (stress wave) techniques. These techniques are all applicable to concrete within certain limitations.

In X- and gamma-ray transmission radiography, a beam of radiation passes through the component and exposes a film in a light-tight packet. The resulting image is a high resolution projection of the object. With this method, limitations are imposed by several requirements: accessibility to both sides of the object, the necessity for long exposure times, and the demand for safety precautions required to protect both the operators and public. Computerized radioactive tomography is a cross-sectional imaging of an object from its X-ray or gamma-ray projections. This method produces high resolution images, but requires expensive and heavy equipment, highly skilled operators, and accessibility to both sides of the structure. The method of infrared thermography is based on the principle that a delamination introduces an air gap in the material, acting as an insulator and restricting heat flow into or out of the material. The drawback of this method is that data interpretation is complicated by varying weather conditions and surface temperature variations related to the surface properties [3]. The radar technique involves propagation and scattering of electromagnetic (EM) energy through materials. This technique allows non-contact, rapid measurements covering large areas, but electromagnetic waves undergo high attenuation in moisture, and difficulties arise in imaging below closely spaced reinforcement. Also, the radar parameters must be carefully optimized for the desired application due to the trade-off between the penetration depth and image resolution [4]. The stress wave methods include techniques of pulse-echo, impact-echo, ultrasonic, acoustic emission and spectral analysis of surface waves (SASW). In principle, the stress wave methods are based on elastic wave propagation in solids. They can provide information about the condition and strength of materials. Disadvantages of these methods include low directivity of low frequency sound waves in concrete, sensitivity of the technique to the maximum aggregate size, and the requirement of intimate contact between the test equipment and the object under testing.

Imaging

An image can be described as a representation of an object that is indirectly or remotely sensed. Imaging is the reconstruction of this representation using the scattered fields either in transmission or reflection mode, obtained by illuminating the object from many directions. This is generally achieved through appropriate inversion methods which are referred to as inverse scattering methods or identification methods [5–7]. The difficulty in image reconstruction depends on the complexity of the concrete target. For example, the thickness of a homogeneous concrete slab with known material properties can be determined by a single pulse-echo experiment through multiplying the velocity of waves inside the slab with the time difference between the front and back surface reflections. On the other hand, if the material properties of the slab are unknown and if it contains various local inhomogeneities, as in the case of pavements and bridge decks, a more involved experimental setup and advanced imaging technique is necessary.

Image reconstruction from scattered data can be performed using either iterative algorithms or transform-based algorithms which involve entirely different approaches [8,9]. Iterative algorithms consist of assuming the object cross-section as an array of unknowns, and then solving for those unknowns in terms of the measured projected data. Commonly used iterative techniques are the Algebraic Reconstruction Technique (ART) and Simultaneous Iterative Reconstructive Technique (SIRT). The main shortcoming of iterative algorithms is that they do not consider diffraction, which can be defined as the interference effects giving rise to illumination beyond the geometrical shadow [10]. Diffraction becomes important when the dimensions of the inhomogeneities are comparable to the wavelength of the radiation, which is generally the case for microwave and ultrasound NDT of concrete. Transform-based methods involves Fourier domain processing of the scattered data.

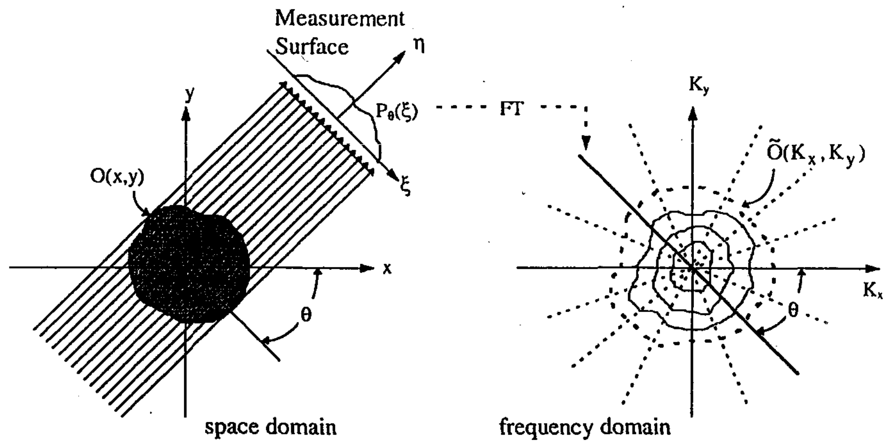


Figure 1 Fourier slice theorem

One-dimensional spatial Fourier transform of the measured projected data is used to determine two-dimensional Fourier transform coefficients of the object. After coherently superposing multi-frequency and/or multidimensional measurement data, the object is reconstructed in two dimensions by a two-dimensional inverse Fourier transform. The advantage of transform-based algorithms is that diffraction effects can be taken into consideration. Disadvantages include large computation and memory requirements, difficulty in incorporating a priori information into reconstruction, and the requirement for linearizing approximations [8]. In this paper, emphasis will be placed on transform-based algorithms, since they provide an intuitive understanding of the reconstruction and consider diffraction, while the examples of both types of algorithms will be given.

Radiography

Radiography is one of the earliest NDT techniques which is used to obtain a shadow image of a solid using penetrating radiation, e.g. X-rays or gamma-rays generated by X-ray tubes or radioactive isotopes, respectively [10]. X- and gamma-rays are forms of electromagnetic radiation, e.g. visible light and microwaves, but their wavelengths are so small that they can penetrate all materials with some absorption and scattering during transmission [11]. X-rays are generated when an electron beam impinges on a solid target, whereas gamma-rays are X-rays of high energy emitted by the disintegration of a radioactive isotope. They propagate through the material along straight paths without any significant diffraction. The intensity of the beam in the material is decreased exponentially by the following relationship:

$$I = I_0 \exp\left(- \int_0^L \mu(x, y, z) \mathrm{d}L \right) \tag{1}$$

where I_0 is the intensity of the incident beam, $\mu(x, y, z)$ is the attenuation coefficient of the material as a function of the spatial coordinates, and L is the path length within the material [10]. The transmitting rays strike the detector which is generally a photographic film and expose it the same way light exposes the film in a camera. The image obtained is in the form of a two-dimensional projection which provides information about the physical characteristics of concrete, e.g. density, composition and inclusions through the degree of attenuation. However, the image does not provide any information about the depth of inclusions in the material.

X- and gamma-ray methods are capable of producing accurate two-dimensional images of the concrete interior. However, their use in concrete testing is generally limited due to their high initial costs, relatively low speed, heavy and expensive equipment, need for extensive safety precautions and highly skilled operators, and perhaps most important of all, the requirement of accessing both sides of the structure.

A recent application of X-ray radiography involves a system called Scorpion developed in France [12]. The system includes a linear accelerator X-ray generator mounted on a crane used to evaluate prestressed bridge girders. Gamma radiography has more field applications, since the source is compact and easy to transport, independent of electrical and water supplies, and low cost [10]. This technique has been used in the field to determine the location and condition of reinforcements, to detect voids and delaminations, and to inspecting the grouting of post-tensioned concrete [12].

Computerized radioactive tomography

Computerized radioactive tomography, also called computerized tomography (CT) is the reconstruction of a cross-sectional image of an object from its projections. In other words, it is a coherent superposition of projections obtained using a scanner to reconstruct a pictorial representation of the object. Mathematical formulation of CT was performed by Radon in 1917, and was first used in medicine as a diagnostic tool after the invention of the X-ray computed tomographic scanner by Hounsfield in 1972 [8]. A schematic representation of the basic parallel beam computerized tomographic image reconstruction is shown in Figure 1. Fourier slice theorem states that the Fourier transform of a parallel projection of an image at an angle θ shown as $P_\theta(\xi)$ in the figure gives the two-dimensional spatial Fourier transform of the object $\tilde{O}(K_x, K_y)$ along a line at an angle θ with the K_x axis. This line is shown as a solid line in the frequency domain. By rotating the source and detector 360° around the object, the Fourier space is filled, as shown by the dashed lines. At this point, the object can be reconstructed by a simple two-dimensional inverse Fourier transform. A better way of object reconstruction is performed by the filtered backprojection algorithm. This algorithm reconstructs the final image by first filtering each projection in the frequency domain, and then adding together the two-dimensional inverse Fourier transform of each weighted projection. Similar reconstruction techniques exist for different sources, e.g. point sources which generate fan-shaped beams [8].

In 1980, Morgan et al. [13] developed a CT system which used an isotopic source to generate photon beams, and tested 6-inch-diameter concrete cylinders to determine the density variations inside the cylinders, to locate the reinforcement and voids, and determine their sizes. Image reconstruction was made using 100 projections obtained by rotating the source 360° around the cylinders. The exposure time for each projection was 40 min due to low source intensity. The system was able to identify the density within 1%. Results of scans of two concrete cylinder specimens are shown in Figure 2. In Figure 2(a), the reconstructed image of a concrete cylinder with a 3/8 inch diameter rebar is shown. As seen from the figure, the rebar and voids in the cylinder are accurately detected. Figure 2(b) shows the image of a cylinder loaded to failure. The failure plane is clearly identified in the image.

A more recent application of CT to concrete is reported by Martz et al. [14]. They developed an X-ray CT system to quantitatively inspect small concrete samples for density variations with a spatial resolution of about 2 mm. Figure 3 shows an image of a 20-cm-diameter hollow cylinder with a 4.4 cm central hole reconstructed from 45 projections at 4° intervals over 180°. On the right of the cylinder image is a one-dimensional attenuation profile extracted along a diagonal white line indicated on the image. The central hole and a smaller void of about 5 mm are clearly identified both on the image and the one-dimensional profile.

Computerized tomography is capable of producing highly accurate images of millimeter or sub-millimeter resolution. However, application of computerized tomography to concrete is generally limited to laboratory studies, since the scanners are expensive, measurements take a long time and are limited to small sizes, and accessibility to both sides of the object is required. Image reconstruction from limited views has been the subject of several studies [15], however, such reconstruction still requires accessibility to both sides. Further research is needed in this area before the technique can be applied in the field.

Infrared thermography

Infrared (IR) techniques are commonly used in military applications, NDT of materials and medical diagnosis. Within certain limitations, infrared thermography is a remote, fast and cost-efficient NDT method with qualitative or quantitative information potential. It can be used to locate and determine the extent of voids, delamination and debonding in reinforced concrete. Civil engineering applications of this technique include thermography of bridges and highways, asphalt pavements, sewer systems and wastewater pipes, canals and aqueducts, and indoor and outdoor thermography of buildings [16]. Infrared thermography is based on the principle that subsurface anomalies in a material result in localized differences in surface temperature caused by different rates of heat transfer at the defect zones. Thermography senses the emission of thermal radiation from the material surface, and produces a visual image from this thermal signal which can be related to the size of an internal defect. Most infrared thermography applications use a thermographic camera in conjunction with an infrared-sensitive detector which images the heat radiation contrasts. Thermographic imaging may involve active or passive sources, e.g. a flash tube or solar radiation [11].

Heat transfer takes place in three modes called conduction, convection and radiation. The mode which interests us most from the NDT point of view is radiation, since IR cameras detect the radiated heat. However, the other modes have to be understood clearly to assess the limitations of IR thermography.

All materials at a temperature above absolute zero continuously emit energy, and the energy thus emitted, called thermal radiation, is transmitted in the space in the form of electromagnetic waves [17]. Infrared waves constitute a part of the electromagnetic spectrum, e.g. microwaves or X-rays. The radiant flux ϕ per unit surface area of the material is related to the fourth power of its absolute temperature T by the Stefan–Boltzmann law:

$$\phi = \epsilon\sigma T^4 \tag{2}$$

where σ is the Stefan–Boltzmann constant, and ϵ is the emissivity of the material.

If some amount of energy is introduced at a given location of a material, the energy given to the system will gradually diffuse into the whole material. This mechanism of heat transfer is called conduction [18]. Significance of conduction in civil engineering applications of infrared thermography is that if the defects are located deep in concrete or if their diameter is small compared to their depth, the thermal contrast at the surface will be very small due to conduction. Thus, such defects may stay undetected by IR thermography. Convection is the mode of heat transfer between the material and a volume of fluid, at a temperature different from that of the material, flowing along the surface of the material. The effect of convection in NDT of concrete structures is important since the majority of the measurements take place in the field. If the wind speed is high at the time of the measurement, heat transfer due to convection

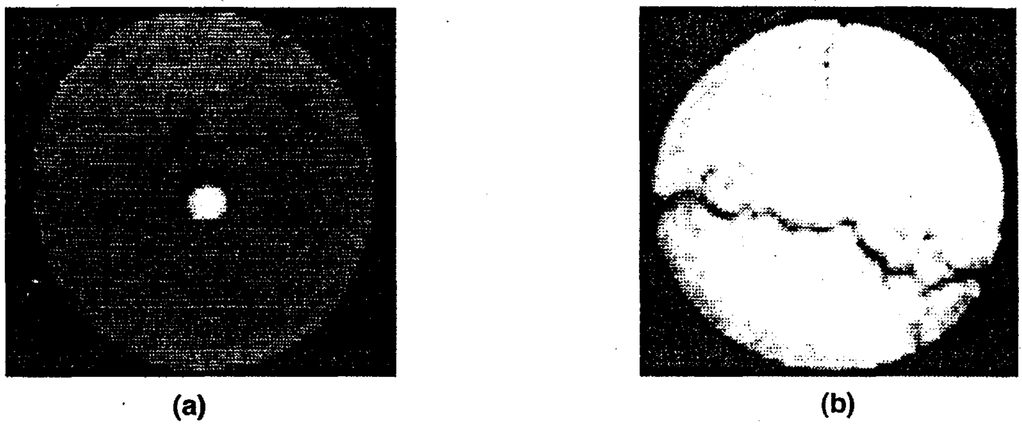


Figure 2 Computerized tomographic imaging of (a) a concrete cylinder with a rebar at the center, (b) a plain concrete cylinder loaded to failure[13]

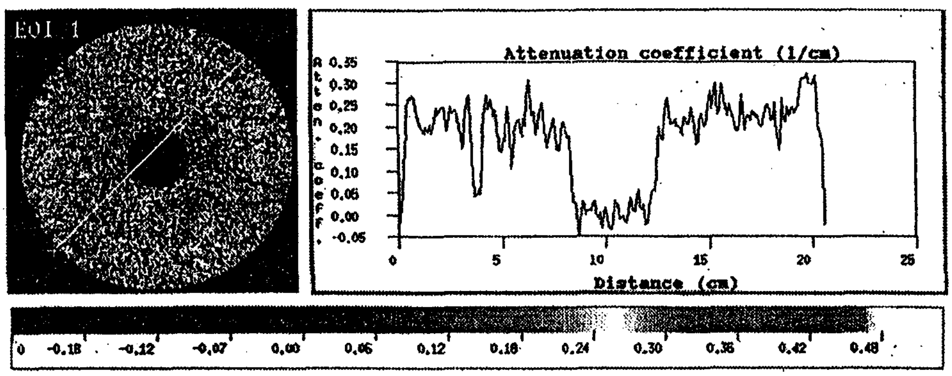


Figure 3 Tomographic image of a concrete cylinder with a hole at the center and one-dimensional profile of attenuation coefficient along the white line [14]

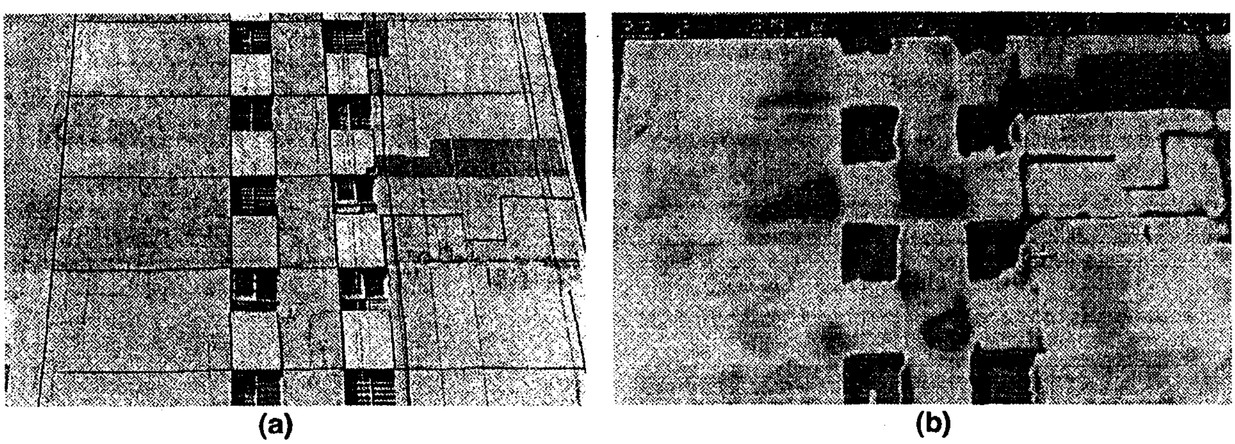


Figure 4 (a) A picture of the end wall of the building. (b) A computer-enhanced tomogram of a part of the picture in (a) [19]

affects the heat radiation from the concrete surface, resulting in false images.

The most critical survey parameters which affect the success of infrared thermography techniques are solar radiation, surface emissivity and wind speed. For quantitative assessment of concrete structures, corrections can be applied to the measurement data considering the effects of emissivity, sky temperature, wind velocity and radiation from the surrounding objects. Still, IR thermography surveys are restricted to certain weather conditions. Another limitation of IR thermography is that it provides no information about the depth of the defects, since it images the radiation from the concrete surface. To remedy this shortcoming, it can be combined with ground-penetrating radar.

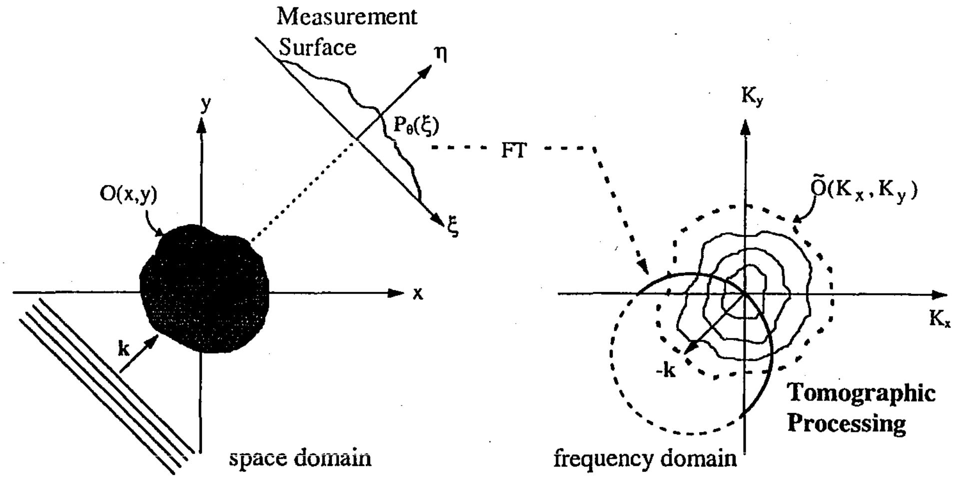


Figure 5 Fourier diffraction theorem and tomographic processing approach

Stanley and Balendran [19] applied IR thermography on the exterior of a building to detect the debonded areas. Figure 4(a) shows the repaired areas and sections cut out and prepared for repair. Figure 4(b) shows a computer-enhanced thermogram of the wall. The newly repaired areas appear dark in the image because of the moisture. Other dark areas are indicative of the debonded sections of the wall.

Radar (microwave) imaging

Radar technique, also known as Ground Penetrating Radar (GPR) has been extensively used in geophysical applications since the 1960s to determine the thickness of glaciers, finding petroleum deposits, locating sewer lines and buried objects, e.g. hazardous waste containers, to assess the bed profile of lakes and rivers, and for subsurface characterization. Civil engineering applications of the radar technique include inspection of highways and bridge decks [20], detection of cavities behind concrete tunnel linings [21], and detection and quantification of local scour around bridge piers [22,23]. Applications of the radar method to structural concrete elements, e.g. beams, columns and walls, are still at the early stages.

The principle of the radar method is to generate and transmit electromagnetic short pulses or time harmonic waves through a transmitter antenna towards a target medium, and record the scattered signals at the receiver antenna. Propagation of electromagnetic waves in free space and media can be described by a set of coupled equations called Maxwell's curl and divergence equations [24]. Incorporating the electromagnetic material properties of the target and appropriate boundary conditions, a unique solution of the forward problem can be obtained using Maxwell's curl equations [25,26].

When the transmitted electromagnetic waves encounter an object or another medium with different EM properties, some portion of the transmitted energy is reflected from the boundary, and the rest is transferred into the new medium undergoing some refraction depending on the material properties of the new medium and the angle of incidence. Thus, the scattered signals recorded at the receiver contain some information about the target's EM properties which can be extracted by processing and interpreting the recorded signals [27,28]. The scattered signals can be acquired either in a bi-static setup (offset experiment, pitch-catch experiment) in which the transmitter and receiver antenna are separate, or monostatic setup (zero offset experiment, pulse-echo experiment) in which both units coincide. Data obtained by moving the observation point within a prescribed aperture either in monostatic or bi-static mode can be used to reconstruct spatial images of the target through imaging algorithms. In the radar method, the ability to image buried inclusions in concrete, e.g. rebars and delaminations, requires understanding of concrete as a dielectric material [29,30], and application of advanced imaging techniques.

Inversion of scattered electromagnetic waves to reconstruct an image is generally based on the scalar wave equation, which implies that there is no depolarization as the electromagnetic wave propagates through the medium. The scalar wave equation, also called the Helmholtz equation, which can be derived from Maxwell's equations [24] has the following form:

$$[\nabla^2 + k_0^2]\Phi(\vec{r}) = \begin{cases} -k_0^2 O(\vec{r})\Phi(\vec{r}) & \vec{r} \in \text{object} \\ 0 & \vec{r} \notin \text{object} \end{cases} \quad (3)$$

where the wavenumber $k_0 = 2\pi/\lambda$ represents the spatial frequency of a plane wave and is a function of the wavelength λ, $\Phi(\vec{r}) = \Phi_i(\vec{r}) + \Phi_s(\vec{r})$ is the total wavefield equal to the addition of the incident and scattered fields, respectively, and $\Phi(\vec{r})$ is the object function given by:

$$O(\vec{r}) = [n^2(\vec{r}) - 1] \quad (4)$$

where $n(\vec{r})$ is the refractive index given by:

$$n(\vec{r}) = \sqrt{\frac{\mu(r)\epsilon(r)}{\mu_0\epsilon_0}} \approx \sqrt{\frac{\epsilon(r)}{\epsilon_0}} \quad (5)$$

ϵ_0 and μ_0 being the free space permittivity and permeability, respectively. The solution of Equation (3) is given by:

$$\Phi_s(\vec{r}) = \int k_0^2 O(\vec{r}')\Phi(\vec{r}')G(\vec{r}-\vec{r}')d\vec{r}' \qquad (6)$$

where $G(\vec{r}-\vec{r}')$ is the Green's function. Equation (6) is nonlinear and does not have a unique solution, since the scattered field depends on the total field, which includes the scattered field. In order to proceed further, approximations are necessary to linearize the problem. Commonly used approximations are the weak scatterer approximations called Born and Rytov approximations which are used for penetrable (dielectric) scatterers, and physical optics assumption which is used for impenetrable scatterers. Born approximation, which is the more commonly used weak scatterer approximation, takes the field inside the object equal to the incident field, therefore, is limited to very small refractive indices and small object sizes [31]. Physical optics approximation can be used to image reinforcement or metal prestressing ducts in concrete [32]. This approximation assumes that the total reflected field is twice the incident field in front of the object, and that the field behind the object is zero [5].

The commonly used imaging algorithms based on the solution of the Helmholtz equation, linearized by the discussed approximations, involve either backpropagation or tomographic processing. Microwave holography involves coherent backpropagation of the recorded wavefields towards the object in the frequency range of the measurement. Then, reconstruction of the object over a line (plane in three dimensions) is achieved by Fourier inversion. This is repeated for incremental depths of the object to obtain its two-dimensional image. An alternative algorithm, diffraction tomography, is based on Fourier diffraction theorem. This theorem states that if an object $O(x,y)$ is illuminated with a plane wave, as shown in Figure 5, the spatial Fourier transform of the forward scattered field recorded along the measurement surface gives the values of the two-dimensional spatial Fourier transform of the object $\tilde{O}(K_x, K_y)$ along a semicircular arc in the spatial frequency domain. A schematic illustration of Fourier diffraction theorem and tomographic processing algorithm is shown in Figure 5. If the source and measurement surface are at the same side of the target, then the Fourier transform of the backscattered fields gives the values $\tilde{O}(K_x, K_y)$ over a different semicircular arc, which completes the one shown in Figure 5 to a full circle, as shown by the dashed lines. K-space coverage of the object function can be increased by multi-frequency and/or multi-directional experiments. The final image can be obtained by a two-dimensional inverse Fourier transform. Transmission tomography yields a low frequency (low-pass) image of the object, whereas reflection tomography yields an image over a frequency band (band-pass) [8,5].

Success of transform-based algorithms in imaging concrete is limited for several reasons. The main limitation is the use of linearizing Born and Rytov approximations, which are both restricted to weakly scattering objects [31]. For a lossy, conductive medium, e.g. concrete, linear inversion methods perform poorly. Hence, iterative transform-based algorithms must be used to solve Equation (6) for $O(x, y)$. The proposed methods are Born Iterative Method and Distorted Born Iterative Method [33]. Applications of these algorithms are still under research.

Another limitation stems from the use of the scalar wave equation as a basis for inversion. It was shown by Büyüköztürk and Rhim [34] through numerical and experimental studies that more information can be obtained from the scattered fields by considering polarization of electromagnetic waves. Development of polarimetric vector inverse scattering algorithms has been the subject of numerous recent studies [35]. Applications of these algorithms are currently under research.

An application of microwave imaging was performed on laboratory size concrete slab specimens with 9–11 GHz waveforms at a range of 20 m [36]. An ultra-wideband stepped frequency imaging radar was used for the measurements. An imaging algorithm was developed, motivated by array antenna theory considerations for focusing a real array at an arbitrary field point in space [37]. Range profiles are constructed by performing a Fast Fourier Transform (FFT) over frequency for each antenna position. The range profiles are then summed with appropriate range delays to focus at each image point. The dimensions and reconstructed images of the specimen with and without a rebar are shown in Figure 6.

Mast and Johansson [38] used a multi-frequency diffraction tomography imaging technique to reconstruct a three-dimensional image of a concrete slab, shown in Figure 7(a). The test slab was 1.8 m square and is 30 cm thick, and its relative permittivity to air was experimentally determined as 9. The slab contained fixed and removable reinforcing bars, two Teflon cylindrical objects, three small hollow plastic spheres to simulate voids, and two Teflon plates to simulate delaminations. The depths of the objects ranged from 6 cm to 25 cm. The measurements were performed using a non-coupled monostatic antenna over a two-dimensional synthetic aperture, at approximately 9 cm from the concrete surface, with a signal having frequency content from approximately 500 MHz to 3.5 GHz. A three-dimensional rendered image of the slab is shown in Figure 7(b). The rebars, delaminations and cylindrical objects are visible in the image. The slanted rebar is visible only at shallow depths due to the shielding effect of the above reinforcing bars and the limited penetration depth.

Davidson et al. [22] and Bungey et al. [23] used subsurface radar to detect scour holes around bridge piers. Both studies involved laboratory and field surveys using commercially available antenna systems. Imaging was performed using the wavefield migration (backpropagation) technique used in geophysics. Bungey et al. performed numerical modeling of the problem, which was validated by additional laboratory experiments. Field surveys were performed by mounting the antenna unit to the side of a boat, close to the

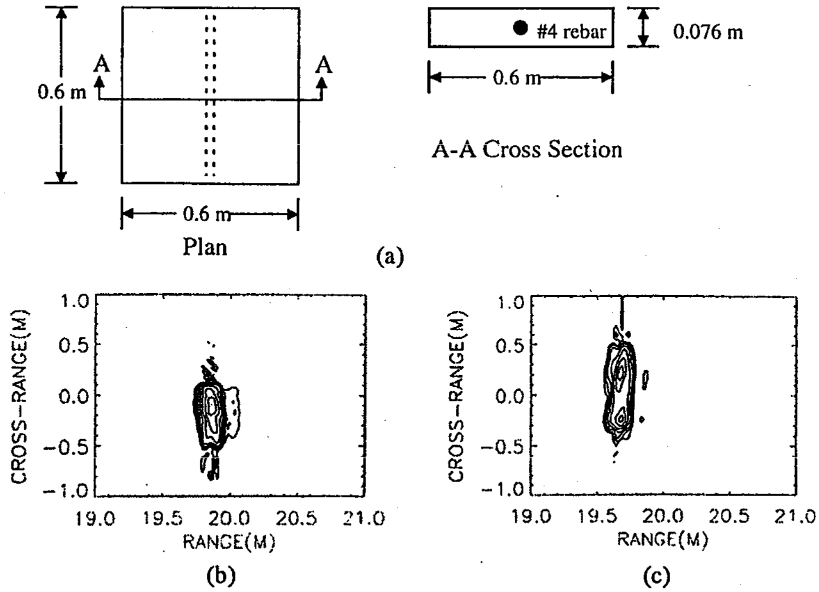
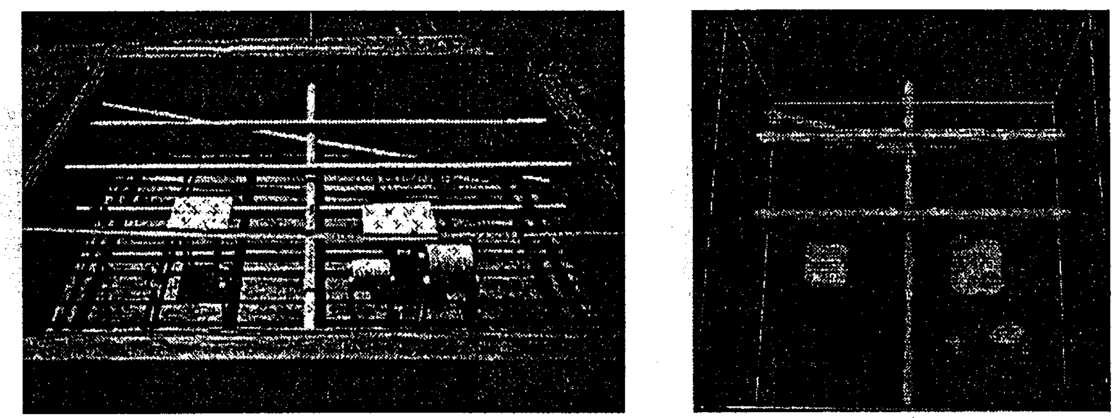


Figure 6 (a) Plan and cross-section dimensions of the slab. (b) Image of the slab without the rebar. (c) Image of the slab with the rebar [36]



(a) **(b)**

Figure 7 (a) A picture of the test slab before placing of the concrete. (b) Reconstructed image of the inclusions [38]

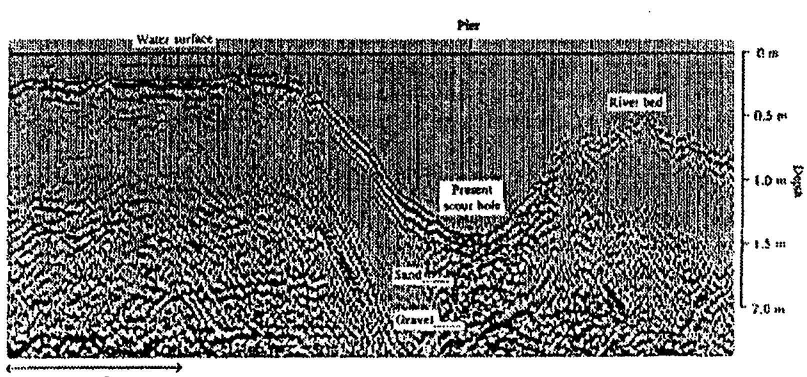


Figure 8 Migrated GPR section of the Float Viaduct spanning sandy bedded R. Clyde [22]

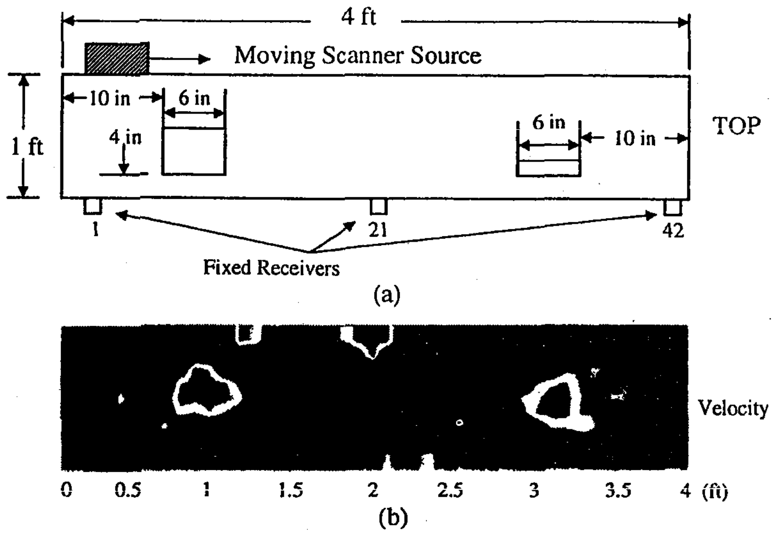


Figure 9 (a) Cross-section of the wall. (b) Reconstructed velocity tomogram (bottom) [40]

water surface. Both studies concluded that subsurface radar has high potential for detecting bridge scour. Frequencies in the range 300–500 MHz were found to be the most successful for scour surveys. The main advantage of subsurface radar against other scour detection techniques, e.g. sonar, is that microwaves can penetrate below the river bed (see Figure 8). Thus, they can provide information about the true depth of the scour holes even if they are backfilled by silt. The main problems with the use of radar for bridge scour is the high attenuation of microwaves in water due to high conductivity, and interference of the bridge columns to the image.

Acoustic imaging

Acoustic techniques include ultrasonics, impact echo and acoustic emission methods. In principle, these methods are based on elastic wave propagation in solids. Propagation of sound takes place in the form of compression (P) waves, shear (S) waves in the solid, and surface waves or Rayleigh (R) waves along the surface. Inhomogeneities in concrete cause scattering of sound waves which can be recorded and interpreted to extract information about the material [39].

Impact-echo technique involves the transmission of a transient pulse into concrete by a mechanical impact, and analysis of the reflected waves recorded at the concrete surface. This technique is not used for imaging because of the low frequency range. The method is useful for a rapid preliminary survey of the area for locating the anomalies. Images of these anomalies may then be performed using more comprehensive ultrasonic testing methods [40].

Acoustic emission (AE) technique is a passive condition monitoring technique which allows continuous testing of a structure while in service rather than at regular intervals [39]. Acoustic emission refers to the pulses due to the change in the elastic strain energy, which occurs locally in the material as a result of deformation and fracture. Part of this energy propagates through the material, which can be detected by highly sensitive transducers placed on the surface of the structure. The AE technique is used for detection purposes rather than providing an imaging capability [11].

Ultrasonics refers to the study and application of ultrasound, which is the sound of a pitch too high to be detected by the human ear, i.e. of frequencies greater than about 18 kHz [39]. The technique involves transmission of ultrasound waves into concrete using a transducer in contact with the surface of the object. The scattered signals are then recorded and interpreted. The data obtained from ultrasonic experiments can be used to reconstruct an image of the inclusions and inhomogeneities in concrete using tomographic imaging algorithms. Applications of this technique to concrete condition assessment include thickness determination [41], measurement of elastic modulus [39], and detection and imaging of cracks, voids and delaminations [42].

Imaging with ultrasound is generally performed considering ultrasound as a scalar acoustic wave phenomenon. Therefore, the imaging approach outlined for microwave imaging is directly applicable to ultrasound imaging. The only difference is that the refractive index given by Equation (5) in microwave imaging is defined in terms of sound wave velocity in concrete [Equation (7)]

$$n(\vec{r}) = \frac{c_0}{c(\vec{r})} \qquad (7)$$

where $c(\vec{r})$ is the wave velocity distribution in the object, and c_0 is the wave velocity in the homogenous medium the object is embedded in [8]. Image reconstruction can be performed using transmission or reflection data obtained using ultrasonic pulse velocity techniques or ultrasonic pulse-echo techniques, respectively.

An application of imaging using transmission data is performed by Jalinoos and Olson [40]. They performed imaging of a concrete wall with voids inside, as shown in Figure 9(a), by combining the impact echo (IE)

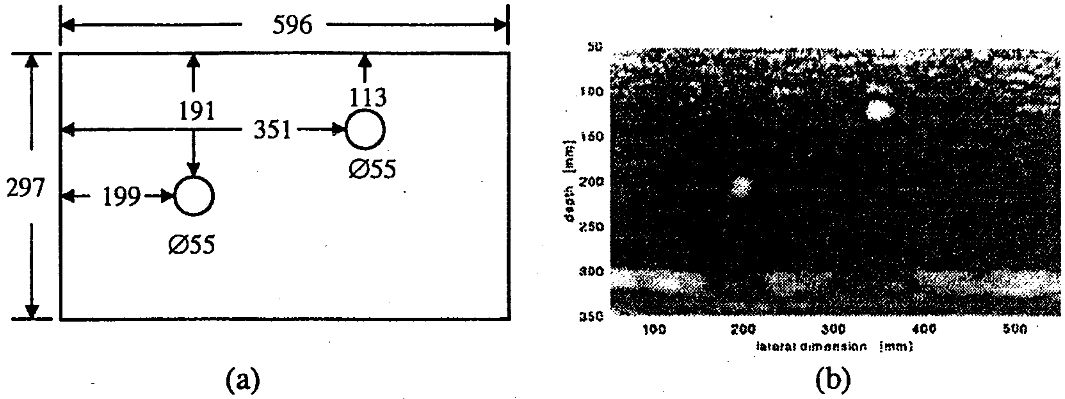


Figure 10 (a) Dimensions of the test specimen in mm. (b) Reconstructed image using SAFT [42]

and ultrasonic pulse velocity (UPV) methods with the cross-medium tomography (CMT) technique used in geophysics. The location of the voids was found using an IE scanner which allowed rapid scanning of the wall. Then, UPV tests were carried out at the void locations for image reconstruction. The image was reconstructed using an iterative approach. The reconstructed image is shown in Figure 9(b).

Ultrasonic pulse-echo techniques involve introduction of a stress pulse into concrete at an accessible surface by a transmitter. The pulse propagates into concrete and is reflected by cracks, voids, delaminations or material interfaces. The reflected waves, or echoes, are recorded at the surface, and the receiver output is either displayed on an oscilloscope or stored for further processing. There are several methods of examining a test specimen using the pulse-echo technique [10].

The A-scan or A-scope method is a one-dimensional view of the defects in concrete. The B-scan or B-scope method involves a series of parallel A-scans and produces a two-dimensional view of the defects in concrete. The C-scan or C-scope method involves a series of parallel A-scans performed over a surface. For high frequency ultrasound imaging applications which can be used for NDT of metals, display of B- or C-scans can provide significant information about the interior defects due to the high directivity of the waves. However, the presence of coarse aggregate, often exceeding 10 mm in diameter, requires that ultrasonic testing in concrete be conducted at relatively low frequencies in order to avoid excessive attenuation caused by scattering [39]. Thus, the ultrasonic beam has virtually no directional characteristics, which makes it difficult to infer the size of the defects. The data obtained from B- or C-scans need to be further processed to extract useful information about the size of the inhomogeneities.

Schickert [42] performed ultrasonic imaging of a laboratory size test specimen with two holes using the pulse-echo technique. For imaging, Synthetic Aperture Focusing Technique (SAFT) was used. SAFT can be considered as a backpropagation technique which produces an image of the object interior by focusing the recorded data [7]. The measurements were performed over a linear aperture (line-SAFT) and the reconstruction was performed in the time domain. Imaging was performed for three specimens of the same geometrical shape but different maximum aggregate sizes to demonstrate the effect of aggregate size on ultrasonic imaging. Figure 10(a) shows the test specimen and Figure 10(b) shows the reconstructed image of the specimen with maximum aggregate sizes of 8 mm. The same procedure was repeated for specimens having maximum aggregate sizes 16 and 32 mm, respectively. A significant decrease in the image quality was observed for the larger aggregate sizes.

Conclusion

Imaging of concrete structures presents many challenges due to the fact that concrete is a non-homogeneous material. Variable grain size distribution and different properties of the constituent materials make it difficult to produce accurate images. In addition, the generally complex physical geometry of the structure, restricted accessibility, and existence of reinforcement and prestressing tendons further complicate the problem.

Imaging of concrete structures may be achieved using techniques, e.g. radiography, radioactive computerized tomography, infrared thermography, radar imaging and acoustic imaging. Although various applications have used these techniques in the evaluation of concrete materials and structures, current imaging capabilities are limited in this field; continued development is needed.

Radioactive techniques generally result in high resolution images due to the use of non-diffracting sources with high penetration capability, but they are limited by the factors related to safety, and the equipment and operation costs. Also, the method requires accessibility to both sides of the object, which is a severe limitation for the NDT of concrete structures. Infrared thermography enables remote, rapid and accurate imaging. Its limitations are the sensitivity of the results to weather and surface conditions. Also, thermographic imaging does not provide information about the depth of the anomalies. Radar and ultrasound techniques do not pose any danger during the measurements, but their imaging capability is limited compared to the radioactive techniques due to diffraction effects and lack of exact inversion algorithms. Radar technique is effective in locating and imaging subsurface defects and inclusions. It allows a rapid and non-contact measurement and imaging of large areas. Imaging limitations include loss of polarization information due to scalar inversion, high attenuation of EM waves in moisture, and total reflection from metals which makes it difficult to image areas beneath closely spaced reinforcement meshes. Ultrasound is not affected by the presence of reinforcements and moisture, but is highly sensitive to the maximum aggregate size. Also, the requirement of surface coupling makes it time consuming to perform imaging of large areas.

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