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Ultrasonic imaging–A novel way to investigate corrosion status in post-tensioned concrete members

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Abstract

The problem of durability in reinforced concrete structures is most prevalent in chloride-induced corrosion of reinforcing steel. Traditional corrosion monitoring techniques such as half-cell potential and corrosion rate measurements often fail when used in this type of structure and standard nondestructive testing methods such as impact-echo have also encountered problems. This study introduces a new method called C-scan imaging to evaluate grouted post-tensioned tendons. Preliminary investigations on lab specimens show promise for the technique.

Keywords: Impact echo, ultrasound sensing, NDT (nondestructive testing), ultrasound bridge inspection system, wireless ultrasound C-scan imaging system.

1. Introduction

Post-tensioned concrete combines efficient use of concrete and steel with durability and speed of construction. Segmental post-tensioned superstructures are particularly favorable alternatives for long spans and for construction in areas where minimal disruption of the environment is required. Post-tensioned structures can be very durable if properly constructed but recent problems with corrosion and voids found in the post-tensioned (PT) tendons have brought awareness of potential durability problems. The objective of nondestructive evaluation (NDE) of post-tensioned structures is to reliably detect and monitor the condition of tendons without any active intervention with the structural member. There are various methods by which this objective can be attained, viz. georadar and covermeter method, potential mapping, impact-echo, remnant magnetism, radiography, reflectometrical impulse measurement (RIMT), ultrasonic methods, acoustic monitoring, thermography, tomography, etc. Researchers tackling the problem of corrosion detection in post-tensioned structures using NDE methods feel that none of the inspection and monitoring methods fulfils the expectations for a complete and meaningful evaluation of post-tensioning tendons in existing structures [1], [2]. Some methods provide partial results in accessible areas, but none allows a full assessment of the condition of an internal, post-tensioned and grouted tendon. At this time, the basic and practical method of carefully opening and visually inspecting a tendon at a location where there is a reasonable doubt is still considered as the most reliable option in the field. Additionally, the above NDE techniques require interpretation by an engineer very experienced in this area.

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Ultrasonic C-scan imaging is an NDE technique that provides real-time, large area imagery of flaws by moving a point-by-point transducer. This technique, which has the ability to provide immediate production control feedback, and in-field structural health monitoring, becomes an even more effective method for field applications. The imaging that is provided to the user allows the data to be more easily interpreted by the engineer.

Although ultrasonic C-scanning was originally developed for biomedical applications and inspection of homogeneous materials, the method has now been applied to inspection of composite materials for the detection of delaminations, cracking, and to monitor the initiation and progression of damage resulting from applied mechanical loads and other environmental factors. Ultrasound C-scan imaging characterizes the signals reflected back from the test specimen and reconstructs images using image processing software. These images serve as visual representation of the internal condition of the structure and can be analyzed for distinctive patterns suggesting corrosion or voids.

Four basic themes are discussed here concerning ultrasonic imaging of post-tensioned concrete members for the purpose of investigating the state of corrosion:

1. brief introduction to corrosion and its effects on post-tensioned members;
2. the present state of corrosion detection methods and limitations;
3. basic ultrasonic C-scan imaging fundamentals and working principle; and
4. laboratory results from preliminary evaluation and field applications utilizing automated and improved inspection equipment.

2. Corrosion in post-tensioned (PT) bridges

Corrosion of reinforcing steel in concrete leading to premature damage to concrete structures is a multibillion dollar problem prevalent all over the world. Corrosion-related damage to bridge structures which requires costly repairs is the single most challenging issue for most highway agencies. It is worthwhile to understand the fundamentals of corrosion theory to gain a deeper perspective of the current problems in the concrete industry pertaining to corrosion-related issues.

2.1. *General corrosion*

An understanding of a general corrosion theory for metals is necessary prior to considering the corrosion of prestressing steel in concrete. Corrosion of iron is an electrochemical process (equations 1 and 2), commonly known as half-cell reactions:

$$\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2e^{-} \quad \text{(anodic half-cell reaction)} \tag{1}$$

$$2\mathrm{H_2O} + \mathrm{O_2} + 4e^{-} \rightarrow 4\mathrm{OH}^{-} \quad \text{(cathodic half-cell reaction)} \tag{2}$$

Electrochemical oxidation takes place at the anode and reduction at the cathode. Both the electrodes form on the metal surface. Iron is oxidized into ferrous ions at the anode as shown by eqn 1. The ferrous ions are converted to $2\mathrm{Fe(OH)_3}$ through a series of reactions and produce rust. The formation of rust can be understood from eqns 3 and 4 [3].

$$2\mathrm{Fe} + 2\mathrm{H_2O} + \mathrm{O_2} \rightarrow 2\mathrm{Fe}^{2+} + 4\mathrm{OH}^{-} \rightarrow 2\mathrm{Fe(OH)_2}. \tag{3}$$

Ferrous hydroxide can react further to yield ferric salt or the popular rust:

$$2Fe(OH)_2 + 2H_2O + \tfrac{1}{2}O_2 \rightarrow 2Fe(OH)_3. \tag{4}$$

The anodic and cathodic areas are regions of different electrochemical potential that develop due to two different metals (which therefore have different potentials) or a single metal with surface differences that could be metallurgical or local variations in electrolyte [4]. The anode and cathode locations can change often and have an irregular pattern leading to a somewhat uniform corrosion or the locations can be more fixed and localized.

The cement paste pore solution acts as an electrolyte and anodes and cathodes are formed on the steel surface when corrosion of steel in concrete commences. The basic corrosion process is shown in Fig. 1. The high alkalinity of the grout (or concrete in traditionally reinforced systems) provides a protective environment for the reinforcing steel. An oxide film develops on the steel protecting it from corrosion. Chlorides break down this passive layer in spots and begin the corrosion process. Areas where the film has broken down are anodes and those with film remaining are cathodes. Pitting corrosion occurs at the anodes and a high cathode-to-anode ratio further speeds up the corrosion process. If the alkaline (high pH) environment is lost, the steel is susceptible to corrosion.

2.2. *Corrosion of prestressing steel*

The steel used in pre- and post-tensioned concrete is prone to corrosion attacks due to chloride-induced corrosion, and theoretically would be susceptible to stress corrosion cracking (SCC) or

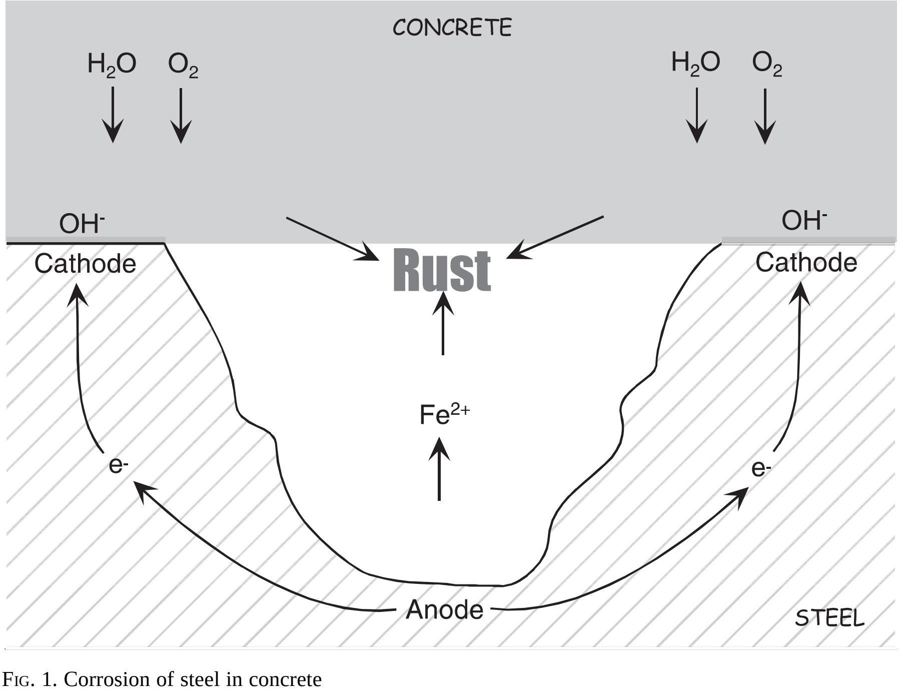


FIG. 1. Corrosion of steel in concrete

hydrogen embrittlement (HE). Chloride-induced corrosion is the most common form of corrosion in reinforced concrete. It can be relatively quick and can localize to cause significant reductions in cross-sectional area. The concrete surface is stained due to the rust produced which also causes cracking and spalling. Corrosion is dependent on several variables and hence controversial views exist regarding chloride thresholds [4]. These variables are: proportioning of concrete, type and specific area of cement, water–cement ratio, sulfate content, curing conditions, age, environment, carbonation, type and condition of reinforcement, temperature and relative humidity.

Uniform corrosion is a generalized corrosion over large area. This type of corrosion may result in large amount of metal loss, but does not cause localized damage and hence a catastrophic failure is less likely to occur as compared to other types of corrosion. Pitting, as typically seen on steel in a high pH environment, is a form of extremely localized attack that results in pits in the metal. Pits may be small or large in diameter, but in most cases are relatively small. Pitting is one of the most destructive and insidious forms of corrosion. Pitting corrosion is very common in reinforced concrete structures and can be quite destructive due to the concentrated pits of corrosion causing large reductions in cross-sectional area with a small amount of overall metal loss. The process is a self-propagating one. As the pits grow, the surface can be undercut resulting in a deceivingly large pit making detection difficult even on bare steel [5].

Cross-sectional geometry of the steel along with high strength and high tensile loadings make a post-tensioned structure a possible candidate for catastrophic failure if chlorides are allowed easy access to the strand. Proper grouting of the post-tensioning ducts is necessary for corrosion protection and bond transfer, but complete grouting can be difficult due to lack of visibility and access to all parts of the duct. A survey of post-tensioned bridges in Denmark indicates that although most of the bridges were satisfactory and in acceptable condition, the majority of post-tensioning ducts were inadequately injected with grout [6]. In some cases, the ducts had been left completely ungrouted. Schupack examined a 35-year-old post-tensioned bridge and found similar problems with ducts [7]. Many of the tendons inspected were either partially grouted or left ungrouted. The grout water–cement ratios varied through the span and in some spans, chloride-contaminated grout had been used. This study points out the importance of a workable, pumpable grout that also has good corrosion protection properties.

The grout injected into post-tensioned ducts serves a dual role of providing bonding between concrete and the prestressing steel as well as protecting the steel from corrosion [8]. Segregation of cement and water may lead to accumulation of bleed water at high points in the tendon profile while the grout is still plastic. As grout sets, bleed water may also collect at intermediate points in very tall grout columns or on top of horizontal prestressing steel. This phenomenon can result in voids in the duct and anchorage area leading to possible corrosion of tendon.

The anchorage zone in a post-tensioned structure or the end anchor of the post-tensioning tendons is a sensitive part of its integrity. Hence the tendons in this region must be protected properly to reduce their vulnerability to corrosion-encouraging agents. Post-tensioning cables tend to be inaccessible to visual inspection, so that corroding tendons may go unnoticed for long periods of time. The potential problem areas can thus be avoided through thoughtful planning, monitoring and periodic inspection.

3. Corrosion detection methods

The service conditions of construction are estimated by taking into account the characteristics of the aggressive environment (indoor and outdoor), the technological process going on inside the structure and the function of the technological installations, including nonstructural elements. The investigation of the damage state (corrosion attack, etc.) of the members/structure in service is made by investigation methods like visual examination, use of nondestructive testing and taking of samples, without endangering the service safety of the members/structures.

3.1. *Visual examination method*

The visual examination of the state of the post-tensioned structure/members and of the anticorrosive protection applied on their surfaces includes the appreciation of aspect changes of the concrete and the (apparent) reinforcement and steel tendon surfaces, the presence of defects/degradation due to corrosion and the evaluation of changes in the condition of anticorrosive protection. The results of the visual examination are registered in the form of surveys of defects/degradations on the layouts and sections of the construction. The details of the investigated members indicating their position and extent of damage are documented in a prescribed format to provide their identification on the structure. Usually in these types of visual examination methods, a conventional mark for each type of defect or damage is adapted. At times, photographs of the defects or damage are taken for additional information. Further details about visual inspection benchmarks for corrosion detection can be found in Spencer [9].

3.2. *Nondestructive testing (NDT)*

Essential structural elements for the safety, serviceability and durability of prestressed concrete structures are the post-tensioning tendons. It is desirable to reliably assess their behavior in existing structures. The most ideal way of attaining this objective is to perform nondestructive or at least low-destructive inspection methods that cause minimum disturbance to the user. These methods help us detect possible defects or damage such as grout voids or tendon corrosion. A few non- or low-destructive inspection and monitoring methods are discussed below that either detect existing grout voids, corrosion of the prestressing steel in progress or even ruptured wires, strands or bars in tendons.

3.2.1. *Georadar and covermeter*

Experience with practical applications has shown that georadar is suitable only for the location of tendons, which often is a prerequisite for a detailed tendon inspection. According to Matt [1], georadar allows the location of tendons to a depth of up to 300 mm under favorable condition, i.e. no congestion of reinforcement. Powerful covermeters are generally capable of detecting ducts at concrete covers of 40–50 mm provided that light reinforcement is present. Hence, overall, the georadar and covermeter applications have been highly limited to special conditions that may not be the case in the field and have not become popular in the concrete world.

3.2.2. *Potential mapping (half-cell potential)*

Potential mapping is a nondestructive method for detecting corrosion on steel reinforcement that has not yet caused visible damage to the post-tensioned structure. The measurements are simple to execute and when properly evaluated in conjunction with other methods, the results may present a reasonably reliable picture of the corrosion state of the strands. The evaluation of the measured results requires experience and competence. The method presents a picture of the corrosion state at the time of measurement and gives no information about the degree of corrosion or the rate of corrosion. Potential mapping should always be supplemented with and evaluated together with visual inspection and measurements of concrete cover as well as chloride content and carbonation depth. Although potential mapping or half-cell potential is a powerful tool for finding corroded normal reinforcement, in the case of tendons, is only successful under very favorable conditions; for example, small concrete cover over ducts and light normal reinforcement as they may exist in thin webs of precast beams. Practical execution of potential mapping has many possibilities for mistakes or uncertainties that may affect the final evaluation of the corrosion state of the reinforcement. The most common cause for error is bad electrical contact, both to the reinforcement from the voltmeter and between the individual bars/strand of reinforcement. This method can only be used on metal ducts and does not work when the post-tensioning duct is made up of PVC material.

3.2.3. *Impact-echo method*

The impact-echo method is a technique for flaw detection in concrete. It is based on monitoring the surface motion resulting from a short-duration mechanical impact. The method overcomes many of the barriers associated with flaw detection in concrete based on ultrasonic methods. Carino provides an overview of this technique and discusses the important parameters involved in this type of testing [10]. This method has been under development primarily in the United States since 1983 and can be used to detect grout voids in tendons [11]. Researchers in Europe have verified the applicability of the method in post-tensioned structures [1]. It can be used to check a tendon for grout voids but is a delicate operation requiring skilled personnel. The presence of cracks and other concrete defects as often found in real structures influences significantly the test results and can make the evaluation impossible at times. Also, it does not work on plastic ducts. It is fairly successful in identifying grout voids under favorable conditions and in accessible areas.

3.2.4. *Remanent Magnetism Method*

This method developed in Germany detects fractures in prestressing steel. The magnetizing and recording equipment has to be moved along the tendon path on auxiliary guidance rails and scaffolding fixed to the concrete surface in order to measure a magnetic leakage field generated by the formation of magnetic dipole distribution around the fracture area. Fracture patterns have typical signatures that are matched and interpreted by experienced personal or pattern recognition (PR) software. Sometimes magnetic testing methods require the magnetization of the object. Often the pulse magnetization proves to be the best technique. The method is suitable to locate fractures of prestressing steel strands and to detect real corrosion. It works for concrete covers of up to 18 cm. The major constraint of this method is the difficulty in coping with the disturbing magnetic signals originating from other embedded steel elements such as normal reinforcement, anchorage elements, duct couplers, steel plates, nails, etc. [12].

3.2.5. *Radiography*

In this method, a portable X-ray betatron (PXB) is used to produce X-ray beams with an energy level of 7.5 MeV (mega-electron-volt). With such high energy, the X-rays can penetrate thick concrete and steel, and reveal flaws inside the concrete structure by high-quality X-ray images. The PXB is easy to transport, assemble, operate and maintain. The radiation levels outside the main beam are low. The application of radiography is limited nowadays to very special cases [1]. Apart from cost, another important reason for the restricted use of this method is that most countries have regulated the use of X-rays to protect people, animals and environment. Hence, this method holds very special application in detecting corrosion and voids in post-tensioned structures and is rarely used.

3.2.6. *Reflectometrical impulse measurement (RIMT)*

RIMT employs time-domain reflectometry to locate anomalies such as corrosion, breakage of wires or whole tendons. It involves the sending of a high-frequency impulse along a tendon or anchor and allows *in-situ* measurement of the integrity of prestressed tendons and rock/soil anchors. To perform RIMT measurements, only the tendon ends or anchors need be exposed. Where this is not possible, an electrical connection can be made to the tendon nearest to the end in question. Prior to RIMT, the only way to evaluate bonded and unbonded prestressed tendons was to select tendons at random and remove them for visual inspection. This method is both incomplete (only a few tendons are actually examined) and expensive because it requires the destruction and restoration of a part of the structure. Some European researchers who carried out a project aimed at developing an understanding of the fundamentals while applying RIMT to a prestressed concrete structure [1] consider that the recorded signals do not contain information on the condition of the tendon but are artefacts of the measurement procedure. Thus, Matt disregards it as a diagnostic technique for grouted tendons [1].

3.2.7. *Ultrasonic methods*

Ultrasonics is the name given 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. Ultrasonic waves have a wide variety of applications over an extended range of intensity, including cutting, cleaning and the destruction of tissue at the upper extremity and NDT at the lower end. A nondestructive test is one in which there is no impairment of the properties and performance in future use of the object under examination. With ultrasonic NDT, which is effectively a mechanical method, periodic mechanical stresses are applied to the object. It is important to note that there are no changes in the dimensions and structure of the object when the test is completed. This can be achieved only when the maximum applied stresses do not exceed the elastic limit below which Hooke’s law is obeyed, so that the resultant strain is proportional to the applied stress. Hence, it is necessary that the ultrasonic intensity is sufficiently low for the elastic limit not to be exceeded. Ultrasonic testing consists effectively of the propagation of low amplitude waves through a material to measure either or both the time of travel and any change of intensity for a given distance. It is reported that ultrasonic methods for grouted tendons have very limited possibilities [1]. Ultrasonic waves sent from a transmitter sitting on the end of the prestressing steel can detect anomalies only in special cases and within a few meters from the tendon anchorage.

3.2.8. *Acoustic monitoring*

Corrosion of prestressing wire in prestressed structures including bridges, buildings, parking structures and concrete cylinder pipe (PCCP) is a widespread concern for owners and managers of these facilities. The general inaccessibility of the prestressing wire makes evaluation difficult, costly and often inconclusive. Random examination of prestressing wires in these structures gives only a much localized knowledge of the prestressing wire condition; conventional investigations can be misleading, resulting often in an underestimate of the extent of corrosion, deterioration or wire failure. The operation of a continuous acoustic monitoring system to detect and locate corrosion-induced failures of prestressing wire has been considered as a favorable alternative in NDT. It can also be successfully applied in practice in equivalent situations such as for unbonded tendons and stay cables. Cullington *et al*. reported that trials, carried out in Great Britain to assess whether the method can also be used for internal bonded tendons, were successful [13]. The authors showed that a single wire fracture can be detected above the ambient noise level, distinguished from other acoustic events and located in position. In spite of promising results, Matt considers it premature to assume the extent and situations in which acoustic monitoring will find place in practical application [1].

3.2.9. *Thermography (infrared-scanner) and tomography*

All objects naturally emit infrared radiation in proportion to their surface temperature. Thermography measures the emitted radiation and displays the information as a visual image. Today's state-of-the-art equipment measures radiation from 490,000 points every second and displays the information as a TV picture. This can then be recorded for subsequent analysis to provide a permanent record of heat loss and surface temperature. With a temperature range of -30°C to 2000°C and a sensitivity of 0.05°C, there are very few applications beyond the reach of this hi-tech technique. By combining infrared and computer technologies, it is possible to generate thermograms (heat pictures), having up to 256 colors, that clearly show thermal profiles and temperature measurements. A combination of thermography and natural heating/cooling cycle allows areas of delaminated concrete and debonded tendons to be detected. The advantages of this technique are that it is a remote operation and is nondestructive.

Acoustic tomographic imaging of concrete is a developing nondestructive evaluation technology and has a potential to assess the condition of concrete structures [14]. Although this technology has been used with great success to image fluid-rich media like biological tissue, the complex behavior of stress waves in solids complicates the imaging of concrete, masonry and other heterogeneous materials such as those used to construct post-tensioned structures.

GPR (ground-penetrating radar) tomography is not a standard method as yet for NDT in civil engineering. Research is in progress to fully evaluate the potential of this method. Travel time and amplitude tomography have been applied to stone pillar testing and to geotechnical surveys by using a frequency stepped radar [15]. However, all applications of this method have experienced the problem of resolution vs penetration.

3.2.10. *Low-destructive testing*

The methods of low-destructive investigation include those for measuring the concrete cover, the depth of concrete that suffered changes under the action of corrosive agents, the examination of the state of the reinforcement, the determination of the type of damage induced by corrosion, as well as performing laboratory tests. Under circumstances of extreme necessity, samples (specimens cut out from the core) are taken of the reinforcement itself, provided measures to protect the integrity and the service safety of the investigated member/structure are taken. The tests and determinations performed in laboratory are physio- and electro-chemical, and physio-mechanical in nature and are performed on the concrete and reinforcement samples taken off from the structures. They mainly consist of measurement of the mechanical characteristics, humidity, water absorption and porosity of concrete, determination of the alkalinity of the concrete (pH of the aqueous solution) and the concentration of corrosive ions (Cl^-, SO_4^{2-}) in the concrete mass and measurement of the mechanical and physio-chemical characteristics of the reinforcement steel. The extent of corrosion of the reinforcement steel is evaluated in accordance with certain main parameters such as the characteristic of corrosion (general, uniform, local, pitting, stress corrosion cracking, etc), the nature, structure and thickness of corrosion products, the physio-mechanical characteristics of the reinforcement and structure of the steel. In the case of diagnosing general and local corrosion phenomena in reinforcement steel, the use of a conventional corrosion degree estimation system is recommended.

4. Proposed ultrasonic C-scan imaging for corrosion detection

The simplest and also the most common technique employed in NDT and medical diagnosis is using a piezoelectric transducer and exciting an acoustic wave in the sample. The transducer is most often placed in a water bath, with acoustic waves propagating through the water into the object being tested. In this method, the transducer is easily moved; however, a large impedance mismatch between the water and sample makes the system inefficient. Another technique is to use transmission imaging, forming an image in a plane perpendicular to the direction of propagation of the acoustic beam. This method is called C-scan imaging and has proven to be very useful in determining the size, shape and location of the defects due to delamination in composite material samples. Post-tensioned concrete samples have not been subjected to C-scan imaging methods for detection of structural integrity problems and hence this paper presents the preliminary evaluation of this technique and discusses the possibility of detecting corrosion and voids using this method. The field representative samples are placed at the focus of the acoustic beam, that is then received by a second receiving transducer. The grouted sample with tendon is mechanically scanned, while the beam is moved back and forth, creating a raster scan. Raster scan is a universally accepted scanning technique used in CRT displays of the PCs. In this technique, the horizontal and vertical deflection signals are generated to move the beam in forward and backward direction across the screen like a raster. The depth focuses of the transducer used are very small and hence allow observation of corrosive or void patterns in different layers by adjusting the transducer up or down in the longitudinal axis direction. Figure 2 shows a typical Ultran NDC 7000 C-scan imager/immersion system and the supporting signal processing tools.

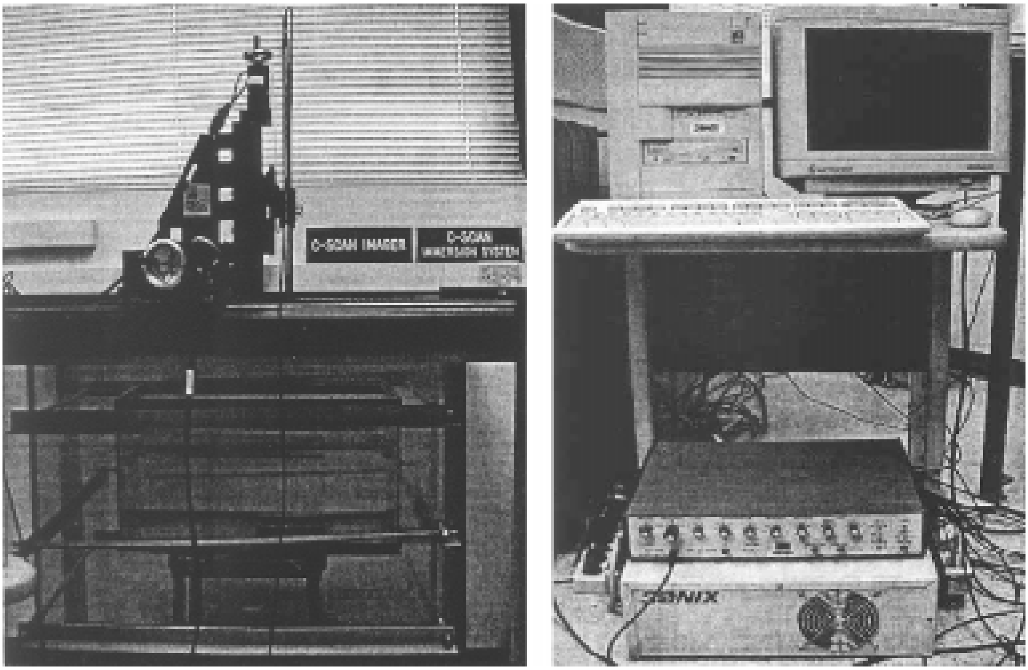


FIG. 2. Ultran NDC 7000 C-scan imager/immersion system with Sonix interface signal processing tools.

4.1. *C-Scan imaging set-up*

An Ultran NDC 7000 system in C-scan mode was used in conjunction with a focused transducer with a center frequency of approximately 500 kHz. A block diagram of the set-up is shown in Fig. 3 [16]. The specimens to be examined were submerged in a water tank. The focused transducer, made of single-crystal sapphire, was attached to an automated computer-controlled x-y-z stage and was excited by a Panametrics Pulser-Receiver (Model 5601A/ST) to generate ultrasonic waves [17]. The focused transducer consisting of the transmitter and receiver was housed in the same assembly thus resembling a single unit transmitter-cum-receiver. The focused beam was reflected by the specimen and returned to the transducer, which also acted as a receiver. The signal reflected from the back surface of the examined plate was gated, and its peak value provided the data for the C-scan image of each gate. The transducer output signals, digitized by a Tektronix TDS-540 four-channel digitizing oscilloscope and processed by a Panametrics Gated Peak Detector (Model 5608), were then acquired using a personal computer to produce a C-scan image. The signal reflected from the bottom surface of the specimen was maximized, and then the transducer was defocused from the back surface to give the best image. This signal was gated, and its peak value provided the data for the C-scan image.

Ultrasonic data (A-scan) is displayed in real time on the digital oscilloscope window. Eight flaw gates per channel are provided to create images (C-scan) of the sample at different depths simultaneously while the B-scan can be displayed to show a cross-sectional view of the part. Analytical tools such as per cent area delaminated, flaw size, distance and depth measurement are available for quantifying inspection results. The software offers eight individually controllable

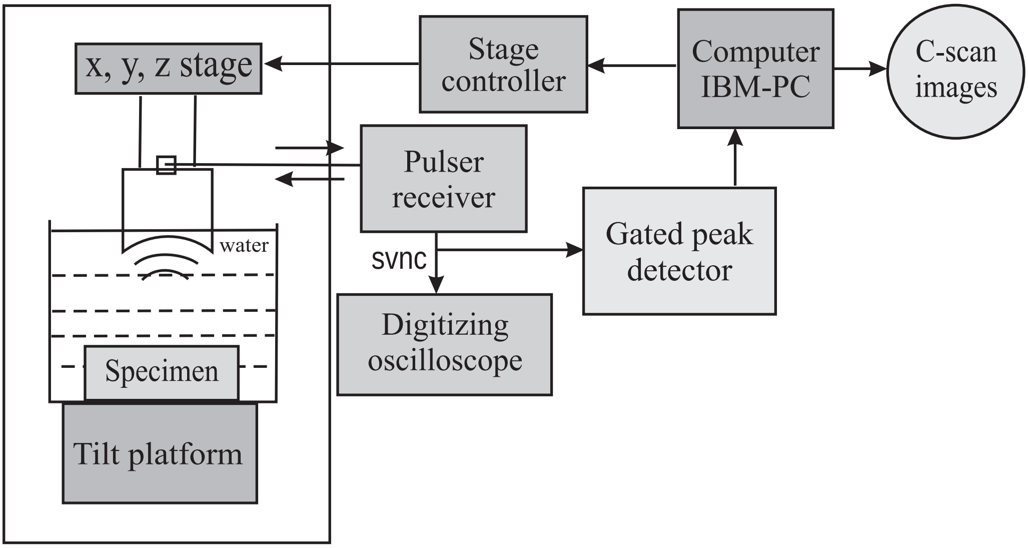


FIG. 3. A block diagram of C-scan imaging set-up.

data gates (G1–G8) per channel for collecting peak amplitude and time-of-flight. In addition, the operator has control of front surface and sub-surface follower gates (for interface synchronization of data gates), phase gate (detects a signal phase inversion), and a B-scan gate (for collecting B-scans). Dynamic gating allows the system to adjust automatically the data gate width to back wall thickness variations. Delta time-of-flight (Δt) displays thickness variation with an accuracy of 0.0002". Figure 4 shows the location of these flaw gates on a signal displayed in the oscilloscope.

4.2. *Experimental testing of grouted tendons*

The evaluation phase included three types of specimen, viz. plain grouted, corroded and voided samples. Corroded samples were prepared at two levels of corrosion, partially and fully corroded. The plain grout specimen is an ideal condition in which the structure has no corrosion or voids. This specimen is used to establish a benchmark image pattern to correlate with corroded or voided specimens to detect any anomalies based on reconstructed images.

4.3. *Specimen characteristics*

The seven-wire prestressing strands were cut in uniform size of 1 foot from a reel of prestressing steel. The basic test specimens for preliminary evaluation include one seven-wire strand located at the center of the duct to form a very basic tendon as shown in Fig. 5. A square cross-section was chosen for the initial evaluation to eliminate additional complexities in the signal due to scattered reflection from a curved surface. The specimens were filled with grout in multiple consecutive lifts in the case of the clean and corroded specimens, whereas the voided specimens were prepared in two separate lifts. Chlorides were dissolved with water to form a 1% NaCl solution before mixing the grout for corroded specimens in order to induce corrosion for detection

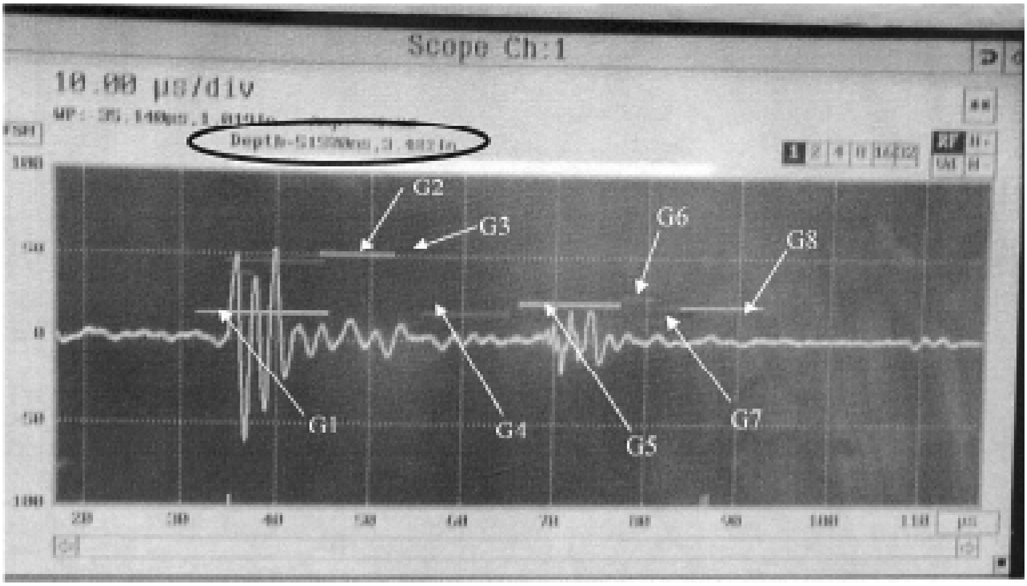


FIG. 4. Signal with flaw gate location.

purposes. All specimens were placed in a curing chamber and allowed to cure for 7 days at 23ºC and 97% relativity humidity. Due to time constraints, voltage was applied to the corroded specimens to speed up the corrosion process after curing.

It is important to understand the correlation of flaw gates on the oscilloscope and the regions on the specimen that it represents during the scanning process. The C-scan software offers eight individually controllable data gates (G1–G8) per channel for collecting peak amplitude and time-of-flight. The flaw gates G1, G4 and G8 on the signal are so adjusted as to cover the entire

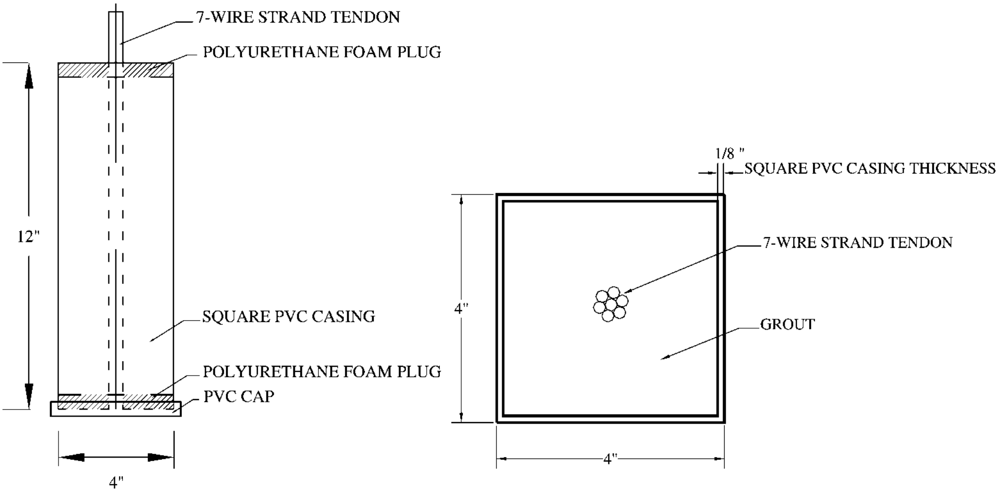


FIG. 5. Elevation and expanded plan of typical grouted specimen.

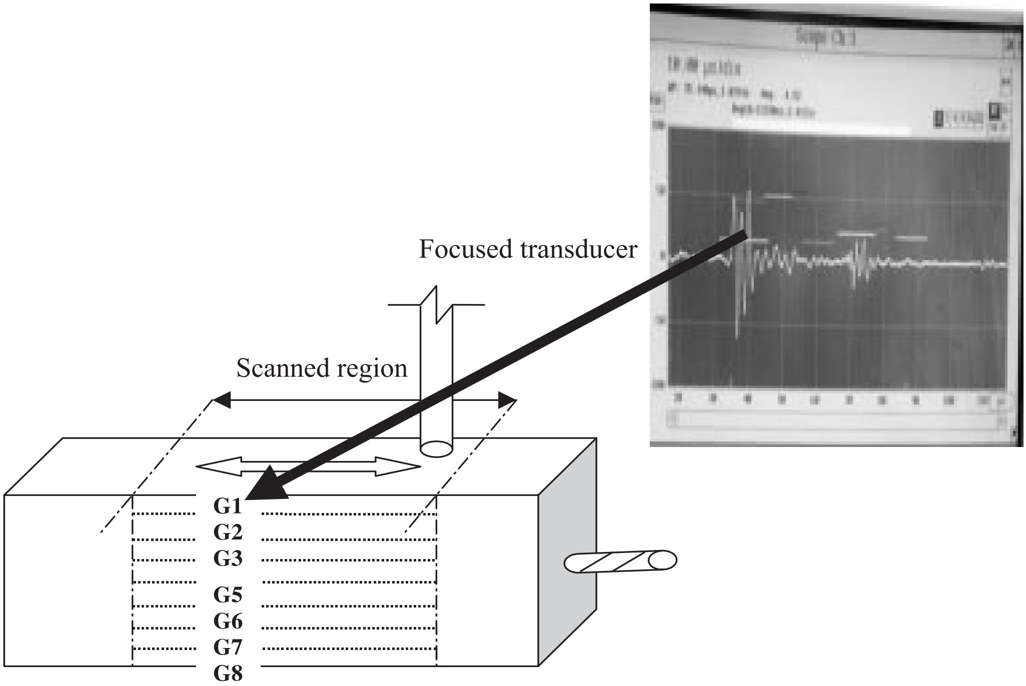


FIG. 6. Flaw gate location on sample and significance.

width of the signal from the top, center (tendon location) and the bottom of the sample. This is important from the point of view of depth and region covered by ultrasound beam. The significance of this action is that the gate width directly corresponds to the width of the region from which the signal reflects. The diagram in Fig. 6 represents the correlation between the location of flaw gates on the signal and the region it represents on the sample.

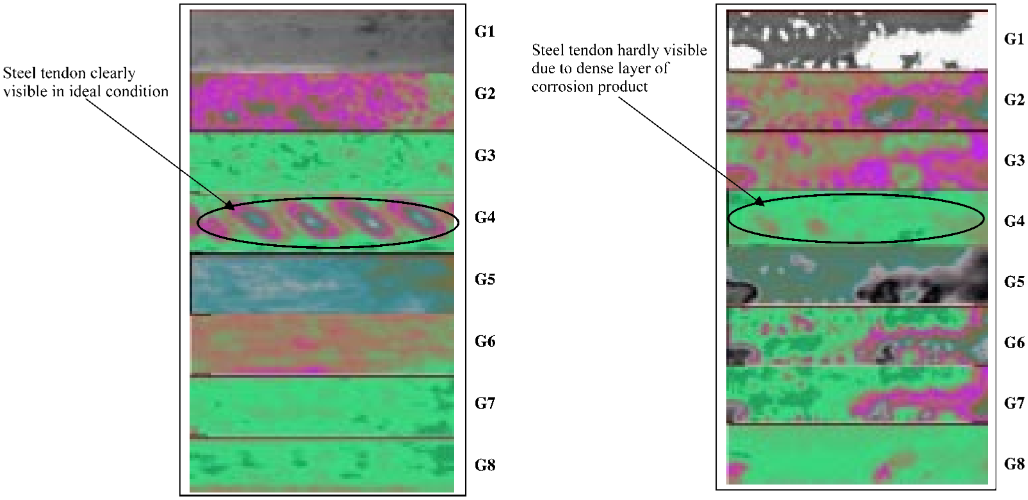
5. Experimental results

5.1. *Plain grout sample*

The plain grouted specimen was prepared with utmost care to ensure that no voids or corrosive agents entered the grout during the mixing or casting stage. It is essential to have a suitable neatly grouted specimen as the ideal case in the field where no corrosion or voids are present. The C-scan image for each of the gates is shown in Fig. 7. The gates have been stacked together in the figure to show a representative slice through the duct and strand as represented in C-scan images. Gate G4 clearly shows the twist of the prestressing strand, while the other gates return a basically solid image.

5.2. *Fully corroded sample*

The fully corroded sample was cast to study the characteristics of the signal and its image reconstruction as compared to the plain grouted specimen so that a pattern or indication of



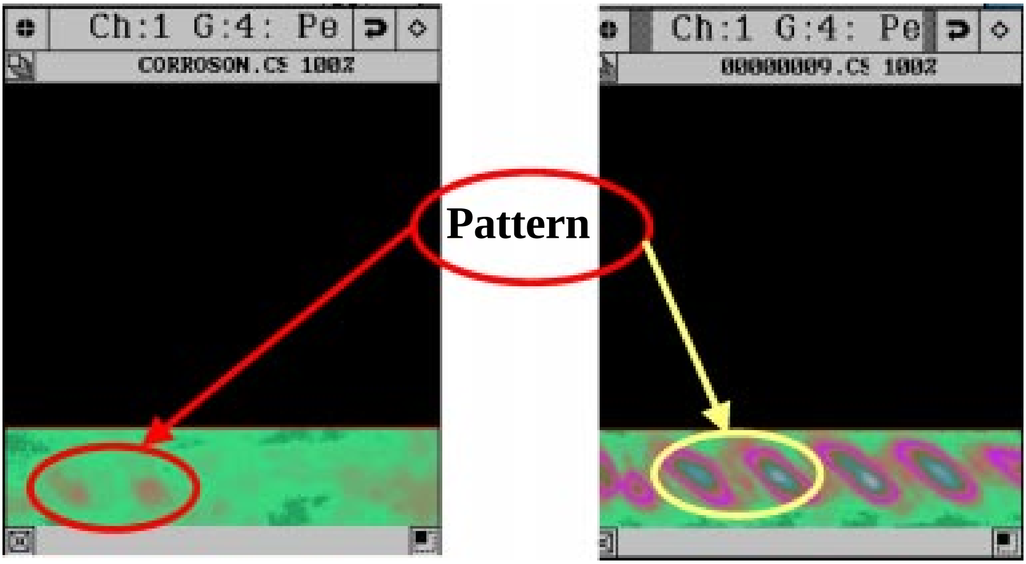
(a) (b)

FIG. 7. Images from all gates for (a) plain grouted and (b) fully corroded specimens.

corrosion may be detected. Figure 7(b) shows the C-scan images for each gate for the corroded specimen. Gate G4 only shows a faint pattern of two twists of the prestressing strand, while the rest is not clear due to the accumulation of corrosion product. The corrosion product in this specimen was extensive, continuing through the grout up to the interface between the PVC casing and the grout, causing a debonding at this interface. The image from G1 clearly indicates that the reflection from the interface of grout and PVC casing is not strong enough to render a clear image and a lot of energy has been dissipated. Energy dissipation may occur due to debonding in the material that has resulted from the action of corrosion of the tendon. Debonding creates energy wells in the atomic structure of the material wherein the ultrasound beam energy is absorbed and dissipated. Hence, the desired reflection–transmission is not achieved and the signal captured by the gates explains the condition of the specimen and the tendon internally. Figure 8 shows the signal from G4 for a plain and a fully corroded specimen. There is a clear and distinct pattern indicating the presence of anomalies within the fully corroded tendon. Autopsies done on the specimen after testing confirm the images to a satisfactory level. Figure 9 shows the autopsied view of the fully corroded specimen.

5.3. *Partially corroded sample*

The partially corroded sample as compared to the fully corroded one has a lesser extent of debonding around the tendon and so the energy available for reflection is higher than in the fully corroded one. For this reason, in spite of corrosion products around the tendon, some parts of the tendon do reflect the ultrasound beam, as it is intact and uncorroded. Figure 10 is a G4 image comparison from a plain grout, partially corroded and fully corroded sample. A few additional steel strands can be seen in the partially corroded specimen. A clear distinctive pattern in representation of the tendon is observed between the ideal condition (plain grout) specimen and samples with two levels of corrosion.



(a) (b)

FIG. 8. Comparison of G4 images from (a) fully corroded and (b) plain grouted samples.

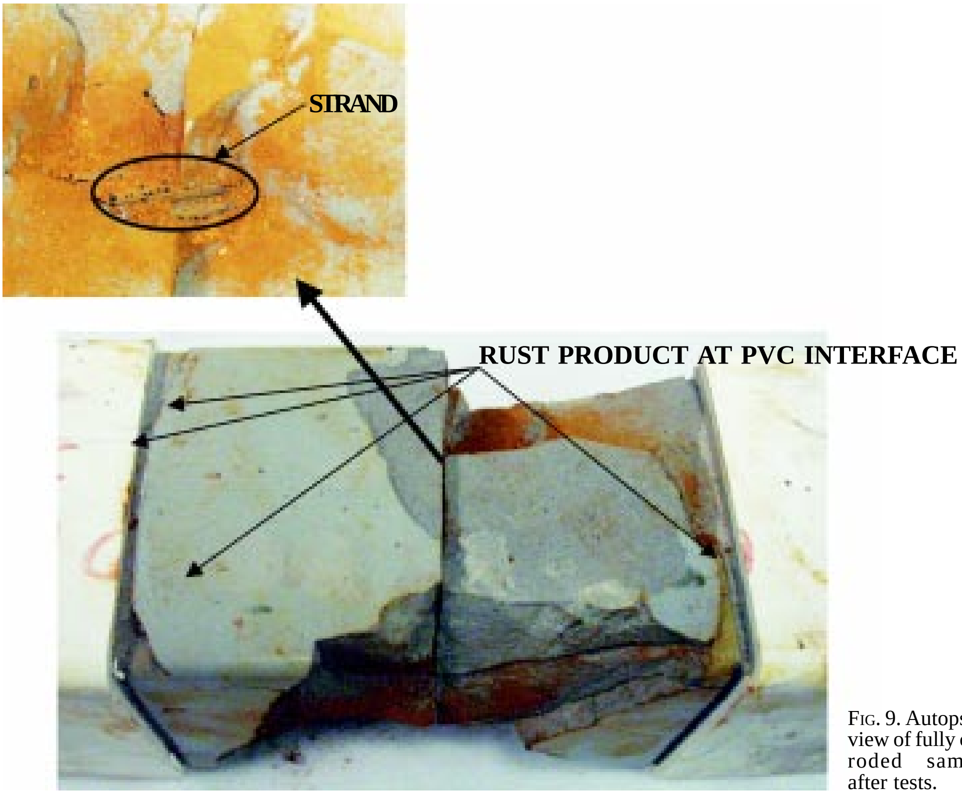
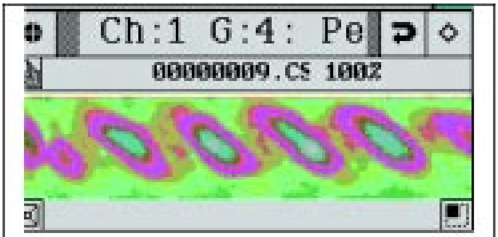
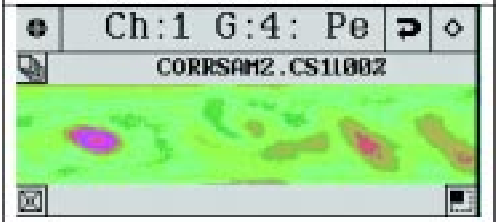


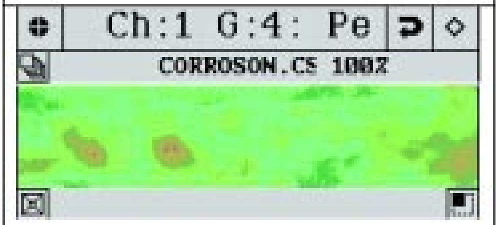
FIG. 9. Autopsied view of fully corroded sample after tests.



GATE 4
Plain Grouted Sample



GATE 4
(Partially Corroded Sample)



GATE 4
(Fully Corroded Sample)

FIG. 10. Comparison of images of plain grouted, partially and fully corroded samples from gate G4.

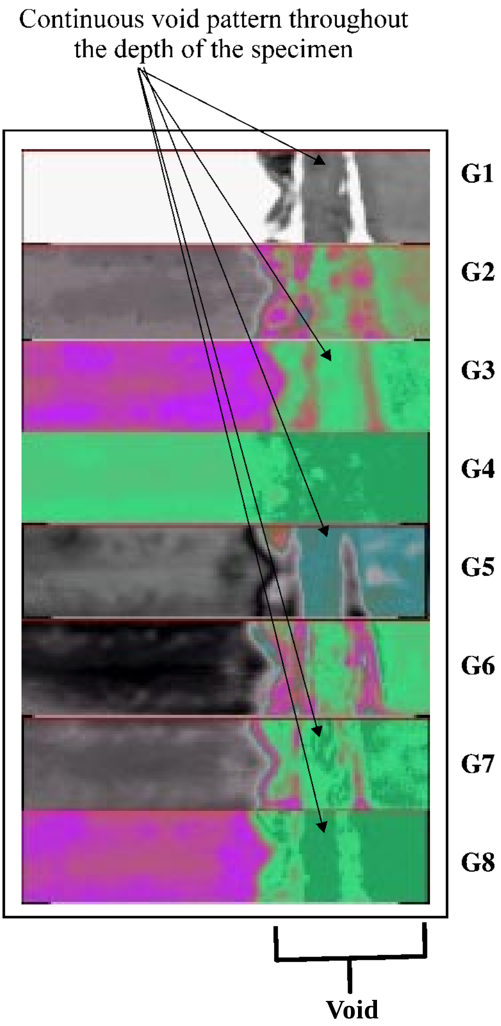


FIG. 11. Complete image capturing from G1–G8 for a voided specimen.

5.4. *Voided sample*

A void was created in a plain grout specimen in order to study the pattern obtained through ultrasound C-scan imaging of a voided specimen. The same region as that of the plain, partially and fully corroded was scanned in this case also with identical scanning parameters to maintain uniformity. Ideally, it is expected that as the ultrasound beam passes through the voids (which is actually entrapped air media), there is no reflection from the region in which the voids are present and hence a black dark spot should appear in the images in comparison to other region where there is a reflection of some kind, either weak or strong depending upon the strength of bond in the interface and the material itself.

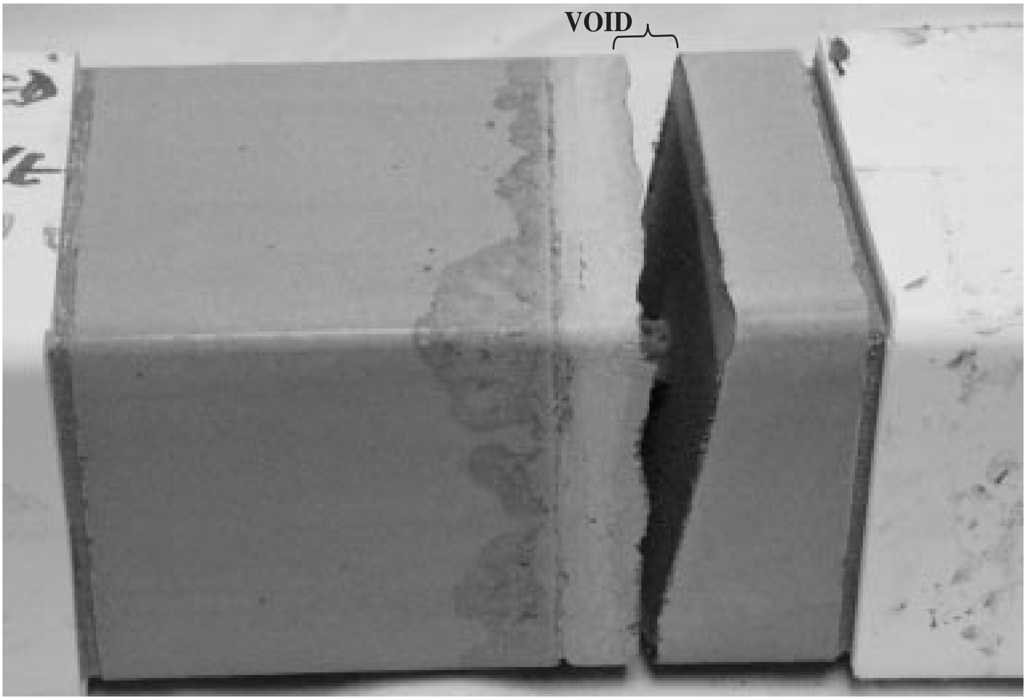


FIG. 12. Autopsied view of voided sample after tests.

Figure 11 shows the C-scan images for each gate for the partially voided specimen. The void is clearly seen in each gate; however, the tendon is not clearly seen in gate G4. In this case, the tendon twist should be evident, but this is likely due to a misalignment of the tendon. If the tendon is moved from the central position, gate G4 will be aligned with the tendon. When this equipment is developed for field use, gates will be adjusted for closer spacing so that strands are not missed. In field specimens, not only do we not know the exact location of the strand, but often multiple strands will also be present. Figure 12 shows the actual voided specimen.

6. Interpretation of results

C-Scan imaging was performed on field representative post-tensioned specimens of four types: plain grouted, fully corroded, partially corroded and voided samples. Images reconstructed from signals acquired at different depths are discussed in this paper with an evident pattern emerging from corroded and voided specimens as compared to plain grouted specimen. Four main issues of interest need to be taken into consideration while interpreting the results of ultrasound C-scan images.

6.1. *Specimen geometry*

It should be noted that all tests were carried out on specimens cast in square PVC casings. The tests program initially considered using round PVC duct as the casing material as found in external post-tensioning. The curvature of the outer surface and concrete attenuation together contribute to nonavailability of the signal as the ultrasound beam does not penetrate the outer surface due to the scattering of beam energy due to curvature effects. Concrete attenuates and whatever little energy enters the interface between the casing and grout is absorbed due to this property creating sufficient conditions for the signal to die out even before it reaches the bottom of the sample. This problem can be addressed by designing a transducer to take the curvature into consideration.

6.2. *Corrosion stages*

The specimens tested were in two stages of corrosion, fully and partially corroded. The images above represent a clear pattern when the tendon is fully or partially corroded. In comparison to the plain grouted specimen, the pattern is easily distinguishable but results from more specimens at varied levels of corrosion are required to develop a robust pattern definition system. If images from specimen with different corrosion stages are available, they can be matched and correlated implicitly or explicitly with the plain grouted sample to detect trends in corrosion.

6.3. *Medium*

There are basically two media, viz. air and water, through which the ultrasound beam travels in the C-scan imaging. In this study, water was used as a medium in the C-scan imager and immersion system. It is easy to shift from one medium to another provided a suitable transducer with a particular frequency is available. For this study, access to a C-scan imaging system with water as medium was available and hence it was decided to prove that the method works on post-tensioned concrete systems before purchasing new equipment. Adapting to air as a medium to attain the same objective is a realizable task and is more practical from the civil engineering application viewpoint.

6.4. *Void detection*

It is observed that the tendon could not be clearly seen by the image reconstructed from signals at G4 from tests carried out on the voided sample. Also, this study is not conclusive in itself in the case of void detection. Although a significant low reflection pattern is visible, it cannot be inferred with a high confidence level that void detection is fully explained by this study. More elaborate tests need to be done to ascertain the existence of voids within the duct. This is critical to the differentiation in pattern between a void and corrosion as most of the corrosion happens where voids are present in the structure. Hence, it is important to have clear distinctive patterns for void and corrosion so that implicit comparison can be made to detect either of them in the structure.

7. Conclusion

Post-tensioned structures have experienced durability problems related to corrosion and voids in the grouted duct due to various reasons. This study deals with the investigation of an NDE method called C-scan imaging to detect corrosion and voids in post-tensioned specimens. The acoustics of ultrasound wave propagation were verified in the samples in this preliminary study to the desired level of satisfaction. It is critical to prove the authenticity of the technique through signal verification and image reconstruction. This study has achieved this. Corrosion at two different stages could be detected and verified with the ideal plain grout sample and a definitive trend in the images was confirmed through this method. Although more tests on samples with different levels of corrosion are required to propose a robust detection and prediction model, the present tests have been successful in correlating the images at different depths using the ultrasound C-scan imaging technique. Voids within the casing were also detected from series of images and verified by autopsy done on the specimen. The location of void on the actual autopsied specimen and reconstructed image corresponded thus validating the method of scanning. This scanning technique has been successfully implemented and proven in the fields of medical diagnosis and fatigue fracture detection in composite or sandwich materials. This study has shown that it can also be used on post-tensioned structures to detect structural integrity problems (like corrosion and voids) detrimental to the structure. A wide scope exists to improve the flaw gate location process which may yield better results in terms of information available from gates to reconstruct images.

Investigations on post-tensioned specimens using ultrasound C-scan imaging technique have proved this method to be promising for future applications in the evaluation of corrosion and voids in post-tensioned tendons. The study recommends further investigations to upgrade the technique from bench-top to a field-ready instrument. The following issues need attention to make the ultrasound C-scan equipment field-ready.

- Specimens used in the study were square in shape and the geometry was dictated by the availability of transducers that could handle only flat surfaces. In the actual field, post-tensioned ducts are typically circular in geometry and hence transducers that can compensate for the curvature effect need to be designed and used in testing specimens. The technology for fabricating a transducer that takes into account the curvature effect and focuses on the ultrasound beam to penetrate the surfaces exists and is accessible.

- There is a tradeoff between the shape of specimen and attenuation offered by concrete (grout) to the focused ultrasound beam. Transducers that can compensate for the curvature and concrete attenuation effects together need to be designed and their performance needs evaluation.

- A 500 kHz transducer was used for this exploratory study as it was part of the equipment. Lower frequency transducers will improve the results and should be incorporated in future testing.

- It is desired to have a processing system that will process the data (images, signals) and recognize a distinctive pattern to propose a detection and prediction model. Pattern recognition (PR) is a very effective methodology to attain the above objective. A PR algorithm can be developed based on *n* number of sample data collected and the neural network can be trained to recognize a pattern based on certain characteristic features in the images. The entire C-scan imaging output can be fed as an input to the PR software for processing and if trained properly will detect and predict the extent of corrosion/voids. There is scope to develop pattern recognition algorithm to handle a large amount of data collected from many samples

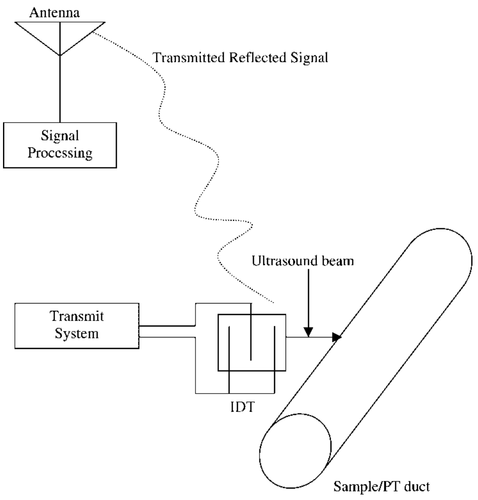


FIG. 13. Schematic of a wireless data acquisition and processing for ultrasound C-scan imaging technique.

with different levels of corrosion and voids. The resulting images would be dramatically improved over those presented from this preliminary study.

- A wireless transducer integrated with an ultrasound C-scanning system that can scan and catch data from the post-tensioned duct with little or no contact with the structure will consist of a very sophisticated measuring system. A remote antenna system needs to be devised to capture the reflected signals from different depths by means of flaw gates. An interdigital transducer (IDT) is cable-connected in order to supply the appropriate voltage required to power the scanning system. The schematic for wireless telemetry system for corrosion/void detection in the field using ultrasound C-scan system is shown in Fig. 13.

- The final field equipment must be tested on a large number of tendons under a wide range of conditions to ensure that the method is robust for field application.

Further research is contemplated to develop this technology into an ultrasonic bridge inspection system which will eventually find application in all concrete structures in general.

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