IMAGING OF REINFORCED CONCRETE: STATE-OF-THE-ART REVIEW

By Geneviève F. Pla-Rucki[1] and Marc O. Eberhard,[2] Associate Member, ASCE

ABSTRACT: Nondestructive evaluation plays an important role in the assessment of the nation's infrastructure. The evaluation methods for reinforced and prestressed concrete facilities can become more reliable if the methods incorporate imaging technology, which has been implemented widely in many fields. Radiography, ground penetrating radar (in B-scan mode) and infrared thermography have established themselves in civil engineering practice. They are used to nondestructively locate steel reinforcement and concrete flaws, such as delaminations, cracks and honeycombing. This paper discusses the principles of these established methods, as well as their advantages and disadvantages. Radioactive computed tomography, microwave holography, microwave tomography and acoustic tomography are in various stages of development. This paper summarizes the basis for each new method and the results of recent research. It also discusses the potential advantages of the new methods and the barriers to their implementation in civil engineering applications. Examples of images obtained with each technology are provided.

INTRODUCTION

Recent advances in signal processing, combined with the development of efficient numerical algorithms and an increased access to powerful computers, have made it practical to implement imaging technology in many fields. Imaging is routinely used in the biomedical, geophysical, and oceanographical sciences, as well as for nondestructive evaluation (NDE) of metals, ceramics, and composites. In contrast, few practical imaging systems have been developed to inspect reinforced and prestressed concrete facilities. This situation may seem paradoxical if one considers the emphasis that is placed on maintaining and repairing the nation's infrastructure, and the potential benefits that a reliable imaging system would bring to the evaluation of a structure's safety and serviceability.

The purpose of this paper is to discuss opportunities and obstacles to improving nondestructive evaluation of reinforced and prestressed concrete structures by implementing imaging technology. Specifically, the paper considers radiography, radioactive computed tomography, infrared thermography, microwave imaging, and acoustical imaging. Each method is an established NDE technique or has been the subject of recent research.

THE CHALLENGE

Nondestructive evaluation can be an essential component of the evaluation or inspection of a bridge or building. To assess the condition of a reinforced concrete structure, it is necessary to locate the major concrete defects, such as large cracks, delaminations and honeycombs. These defects can decrease a member's load-carrying capacity and its resistance to corrosion. Structural assessments and inspections also depend on the reliable determination of the reinforcement's location and size. In posttensioned bridges and parking garages, it is necessary to locate broken strands and regions with poor grouting because these regions are prone to corrosion. Because of safety considerations, the location of unbonded prestressing tendons is particularly important when coring and drilling operations will be performed.

For simple geometries, common nondestructive equipment, such as ultrasonic pulse velocity meters and magnetic pachometers (covermeters), provide reliable information at a relatively low cost. This equipment is much less helpful when the geometry is complex, because various configurations can produce the same individual measurement. In these situations, imaging techniques are attractive because they provide a unique interpretation of a large number of measurements.

The development of an imaging system for reinforced-concrete applications, however, poses challenges that are not present in many other applications. Unlike medical imaging systems, a practical civil engineering system should be portable, rugged, and easily adaptable to a variety of geometries. In addition, the properties of concrete make it particularly difficult to image. Whereas only compression waves can propagate through human tissues and ocean water, shear and surface waves also travel through concrete. Moreover, unlike metals and ceramics, concrete is highly inhomogeneous on a macroscopic level. For example, whereas grain sizes in steel are usually smaller than 1 mm, coarse aggregates in concrete are several centimeters in size.

The economics of civil engineering NDE may place the greatest limit on implementation of imaging technology. For most civil engineering applications, a system is unlikely to be affordable if it requires expensive equipment and highly-trained operators. A technology's economic viability will also depend on the extent to which an inspection disrupts a facility's functions. In some cases, the indirect costs of disrupting a facility's function can exceed the direct costs of the inspection.

RADIOGRAPHY

The first modern imaging technique, radiography, originated with the discovery of X rays by Röntgen in 1895. Today, radiography is the most common imaging modality, and it is used for both medical and industrial applications. The radiation usually takes the form of X rays, which are produced in X-ray tubes, or gamma rays, which are emitted from radioactive isotopes. The wavelengths of X rays range from 10^{-6} μm to 10^{-2} μm, whereas gamma rays have wavelengths that are less than 10^{-4} μm. A radiographic imaging system consists of three components: the radiation source, the object to image, and a detector, usually a photographic film. As the radiation is sent through the object, some of the photons are absorbed by the object while others travel through and are recorded on the detector. The transmitted intensity, I, is related to the incident intensity, I_o, by the following relation:

$$I = I_0 \exp\left[-\int_0^t \mu(x, y, z)\, dt\right] \qquad (1)$$

[1]Grad. Res. Asst., Dept. of Civ. Engrg., Univ. of Washington, FX-10, Seattle, WA 98195.

[2]Asst. Prof., Dept. of Civ. Engrg., Univ. of Washington, FX-10, Seattle, WA.

Note. Associate Editor: Ken P. Chong. Discussion open until November 1, 1995. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on November 8, 1994. This paper is part of the ***Journal of Infrastructure Systems***, Vol. 1, No. 2, June, 1995. ©ASCE, ISSN 1076-0342/95/0002-0134–0141/ $2.00 + $.25 per page. Technology Review No. 9562.

where $\mu(x, y, z)$ is the attenuation coefficient, which depends on the object's density at location (x, y, z). The integral is evaluated over the thickness, t, of the object (Stern and Lewis 1971). Therefore, the ratio of the measured to incident intensity is a two-dimensional projection of the attenuative properties of the object.

Radiography produces good two-dimensional images for reinforced concrete because the attenuative characteristics of steel, concrete, and air differ greatly. Whereas the attenuation coefficient for steel is 1, it is 0.3 for concrete and 0 for air. A major limitation to radiography is its expense; in addition to the cost of the equipment, the procedure is time consuming, and the operators must be highly trained because of the radiation hazard. To minimize the hazard, extensive shielding must be provided, and the vicinity of the radiation source must be free of people.

Radiography has been applied to both laboratory studies and field inspection. Laboratory use of radiography is mainly oriented towards microcracking studies (Mitchell 1991). In the field, radiographic systems are used to locate reinforcement, voids and cracks, as well as to assess the quality of the grouting in prestressed concrete structures. Gamma radiography, or gammagraphy, has been used since 1968 by the Laboratoire Régional des Ponts et Chaussées (LRPC) of Blois, France, to assess the quality of both new and existing prestressed concrete structures. A number of gamma-ray devices, with weights varying from 30 kg to 850 kg, have been developed. Depending on the device, concrete thicknesses varying from 100 mm to 600 mm can be inspected. In 1985, the LRPC deployed an X-ray radiographic system, called the Scorpion, which consists of a miniaturized X-ray source (250 kg) mounted on a 37-t movable crane. This X-ray system provides higher-quality images than the gammagraphic system and can image elements that are up to 1.1 m thick (Guinez 1991). Fig. 1 is an example of a radiographic image of a defect in a prestressed concrete member. The image shows a major lack of grout injection (white areas) around the prestressing tendons (darker horizontal lines).

The LRPC also developed a radioscopy system to inspect the grouting of I-beam and box-girder prestressed concrete bridges. Radioscopy is a form of radiography in which the transmitted radiation is converted into visible light and recorded by a video camera. Though it provides lower-quality images than those provided by conventional film radiography, its advantage is that it is a real-time imaging technique. Usually radioscopy is used to select the structures that need to

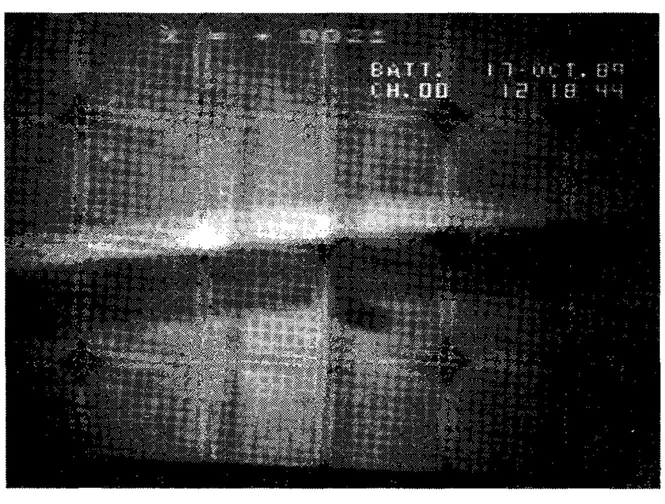

FIG. 1. Radiographic Image of Prestressing Cable (Courtesy of R. Guinez, LRPC, Blois, France)

be reinjected with grout. Then, either radiography or gammagraphy are used to locate defects precisely (Guinez 1991).

RADIOACTIVE COMPUTED TOMOGRAPHY

The intensity of the transmitted X-ray or gamma-ray signal is a function of the integral of the attenuation coefficient over the travel path, not the value of the coefficient on a particular plane, (1). Therefore, with conventional radiography, it can be difficult to isolate the plane on which a defect or a reinforcing bar is located. X-ray and gamma-ray computed tomography (CT) is a method in which the measured intensities are processed to produce cross-sectional images.

The mathematical basis for computed tomography was established in 1917 by Radon, who demonstrated that a function could be reconstructed from an infinite set of projections. To construct a tomographic image of the attenuation coefficient, $\mu(x, y, z)$, one needs to measure the integral of the attenuation coefficient along a large number of lines and at various angles in a selected plane. By transforming (1), it can be shown that this integral for a particular path is equal to the logarithm of the ratio of the measured to incident intensities:

$$\int_0^t \mu(x, y, z)\, dt = -\ln\left(\frac{I}{I_0}\right) \quad (2)$$

The incident intensity (I_0) is known, and the transmitted intensity (I) for a particular path can be measured with a CT scanner. If the ratio of intensities are measured for a sufficient number of ray paths, it is possible to reconstruct the distribution of the attenuation coefficient in each plane (Kak and Slaney 1988).

In 1980, Morgan et al. reported the development of a CT system to locate voids and reinforcement, and to determine the density of mortar and aggregates. This study was limited to the imaging of concrete cylinders. More recently, Synolakis et al. (1993) used CT to study crack development in a concrete cylinder under loading. To monitor opening of the cracks as the load was increased, the cylinder was placed in a CT scanner after each loading step. By comparing sequences of images, it was possible to show the opening of the cracks. Such a detailed reconstruction of crack development would have been impossible using conventional radiography.

The potential of gamma-ray CT as a tool for the NDE of reinforced concrete was also studied by Martz et al. (1992). Fiber-reinforced concrete cylinders, some containing reinforcing bars, were inspected by CT in order to establish the ability of this technique to determine the size and location of reinforcing bars, as well as voids and cracks. Fig. 2 is a series of CT scans of loaded cylinders at various slice planes. Cracks and voids, which appear as dark regions in the figure, are clearly differentiated from the concrete. The researchers concluded that the technique appeared promising but that further research was needed before a practical system could be developed for field use. Current research focuses on the development of limited angle reconstruction algorithms that would allow an image to be constructed without having access to the entire perimeter of a member (Heiskanen et al. 1991).

Despite the extensive information provided by X- and gamma-ray–computed tomography, this technique is mainly used for laboratory studies. Radioactive computed tomography is even more expensive than radiography, and it presents the same hazards. The cost of the equipment will have to decrease drastically and the portability will have to increase before radioactive computed tomography is implemented widely in civil engineering.

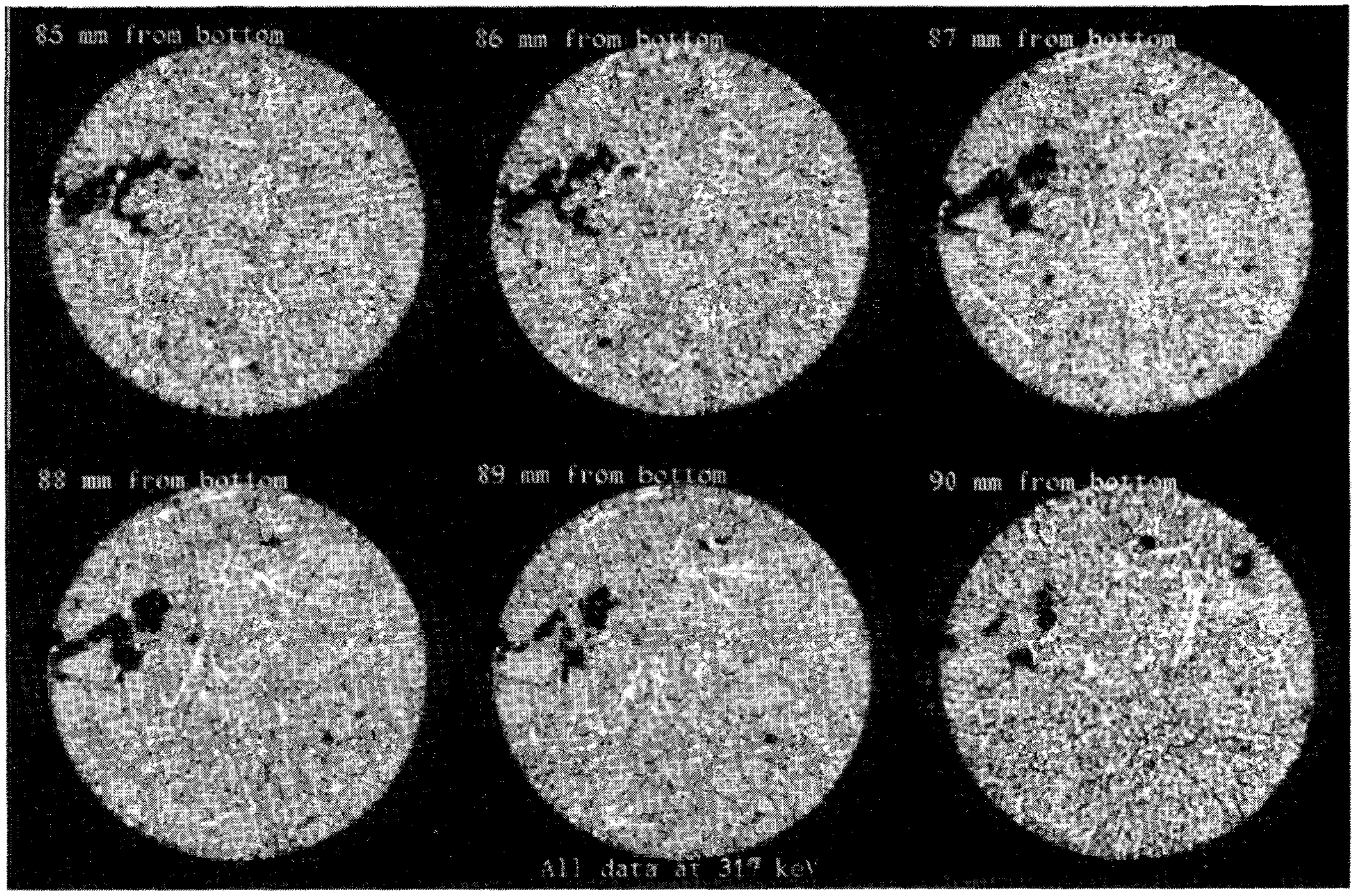

FIG. 2. CT Images of Concrete Core (Martz et al. 1992) (Courtesy of H. Martz, Lawrence Livermore Laboratory, and P. Monteiro, U.C. Berkeley)

INFRARED THERMOGRAPHY

One means of avoiding the hazards and expense associated with radioactive sources is to use a passive technology, such as infrared (IR) thermography. Infrared thermography is common in military applications, such as missile guidance, target tracking, and surveillance. Civilian applications of IR thermography include medical imaging, geophysical surveys, NDE of materials, and heat-flow monitoring (Ravich 1986). IR cameras measure the infrared radiation that is naturally emitted by a body (wavelengths ranging from 0.7 μm to 14 μm); thermal images are produced by converting the IR radiations emitted by a body into electrical signals, which are further processed to create maps of the surface temperature. The emitted energy is related to the surface temperature by the Stefan-Boltzmann law:

$$W = \varepsilon \sigma T^4 \quad (3)$$

where W = radiated power per unit area; ε = emissivity factor; σ = Stefan-Boltzmann constant ($5.67\ 10^{-8}$ Wm^{-2} K^{-4}); and T = absolute temperature. Information about the subsurface can be deduced from the surface temperature because the heat flow through the body is affected by the presence of internal anomalies (Van Anda and Carter 1991).

IR thermography is commonly used to detect concrete defects, such as cracks, delaminations and concrete disintegration in bridge decks, as well as in highway and airport pavements (Maser and Roddis 1990). In addition to the low hazard associated with IR thermography, a further attraction is that inspections can be performed relatively quickly. The thermocameras can be mounted on a vehicle traveling at 1.6 to 16 km/h (Weil 1992), and inspections can be performed at night, which minimizes traffic disruption. Another advantage of IR thermography is that it is possible to identify the horizontal extent of a large defect because of the thermocameras' large coverage.

On the other hand, image interpretation is difficult because the surface temperature and emmissivity factor depend on the environment and on the surface conditions. Wind, cloud cover, surface moisture, and surface roughness are parameters that must be considered in interpreting IR images. In addition, causes of the anomalies are left to the interpretation of the operator. Other limitations of IR thermography are that the method does not provide information about the depth of a flaw and that deep flaws are difficult to detect. To overcome these limitations, IR thermography is often combined with another technique, such as ground-penetrating radar (Weil 1992). ASTM standard D 4788 ("Standard" 1994) provides further guidance on making infrared radiation surveys of pavements.

Fig. 3 shows an IR thermogram of a region of suspected delamination or debonding within a concrete bridge deck. The defect shows up as white, whereas the sound concrete around it appears darker. A visual image of the scanned area is placed next to the thermal image. Further defect classification was done by comparing the thermogram of the unknown defect with representative thermograms of delamination and debonding that were confirmed by coring.

MICROWAVE IMAGING

Ground penetrating radar (GPR) was first used to locate buried objects, but advances in computer technology and in the understanding of inverse scattering problems, have made microwaves a technically competitive choice for many imaging applications. GPR has become an indispensable tool for geophysical exploration, archaeological surveys, and asphalt and concrete pavement testing, as well as for locating cables, pipes, and hazardous-waste containers (Daniels et al. 1988).

In the case of concrete imaging, microwaves present some significant advantages over other sources of energy. Microwaves can penetrate deep members without posing a hazard. In addition, unlike acoustical waves, they scatter little and provide an excellent contrast between the concrete and steel. The main drawback to microwave imaging is that they diffract greatly because the wavelengths of microwaves (1 to 300 mm) are of the order of the member's dimensions (Bolomey and Pichot 1992). The diffraction increases the complexity of the reconstruction procedure.

B-Scans

Ground-penetrating radars send short microwave pulses into an object. The pulses are reflected at interfaces between media of differing dielectric properties, and the echoes are monitored by a receiver. The depth of the interface can be estimated from the round-trip travel time of the pulse if the pulse velocity is known (Bungey et al. 1992). Usually, the pulse velocity is determined on a cored sample or on a member of known depth, and it is assumed to be the same everywhere. Ground-penetrating radar systems usually provide plots of signal magnitude as a function of the time of arrival of the echo and as a function of the antenna location (B-scans). The signal magnitude at a particular time and location is usually indicated by variations in shading or by variations in color.

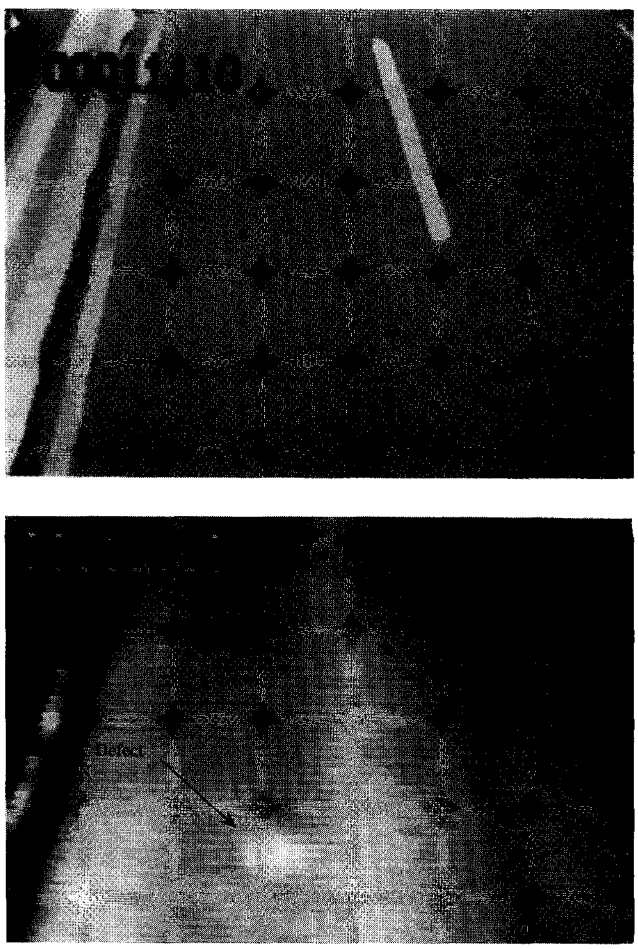

FIG. 3. Visual and Thermal Images of Concrete Deck Defect (Courtesy of D. Ulrikson, RUST Environment & Infrastructure, Inc., Milwaukee, Wis.)

A B-scan of a slab with four reinforcing bars is shown in Fig. 4. The horizontal coordinate corresponds to the source/receiver horizontal location, and the vertical coordinate corresponds to the round-trip travel time. If the wave-propagation velocity is known, the time scale can be converted to a depth scale. The vertical dotted lines are reference location marks. The other dark regions correspond to times and locations at which the reflected signal amplitude exceeds a threshold value, which is controlled by the operator. The bars appear as crescents because the travel time is a minimum when the antenna is located directly above a bar. As the antenna moves away from the bar, the round-trip travel time increases.

Ground-penetrating radar has become a common tool to inspect concrete pavements, buildings, and bridge decks. It is used to determine the depth of defects, such as cracks, voids, delaminations, and debonding of the asphalt overlay. It is also used to evaluate the thickness of concrete members and to detect steel reinforcement. For dry, unreinforced concrete, the sounding depth can reach 0.6 m (Weil 1992).

Ground-penetrating radars operate in any type of weather because atmospheric conditions do not affect microwave propagation. Another important advantage of GPR for concrete inspection is that it is not necessary to couple the antennas to the concrete surface because the reflection at the air-to-concrete interface is very low. A drawback to B-scans is that they can be difficult to interpret, especially if the reflectors are closely spaced. In addition, the threshold setting greatly affects the plot. Another limitation of GPR imaging is that the estimate of the reflector depth depends on the assumed wave-propagation velocity. Though this uncertainty can be reduced by measuring the velocity within cored samples, the velocity estimate is often inexact because the concrete's dielectric properties, which affect the velocity, vary with moisture content.

Holography

It is possible to further process the ground-penetrating radar measurements to obtain images that are easier to interpret. Mast (1992) implemented a holographic reconstruction algorithm (wavefront reconstruction) on the basis of the following assumptions: (1) the medium between the reflector (bars or voids) and the transducer was homogeneous; (2) the

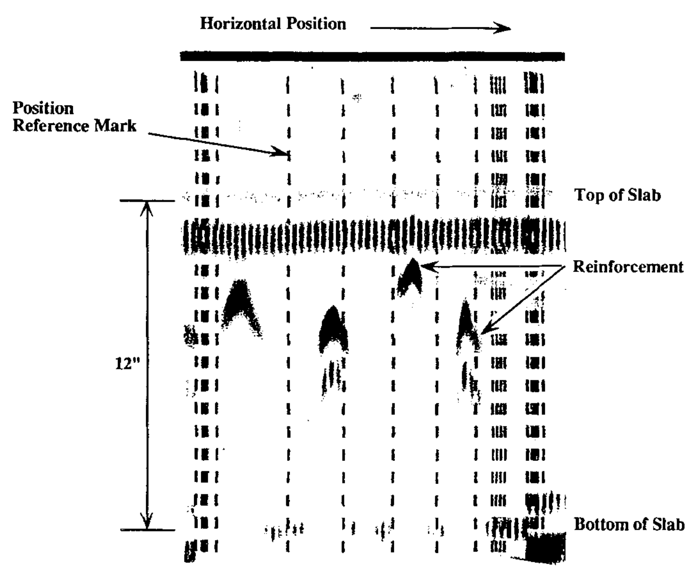

FIG. 4. Ground Penetrating Radar B-Scan of Reinforced-Concrete Slab (Courtesy of B. Simmons, AGRA Earth & Environmental Group, Albuquerque, N.M.)

propagation velocity was constant; and (3) multiple scattering effects could be ignored. Data was acquired by towing a single pulse-echo transducer across the concrete surface. The first step of the image reconstruction consisted of filtering the received data to determine the exact arrival time of the echoes. Then, the sources of the echoes were reconstructed by back-propagating the received signals. Backward propagation was performed at each wavelength contained in the received signal, and the results for each wavelength were superimposed to reconstruct an image. This reconstruction algorithm was tested by simulation and laboratory experiments of concrete slabs with single and multiple bars. Though many images were of good quality, limitations included shadowing effects and multiple reflections between reflectors that produced false targets. Reconstruction accuracy decreased when multiple reflectors were closely spaced (Mast 1992).

Mast et al. (1992) used this imaging technique to nondestructively evaluate the New York State Capitol Building. The researchers were able to detect wire mesh and reinforcement in the concrete slabs, as well as supporting masonry arches and steel beams. The system was unsuccessful in detecting air spaces between floors and walls, and uncured concrete. Mast and his colleagues found that the main impediment to further image improvement was the uncertainty in the pulse velocity.

Microwave Tomography

The development of a tomographic reconstruction procedure for microwaves is a complex problem. Unlike X rays, which travel along straight paths, microwaves are strongly diffracted because their wavelengths are on the order of the dimensions of the objects that are imaged. Furthermore, the scattered field is nonlinearly related to the property that most strongly influences the material's interaction with microwaves, the material's permittivity. The nonlinearity results from the fact that the scattered field that is measured depends both on the material's permittivity and on the total electric field within the object. This total field, in turn, depends on the scattered field within the object and hence, on its permittivity distribution (Bolomey and Pichot 1992).

It is possible to linearize the reconstruction procedure if one assumes that the total magnetic field is known, or at least, can be approximated. For example, it is common to assume that the total field is equal to the incident field (i.e., the Born assumption). Images are constructed on the basis of the Fourier Diffraction Theorem, which is a generalization of the theorem used in x-ray tomography. This approach, referred to as a spectral formulation, can be implemented on a personal computer (Bolomey and Pichot 1990).

Pichot and Trouillet (1990) discuss the implementation of microwave tomography to locate reinforcement in reinforced-concrete members. They developed a prototype "Microwave Camera," which consisted of a microwave source (7 GHz to 13 GHz), one or two transmitting antennas and a linear array of 64 sensors. Typical data-acquisition time was approximately 1.5 min; another 4 min was needed to reconstruct images using a spectral approach. The authors reported that the maximum sounding depth was between 70 mm and 80 mm and that the average error in estimating the reinforcing bar diameter was 6 mm for large diameter bars and 8 mm for small diameters. The uncertainty in the reinforcement depth varied from 4 mm for large diameter bars to 9 mm for small bars (Pichot and Trouillet 1990).

More recently, a compact prototype of the "Microwave Camera" was developed commercially (Belkebir et al. 1994). The new prototype weighs 4 kg and can display a tomographic image, such as the one shown in Fig. 5, on a color television screen in about 1 min. Fig. 5 shows the image of a single

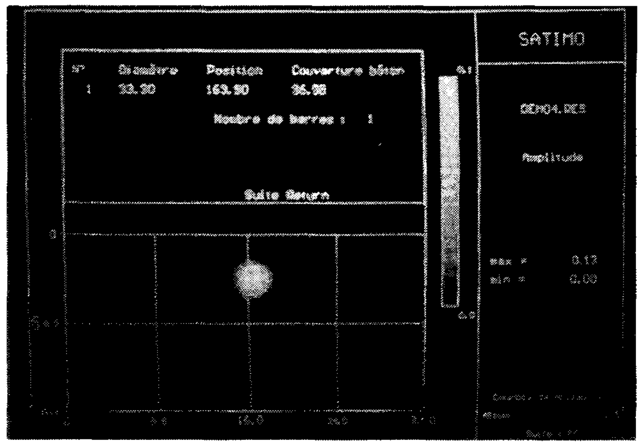

FIG. 5. Microwave Tomographic Image of Reinforcement in Concrete (Courtesy of C. Pichot, CNRS, Université de Nice, Sophia Antipolis, France)

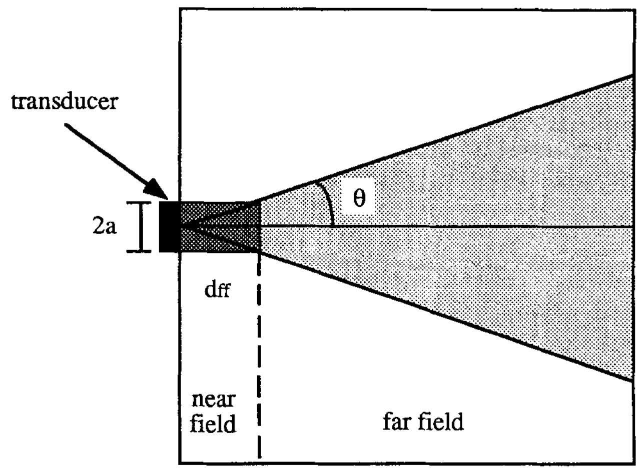

FIG. 6. Acoustical Beam Created by Circular Transducer

reinforcing bar, but the system can also identify more complex reinforcement configurations. Although the commercial viability of this technology has not yet been proven, microwave tomography appears to be a promising means of assessing reinforced-concrete structures. The next development of this technique will be in the direction of quasi-real-time acquisition and processing.

If the medium is highly inhomogeneous, it is necessary to resort to spatial iterative techniques. Though several iterative procedures exist, the algorithms are similar. On the basis of the scattered field and an assumed total field, the permittivity distribution is computed. The calculated permittivity distribution is then used to revise the estimate of the scattered and hence, total electromagnetic field, and the permittivity distribution is calculated again. The process is repeated until it converges. Unfortunately, these iterative techniques are computationally intensive (Bolomey and Pichot 1992).

ACOUSTICAL IMAGING

Acoustical imaging originated during World War I with the work of Paul Langevin, who developed the sound navigation ranging method (SONAR) to locate submarines (Schueler et al. 1984). The present range of application of acoustical techniques includes medical imaging, NDE of metals and ceramics, underwater detection, and geophysical exploration.

Acoustical imaging is an attractive solution for concrete applications because it is safe and relatively inexpensive. To

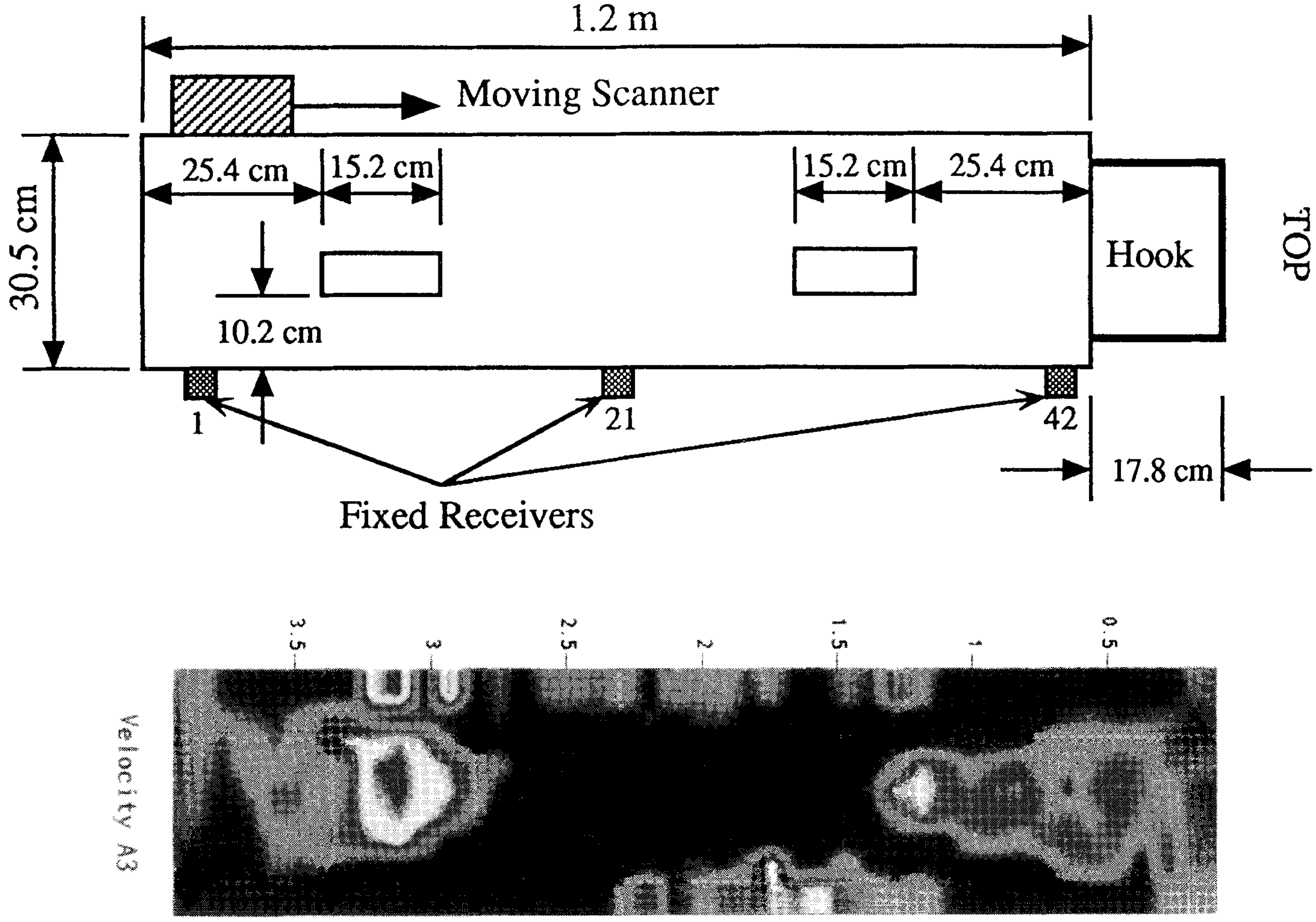

FIG. 7. Acoustic Velocity Tomogram of Two Voids (Courtesy of L. Olson, Olson Engineering, Inc., Golden, Colo.)

TABLE 1. Evaluation of Established Methods

Technique (1)	Common application (2)	Image interpretation (3)	Portability/adaptability (4)	Disruption to facility's function (5)
Radiography	Location of reinforcing and prestressing steel	Good contrast	Requires access to both sides of member	Radioactive source requires evacuation of occupants and shielding
	Location of voids in concrete	2D projection of 3D objects	Penetration depth up to 1.5 m	Time consuming
	Location of regions with inadequate grouting	Insensitive to environmental conditions		
Infrared thermography	Detection of cracks, voids and delaminations	No depth information	Can be mounted on vehicle moving up to 16 km/h	Minimal disruption
	Particularly suited for scanning large surfaces	Image sensitive to environmental conditions		
Microwave B-scan	Detection of cracks, voids and delaminations	Difficult	Can be mounted on vehicle	Minimal disruption
	Location of reinforcement	Pulse velocity sensitive to water content	Penetration depth up to 0.6 m	
	Evaluation of member thickness	Insensitive to environmental conditions		

understand some of the difficulties of implementing this technology, it is necessary to consider a typical acoustical beam, which is characterized by two parameters: its opening and the size of its near field. Both parameters depend on the transducer's radius, a, and the signal's wavelength, λ (10^{-6} m to 1 m). The opening of the beam, described in Fig. 6 by the angle θ, is given by:

$$\theta = \arcsin\left(\frac{0.61\lambda}{a}\right) \quad (4)$$

The extent of the near field, d_{ff}, a zone in which much interference occurs, is given by

$$d_{ff} = \frac{a^2}{\lambda} \quad (5)$$

To obtain good resolution, it is necessary that the beam be narrow. The opening angle of the beam is small if one uses short wavelengths (i.e., high frequencies) or large transducers, as shown in (4) and Fig. 6. Unfortunately, neither solution is satisfactory for reinforced concrete. High frequencies are quickly attenuated in reinforced concrete, and large transducers are not practical because their large near-field region makes it impossible to image shallow layers [Eq. (5) and Fig. 6]. Furthermore, the larger the transducer radius, the more difficult it is to realize a good coupling between the transducer and the concrete surface. A further complication is due to the fact that concrete is a solid. Whereas only compression waves travel through liquids or human tissue, concrete also transmits shear and surface waves (Krautkramer and Krautkramer 1990). Therefore, image reconstruction is more difficult.

As a result of these difficulties, no practical acoustical imaging system has yet been developed for reinforced concrete. The methods discussed in this section, transmission C-scans and acoustic tomography, have yet to be implemented outside the laboratory for reinforced-concrete applications.

Transmission C-scan

Ultrasonic C-scan imaging of concrete has been performed by combining the intensity-mapping technique with the time-of-flight measurement method. The intensity-mapping technique is based on the observation that the attenuation of acoustical energy is a function of the material. A pulse is sent on one face of the object to image, and the transmitted wave is recorded on the other side (Schueler et al. 1984). The time-of-flight method consists of measuring the time a pulse takes to travel a known distance. The known time and distances are then combined to evaluate the pulse velocity. This method is commonly used to assess the quality and relative strength of concrete.

Hillger (1988) developed an ultrasonic imaging system that used both amplitude and frequency of the transmitted signals, in addition to time-of-flight measurements, to construct a C-scan image. The images showed the size and location of the defects, as well as the shape of the specimen. Cracks or voids were particularly well contrasted with this technique because the air they contained reflected most of the incident signal, decreasing largely the amplitude of the transmitted signal. Unfortunately, to realize a good coupling, which is particularly important when amplitude is a principal parameter, the concrete specimen had to be immersed in water (Hillger 1988). This constraint limited the application of the system to laboratory testing.

Acoustic Tomography

The use of acoustic tomography for the assessment of structural concrete is being researched by Olson et al. (1993). Their initial work focused on locating defects using velocity and amplitude tomography of ultrasonic compression waves. A key step in making acoustic tomography practical has been the development of a rolling ultrasonic pulse velocity scanner, which greatly reduces the time necessary to acquire data.

The researchers found that the technique was successful in detecting voids in concrete. For example, Fig. 7 shows the geometry of a laboratory specimen and its corresponding tomogram. Two voids were intentionally cast in a concrete slab. The scanner source was moved along a single line, and the transmitted signals were measured at 42 locations. According to the authors, acquisition of 1,764 measurements on single source-receiver basis would have taken 40–60 h. With the aid of the scanner, the data-acquisition time was reduced to about 1.5 h.

The technique appears promising, but it requires further development to accurately characterize honeycombs and weak concrete. The development of velocity and amplitude tomography of shear waves may aid in characterizing these types of defects.

CONCLUSION

This paper discussed the status of imaging technology for the nondestructive evaluation of reinforced- and prestressed-concrete structures. Although progress has been made in im-

TABLE 2. Evaluation of New Methods

Technique (1)	Potential applications (2)	Stage of development (3)	Potential improvements (4)	Potential obstacles to implementation (5)
Radioactive tomography	Microstructure studies	Commonly used in laboratory	Provides cross-sectional image of 3D objects	Expensive
	Location of reinforcement, voids and cracks	Limited development of field prototype		Disrupts occupant
				Limited adaptability (need for access to member perimeter may be reduced by limited angle tomography)
				Limited portability
Microwave holography	Location of reinforcement, voids and cracks	Applied to laboratory specimens	Easier to interpret than B-scans	Expensive
		Few evaluations under field conditions		Does not take diffraction into account
				Sensitive to pulse velocity
				Imaging of multiple reflectors difficult
Microwave tomography	Location of reinforcement, voids and cracks	Industrial prototype has been developed	Easier to interpret than B-scans	Expensive
			Provides cross-sectional image of 3D objects	
			Takes diffraction into account	
Acoustic tomography	Location of voids	Under investigation in laboratory studies	Provides cross-sectional image of 3D objects	Lengthy data acquisition process because of coupling requirements
			Takes diffraction into account	

aging technology over the last decade, the current application of imaging techniques for the NDE of concrete is limited. Of the technologies discussed in this paper, only radiography, infrared thermography and Ground Penetrating Radar are commonly used in the field to locate defects and reinforcement.

Each technology has its advantages and limitations, which are summarized in Table 1. Radiography produces good quality images, but it is limited by cost and safety considerations. In addition, with conventional radiography it can be difficult to determine the plane on which a defect is located. Infrared thermography is fast, safe, and can be used to inspect large areas, but the results are sensitive to many environmental parameters, and thermography does not provide any information about the depth of the defects. For this reason it is often supplemented with another technique, such as ground penetrating radar. GPR is also a fast and safe technique. Unfortunately, the information provided is based on the assumption that the pulse velocity is the same everywhere in the member, which is rarely the case. Also, the correct interpretation of B-scans requires experience and training. If the geometry is complex, B-scans are particularly difficult to interpret.

Recently, a number of researchers have implemented sophisticated tomographic and holographic reconstruction algorithms to improve image quality. Four examples are listed in Table 2. X-ray and gamma-ray computed tomography have been successfully used to study reinforced concrete in laboratory studies. Though the techniques provide high-quality images, practical constraints, particularly economic ones, have so far prevented the widespread implementation of radioactive computed tomography in the field. Further development of limited angle tomography may increase the versatility of the method because this method does not require access to all sides of a member.

An imaging system, based on a holographic reconstruction algorithm, was developed to interpret ground penetrating radar measurements. The system was tested in the laboratory and has been subjected to at least one field test. Other researchers have developed tomographic reconstruction algorithms that take into account the effects of diffraction. These researchers have developed a "microwave camera" to locate reinforcing bars. The economic viability of the microwave systems has yet to be proven, but the techniques appear to be promising.

Acoustical imaging techniques are attractive for concrete applications because one can generate acoustical signals with little cost and no hazard. However, the properties of concrete make it difficult to implement imaging algorithms for acoustical signals. As a result, the methods discussed in this paper, transmission C-scan imaging and acoustic tomography, have not yet been applied to practical NDE of reinforced concrete. The development of a rolling transducer, which greatly reduces the time required to acquire data, has greatly increased the possibility of developing a practical system for acoustic tomography.

ACKNOWLEDGMENT

The work reported here was supported by grant MSS-9158152 from the National Science Foundation.

AUTHORSHIP

This paper is based on Ms. Pla-Rucki's Master's thesis at the University of Washington. Ms. Pla-Rucki and Dr. Eberhard jointly prepared this paper.

APPENDIX. REFERENCES

Belkebir, K., Pichot, C., Bolomey, J. C., Berthaud, P., Cottard, G., Derobert, X., and Fauchoux, G. (1994). "Microwave tomography system for reinforced concrete structures." *24th Eur. Microwave Conf.*, Cannes, France

Bolomey, J. C., and Pichot, C. (1992). "Some applications of diffraction tomography to electromagnetics—the particular case of microwaves." *Inverse Problems in Scattering and Imaging*, M. Bertero and E. R. Pike, eds., Adam Hilger, Philadelphia.

Bolomey, J. C., and Pichot, C. (1990). "Microwave tomography: from theory to practical imaging systems." *Int. J. Imaging Systems and Technol.*, 2, 144–156.

Bungey, J. H., Millard, S. G., and Shaw, M. R. (1992). "Use of subsurface radar for structural assessment of in-situ concrete." *Proc., ACI Int. Conf. on Evaluation and Rehabilitation of Concr. Struct. and Innovations in Design: SP-128*. V. M. Malhotra, ed., ACI Detroit, 497–514.

Daniels, D. J., Gunton, D. J., and Scott, H. F. (1988). "Introduction to subsurface radar." *IEE Proc.*, Part F, 135(4), 278–284.

Guinez R. (1991). "Contrôle nondestructif des ouvrages d'art par gammagraphie, radiographie et radioscopie." *Bulletin de Liaison des Laboratoires des Ponts et Chaussées*, Paris, Jan.-Feb., 83–93.

Heiskanen, K. A., Rhim, H. C., and Monteiro, P. J. M. (1991). "Computer simulations of limited angle tomography of reinforced concrete." *Cement and Concrete Res.*, 21(4), 625–634.

Hillger, W. (1988). "Inspection of concrete by ultrasonic testing." *Proc., Non-Destructive Testing: 4th Eur. Conf.*, J. M. Farley and R. W. Nichols, eds., Pergamon Press PLC, Oxford, U.K.

Kak, A. C., and Slaney, M. (1988). *Principles of computerized tomographic imaging*, IEEE Press, New York.

Krautkramer, J., and Krautkramer, H. (1990). *Ultrasonic testing of materials*, Springer-Verlag, Berlin.

Martz, H. E., Schneberk, D. J., Roberson, G. P., and Monteiro, P. J. M. (1992). "Computed tomography assessment of reinforced concrete." *Nondestructive Testing and Evaluation*, 8–9, 1035–1047.

Maser, K. R., and Roddis, W. M. (1990). "Principles of thermography and radar for bridge deck assessment." *J. Transp. Engrg.*, ASCE, 116(5), 583–600.

Mast, J. E. (1992). "Microwave pulse-echo radar imaging for the nondestructive evaluation of civil structures," PhD thesis, Univ. of Illinois, Urbana-Champaign, Ill. (Advanced Construction Technology Center Document No. 92-30-29). 1992.

Mast, J. E., Lee, H., and Murtha, J. P. (1992). "Application of microwave pulse-echo radar imaging to the nondestructive evaluation of buildings." *Int. J. Imaging Systems and Technol.*, 4(3), 164–169.

Mitchell, T. M. (1991). "Radioactive/nuclear methods." *Handbook on nondestructive testing of concrete*, V. M. Malhotra and N. J. Carino, eds., CRC Press, Boca Raton, Fla., 227–252.

Morgan, I. L., Ellinger, H., Klinksiek, R., and Thompson, J. N. (1980). "Examination of concrete by computerized tomography." *ACI J.*, 77(4), 23–27.

Olson, L. D., Jalinoos, F., Aouad, M. F., and Balch, A. H. (1993). "Acoustic tomography and reflection imaging for nondestructive evaluation of structural concrete." *Phase I final report*, National Science Foundation, Washington, D.C.

Pichot, C., and Trouillet, P. (1990). "Diagnosis of reinforced concrete structures: an active microwave imaging system." *Bridge evaluation, repair and rehabilitation*, A. S. Nowak, ed., Kulwer Academic Publishers, Rotterdam, The Netherlands, 201–215.

Ravich, L. E. (1986). "Thermal imaging: a review." *Laser Focus/Electro-Optics*, 22(2), 98–110.

Schueler, C. F., Lee, H., and Wade, G. (1984). "Fundamentals of digital ultrasonic imaging." *IEEE Trans. on Sonics and Ultrasonics*, 31(4), 195–216.

"Standard test method for detecting delaminations in bridge decks using infrared thermography." (1994). *D 4788-88*, ASTM, Philadelphia, 496–497.

Stern, B. E., and Lewis, D. (1971). *X-rays*, Pitman Publishing, London.

Synolakis, C. E., Leahy, R. M., and Singh, M. (1993). "The development of an asphalt core tomographer." Strategic Highway Research Program, National Research Council, Washington, D.C.

Van Anda, J. B., and Carter, C. L. (1991). "Infrared imaging—television in the dark." *SMPTE J.*, 100(5), 351–357.

Weil, G. J. (1992). "Nondestructive testing of bridge, highway and airport pavements." *Proc., Nondestructive Evaluation of Civ. Struct. and Mat.*, University of Colorado, Boulder, Colo., 385–394.