DETERIORATION AND NONDESTRUCTIVE EVALUATION OF CONCRETE

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ABSTRACT

Demand for reliable and cost effective condition assessment strategies has increased with the growing concern about the deteriorating nature of World's infrastructure. In the Arabian Gulf region, accelerated deterioration of concrete structures due to the hot and aggressive environment has stimulated interest in structural condition assessment as a basis for quality control, early detection of deficiencies and signs of deterioration, and for timely preventive measures. Nondestructive evaluation (NDE) techniques, due to their non-intrusive nature and their potential for providing quantitative information, are particularly convenient for use in condition assessment of concrete structures. Incorporation of the quantitative results of standardized NDE techniques in infrastructure management systems can provide the needed feedback in monitoring the state of health of the concrete infrastructure, and in setting up priorities for repair, retrofitting, or replacement actions. Although, presently, advanced NDE techniques are routinely used in various fields, implementation of these technologies in NDE 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 gives a brief review of concrete deterioration and presents basic principles, capabilities and limitations, and application examples of several NDE techniques applicable to concrete structures.

KEYWORDS

Concrete; deterioration; condition assessment; nondestructive evaluation; imaging.

INTRODUCTION

There is a growing concern about the deteriorating nature of the World's concrete infrastructure (Chong, 1995; Scalzi, 1995). Deterioration of concrete severely affects the service lives, safety, and maintenance costs of concrete structures. The rate of concrete deterioration accelerates in time when prompt remedial actions are not taken and may result in reduced safety, expensive repairs or replacement, or even total breakdown of the structure. The direct costs of maintenance, repair, or replacement are often accompanied by indirect costs that are induced by capacity reductions and disruption of services.

In order to achieve efficient infrastructure management, it is of critical importance that the state of health of the constructed facilities are regularly monitored and preventive maintenance is performed while the degree of deterioration is low. Nondestructive evaluation techniques, when properly adopted and developed, could provide the needed feedback to maintain constructed facilities properly and prolong the their service lives. In this paper, a brief review of concrete deterioration with emphasis on the conditions of the Arabian Gulf region is provided and several nondestructive evaluation (NDE) techniques applicable to concrete structures are discussed.

CONCRETE DETERIORATION

Several factors contribute to the deterioration of existing concrete structures including mechanical, physical, chemical and electro-chemical effects associated with loading and environmental conditions (ACI, 1992a; Rostam, 1996). Mechanical effects result in cumulative damaging of the structure through concrete cracking and crushing, and reinforcement yielding and pull-out. Physical effects include shrinkage cracking, steep thermal gradients, and pressure due to recrystallization of salts in pores. Chemical effects, which include carbonation, chloride contamination, alkali silica reactions, sulphate attack, and acid attack, generally result in expansive reactions and subsequent damage in concrete. Electro-chemical effects include corrosion of steel reinforcement whose protective cover is already depassivated by carbonation and chloride attack. The corrosion process forms rust, which occupies a volume several times the original steel it replaces. Formation of rust applies pressure to the surrounding material resulting in stress levels greater than the tensile strength of concrete; thus, concrete fracture and rebar separation takes place. Reinforcement corrosion results in extensive cracking, delamination, and spalling of concrete and is most detrimental to the integrity of a concrete structure. Environmental deterioration of concrete generally is a result of some substance penetrating from the outside into concrete through the surface. Temperature strongly affects the rate at which deterioration takes place, approximately doubling the rate of chemical and electrochemical reactions at every ten degrees.

In the Arabian Gulf region, deterioration of concrete structures takes place at relatively higher rates due to the hot climate and the aggressive environment (Zein Al-Abideen, 1995). Climatic factors that influence the properties of fresh and hardened concrete are ambient temperature, relative humidity, wind velocity, and solar radiation (FIP, 1986). Placing of concrete under adverse combinations of these factors may substantially decrease its quality and durability (RILEM, 1992, ACI 1992b, Soroka, 1993). Hot weather concreting, especially at high wind speed and low relative humidity, may give rise to high porosity and permeability, plastic shrinkage cracks, cold joints, reduced bond with reinforcement, and reduced ultimate strength. High chloride contamination in coastal areas accelerates reinforcement corrosion and concrete cracking.

Premature deterioration and low durability of concrete construction in the Arabian Gulf region is attributed not only to the climate and environment, but also to a number of reasons associated with inadequate design, materials, construction, and quality control, especially before 80's. The primary mechanisms of concrete deterioration in this region are reported as reinforcement corrosion in the coastal areas, and cracking and deflection due to thermal expansion in the inland areas. Surveys on existing concrete structures have revealed that inadequate thickness and quality of concrete cover is the primary cause of chloride attack and reinforcement corrosion (Zein Al-Abideen, 1995).

NEED FOR CONDITION ASSESSMENT AND NDE

Demand for reliable and cost effective condition assessment strategies has increased with the growing concern about the deteriorating nature of World's infrastructure. 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 NDE techniques which will facilitate rapid, cost efficient, and reliable condition assessment of existing infrastructure to ensure public safety. In the Arabian Gulf region, accelerated deterioration of concrete structures due to the hot and aggressive environment has stimulated interest in structural condition assessment as a basis for quality control, early detection of deficiencies and signs of deterioration, and for timely preventive measures. Nondestructive evaluation techniques, due to their non-intrusive nature and their potential for providing quantitative information, are particularly convenient for use in condition assessment of concrete structures. Incorporation of the quantitative results of standardized NDE 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.

The primary goal of any nondestructive 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. NDE of concrete is a challenging task since concrete is a highly nonhomogeneous 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.

Several NDE techniques which are known in medical diagnostics, aerospace and geophysical applications, and in NDE 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 NDE 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 NDE to determine the spatial extent of the anomalies in two or three dimensions as well as the nature of such anomalies by applying various imaging techniques. The NDE techniques considered in this paper are radiography, computerized radioactive tomography, infrared thermography, radar, and acoustic techniques. Principles and application considerations of imaging using these techniques are discussed and examples are given.

RADIOGRAPHY

Radiography is one of the earliest NDE techniques which is used to obtain a shadow image of a solid using penetrating radiation such as x-rays or gamma-rays generated by x-ray tubes or radioactive isotopes respectively (Cartz, 1995). X- and gamma-rays are forms of electromagnetic radiation such as visible light and microwaves, but their wavelengths are so small that they can penetrate all materials with some absorption and scattering during transmission (Halmshaw, 1991). 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:

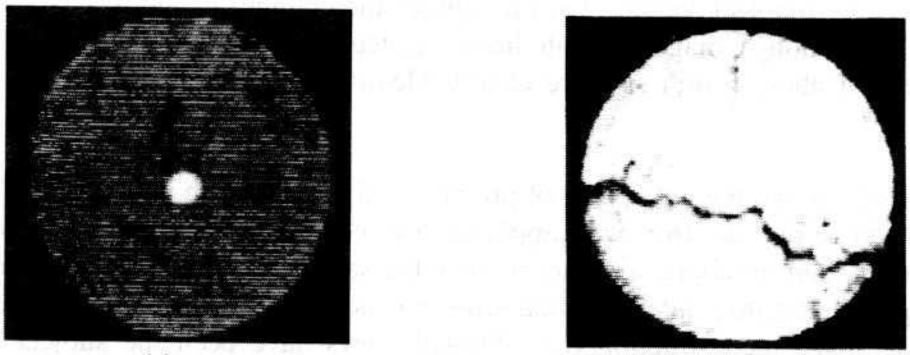
$$I = I_o \exp\left(-\int_0^L \mu(x,y,z)\, dL\right) \tag{1}$$

where I_o 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. 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 2-D projection which provides information about the physical characteristics of concrete such as 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 2-D 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 the most important of all, the requirement of accessing both sides of the structure. Gamma radiography has more field applications since the source is compact and easy to transport, independent of electrical and water supplies, and low cost. 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 (Mitchell, 1991).

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 in different directions 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



(a) (b)

Figure 1. Computerized tomographic imaging of (a) a concrete cylinder with a rebar at the center, (b) a plain concrete cylinder loaded to failure (Morgan et al. 1980)

invention of the X-ray computed tomographic scanner by Hounsfield in 1972 (Kak and Slaney, 1988).

Morgan et al. (1980) 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 degrees around the cylinders. The exposure time for each projection was 40 minutes due to low source intensity. The system was able to identify the density within 1 percent. Results of scans of two concrete cylinder specimens are shown in Fig. 2. In Fig. 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 the voids in the cylinder are accurately detected. Fig. 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. (1991). They developed an x-ray CT system to quantitatively inspect small concrete samples for density variations with a spatial resolution of about 2 mm. Fig. 3 shows an image of a 20 cm diameter hollow cylinder with a 4.4 cm central hole reconstructed from 45 projections at 4

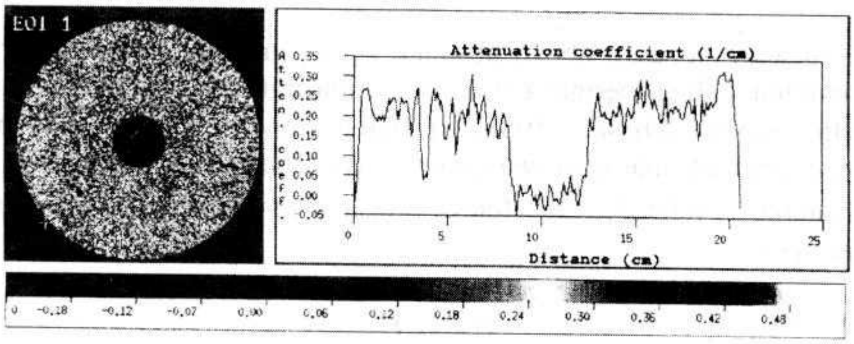


Figure 2. Tomographic image of a concrete cylinder with a hole at the center and 1-D profile of attenaution coefficient along the white line (Martz et al. 1991)

degree intervals over 180 degrees. On the right of the cylinder image is a 1-D attenuation profile extracted along a diagonal white line indicated on the image. The central hole and a smaller void of about 5 mm size are clearly identified both on the image and the 1-D 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 have been the subject of several studies (Tam, 1988), 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

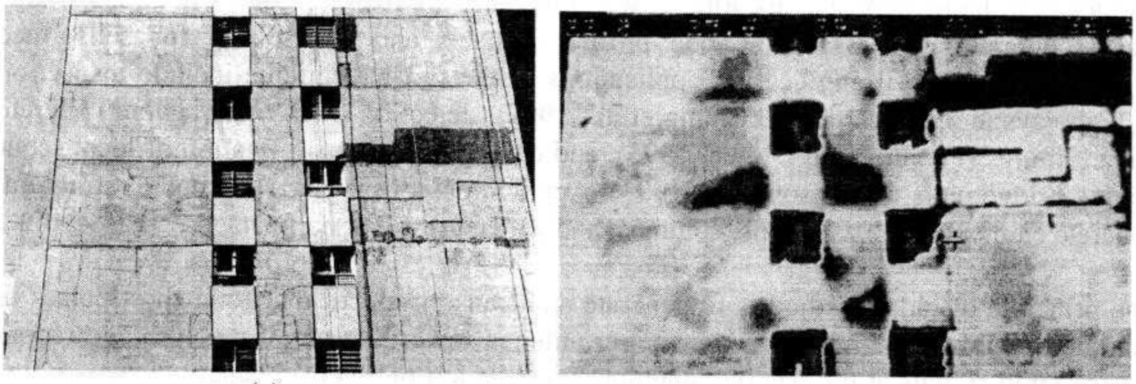
Infrared (IR) techniques are commonly used in military applications, NDE of materials, and medical diagnosis. Within certain limitations, infrared thermography is a remote, fast, and cost efficient NDE method with qualitative or quantitative information potential. It can be used to locate and determine 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 (Ljungberg, 1994). 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 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 such as a flash tube or the solar radiation (Halmshaw, 1991).

Heat transfer takes place in three modes called conduction, convection, and radiation. The mode which interests us most from the NDE 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 (Ozisik, 1985). Infrared waves constitute a part of the electromagnetic spectrum like 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-Boltzman law:

$$\varphi = \varepsilon \sigma T^4 \tag{2}$$

where σ is the Stefan-Boltzman constant, and ε is the emissivity of the material.



(a) (b)

Figure 3. (a) A picture of the end wall of the building, (b) a computer enhanced tomogram of the wall (Stanley and Balendran, 1994)

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 (Beaudoin and Bissieux 1994). 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. Effect of convection in NDE of concrete structures is important since a 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 affects the heat radiation from the concrete surface, resulting in false images.

The most critical survey parameters which affect the success of infrared thermography technique 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.

Stanley and Balendran (1994) applied IR thermography on the exterior of a building to detect the debonded areas. Fig. 4(a) shows the repaired areas and the sections cut out and prepared for repair. Fig. 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) TECHNIQUE

Radar technique, also known as Ground Penetrating Radar (GPR) has been extensively used in geophysical applications since 1960's to determine the thickness of glaciers, finding petroleum deposits, locating sewer lines and buried objects such as 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 (Chung et al., 1992), detection of cavities behind concrete tunnel linings (Fenning and Brown, 1995), and detection and quantification of local scour around bridge piers (Davidson et al. 1995). Applications of the radar method to structural concrete elements such as beams, columns, and walls are still at early stages.

The principle of 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 in media can be described by a set of coupled equations called Maxwell's curl and divergence equations (Kong, 1990). 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 (Buyukozturk and Rhim, 1995b).

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

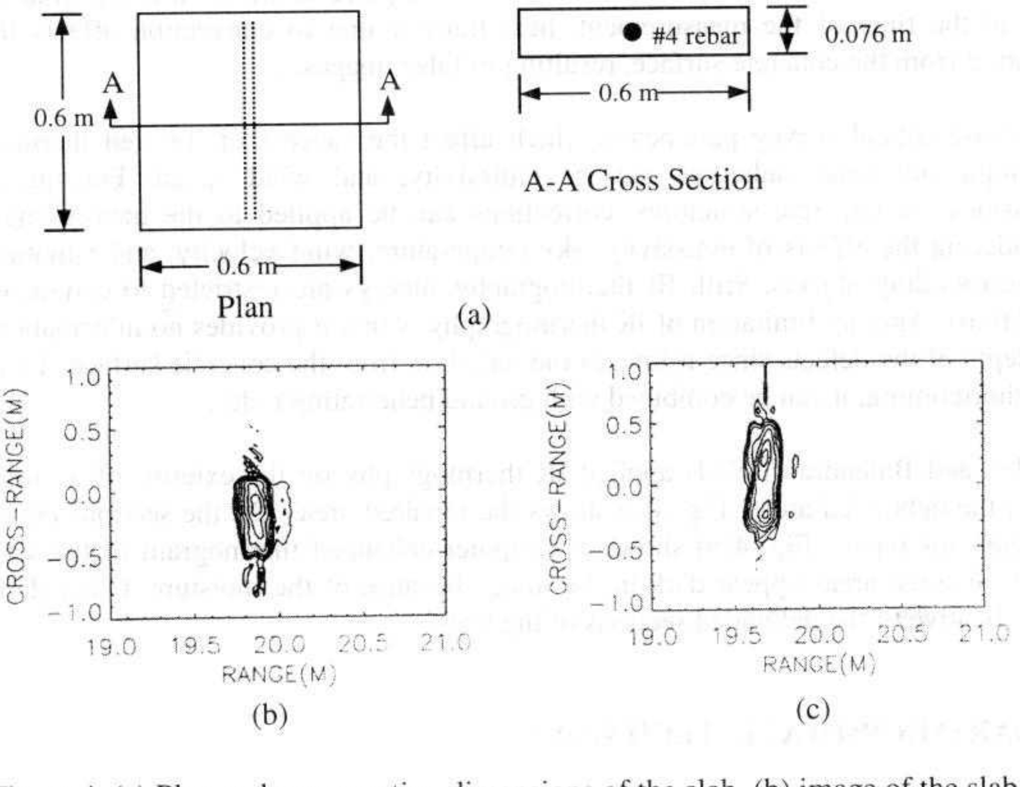


Figure 4. (a) Plan and cross section dimensions of the slab, (b) image of the slab without the rabar, (c) image of the slab with the rebar (Rhim et al., (1995)

(Buyukozturk and Rhim, 1995c, 1996). In the radar method, the ability to image buried inclusions in concrete such as rebars and delaminations requires understanding of concrete as a dielectric material (Rhim and Buyukozturk, 1998) and application of advanced imaging techniques.

An application of microwave imaging was performed on laboratory size concrete slab specimens with 9-11 GHz waveforms at a range of 20 meters (Rhim et al., 1995). 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 (Verbout and Blejer, 1991). 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 the reconstructed images of the concrete specimen with and without a rebar are shown in Fig. 4.

More recently, a numerical study is performed by the authors (Gunes, 1998) with the objective of investigating the potential of radar technique for use in NDE of concrete. A simulation of electromagnetic wave propagation through a concrete cylinder is performed using finite difference-time domain technique (Buyukozturk and Rhim, 1994, 1995a). The transmitted and reflected data obtained from the simulation is processed to reconstruct images of the concrete cylinder using an imaging technique called wavefield backpropagation. Three snap shots from the simulation and the reconstructed images in transmission and reflection modes are shown in Figure 5.

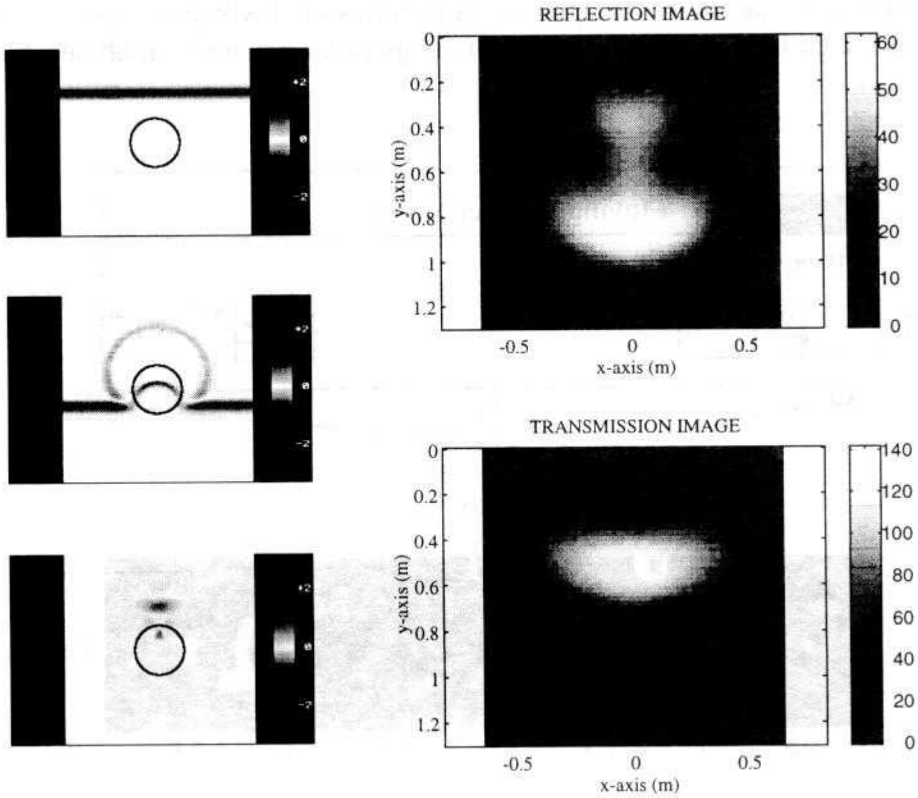


Figure 5 Simulation of EM wave propagation through a concrete cylinder and image reconstruction using transmitted and reflected data

ACOUSTIC TECHNIQUES

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 forms 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 (Blitz and Simpson, 1996).

Impact-echo technique involves 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 (Jalinoos and Olson, 1995).

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. 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. AE technique is used for detection purposes rather than providing an imaging capability (Halmshaw, 1991).

Ultrasonics refers to the study and application of ultrasound which is sound of a pitch too high to be detected by the human ear, i.e. of frequencies greater than about 18 kHz. The

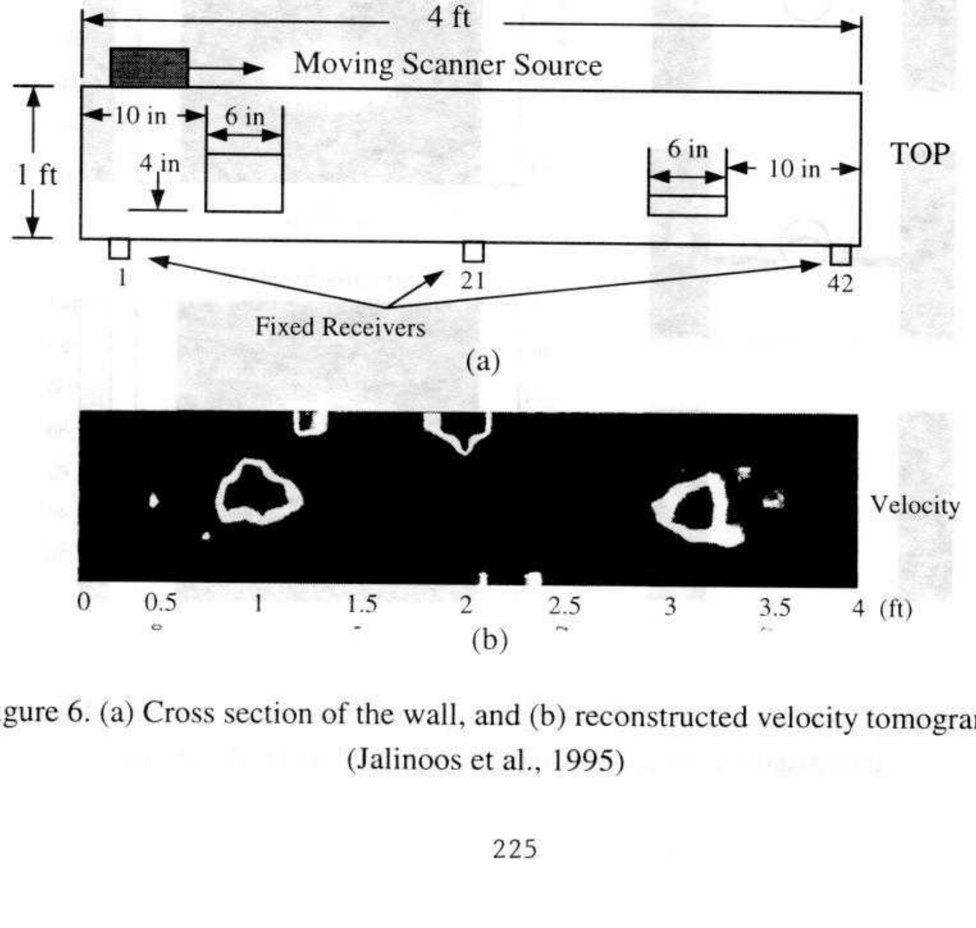


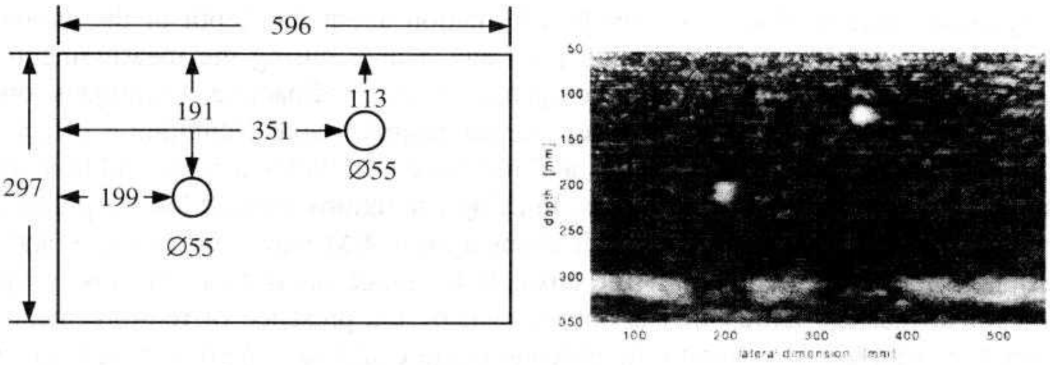
Figure 6. (a) Cross section of the wall, and (b) reconstructed velocity tomogram (Jalinoos et al., 1995)

technique involves transmission of ultrasound waves into concrete using a transducer in conctact 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 (Krause et al. 1995), measurement of elastic modulus (Blitz and Simpson, 1996), and detection and imaging of cracks, voids and delaminations (Schickert, 1995).

An application of imaging using transmission data is performed by Jalinoos et al. (1995) They performed imaging of a concrete wall with voids inside as shown in Fig. 7(a) by combining the impact echo (IE) and ultrasonic pulse velocity (UPV) methods with the crossmedium 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 Fig. 7(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, is 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 (Cartz, 1995).

Schickert (1995) performed ultrasonic imaging of a laboratory size test specimen with two holes using 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. 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 same geometrical shape but different maximum aggregate sizes to demonstrate the effect of aggregate size on ultrasonic imaging. Fig. 8(a) shows the test specimen and Fig 8(b) shows the reconstructed image of the specimen with maximum aggregate sizes of 8 mm. Same



(a) (b)

Figure 7. (a) Dimensions of the test specimen in mm, (b) reconstructed image using SAFT (Schickert, 1995)

procedure was repeated for specimens having maximum aggregate sizes 16 mm and 32 mm respectively. A significant decrease in the image quality was observed for the larger aggregate sizes.

CONCLUSION

The Arabian Gulf region presents an unfavorable environment to concrete structures. The hot climate and aggressive environmental conditions in this region result in premature deterioration of many structures, especially when coupled with inadequate design and construction. Quality control and early detection of deficiencies and deteriorated areas in concrete plays a vital role in maintaining the safety and serviceability of concrete structures. Thus, inspection and condition assessment of concrete structures must be performed on a regular basis for effective infrastructure management.

Nondestructive evaluation techniques, provide a convenient means for condition assessment of concrete structures due to their non-intrusive nature and their potential for providing quantitative information. NDE of concrete structures presents many challanges due to the fact that concrete is a nonhomogeneous 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.

NDE of concrete structures may be achieved using techniques such as radiography, radioactive computerized tomography, infrared thermography, radar imaging and acoustic imaging. It is important to note that each technique has certain capabilities and limitations, and no single technique is sufficient for complete characterization of concrete.

Radioactive techniques generally result in high resolution images due to the use of nondiffracting 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 NDE 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 make 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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