

Other Major Component Inspection III

Nondestructive Evaluation of Reinforced Concrete Components of Nuclear Power Plants

D. Algernon, H. Ernst

SVTI – Swiss Association for Technical Inspections, Switzerland

D. Algernon, C.C. Ferraro, D.R. Hiltunen

University of Florida, Department of Civil and Coastal Engineering, USA

C.A. Ishee

Florida Department of Transportation, USA

ABSTRACT

Structural concrete components of nuclear power plants are designed to withstand dynamic loads such as earthquakes or airplane crashes and to protect the internal components from thermal exposure or moisture. Additionally, they serve as a protective barrier for the environment against radioactivity. Most of the concrete components are highly reinforced, and as engineers strive to enhance the efficiency structures, prestressed and post-tensioned reinforcement has become more prevalent in the construction of newer nuclear facilities.

To ensure the integrity of the concrete components, especially with regard to the extension of the life-span of nuclear plants, non-destructive testing (NDT) methods are essential for the examination of the concrete and the embedded reinforcement. As a result of the research and development conducted during the past decades, especially in the transportation and construction sector, it is possible to obtain detailed information on the internal structure of concrete components through the application of electromagnetic and acoustic methods. The measurements can be performed by fully automated scanners, which collect the data along a defined grid with a large number of measurement points. Signal processing techniques such as the Synthetic Aperture Focusing Technique (SAFT) in combination with 2D and 3D imaging techniques are applied to the collected data to create a visual image.

For a detailed study of the capabilities and limitations of the NDT different methods, a variety of laboratory specimens were created to investigate relevant testing problems; for example localization of dense reinforcement in concrete components, tendon duct inspection and wall thickness measurements were investigated in the laboratory on various test specimens created to emphasize the limitations faced by NDT methods as per the literature.

To optimize the inspection, semi-analytical simulation techniques are applied prior to the actual examination of the component. The strengths and possible applications of the different methods as well as their limitations are discussed.

INTRODUCTION

Concrete components of nuclear power plants protect against mechanical loads such as earthquakes or airplane crashes, protect certain components from thermal exposure or incoming moisture and serve as an additional barrier against radiation.

Given the safety significance of the containment (e.g. Figure 1) as the final barrier to the release of radiation into the environment, it is typically this type of structure that has attracted greatest attention in terms of aging management [1]. A number of other structures impact, perhaps indirectly, on the overall safety of nuclear power plants. This influences their design and assessment requirements. Such structures are referred to as safety related concrete structures. These would include structures containing critical plant components, where substance failure could lead to consequential damage or active waste contaminants (e.g. fuel cooling ponds, supporting structures, crane platforms, etc.) [1].

Typically, the aging management for the concrete components of a nuclear plant consists of mostly visual inspections, which are indeed essential in the structural condition assessment. However, especially regarding the extension of the service life of nuclear plants, more detailed and quantitative information about the structural condition of the entire plant including the concrete components is needed. This information can be provided by advanced NDT methods, as they have been developed especially in the transportation and construction sector to test bridges and other structures.

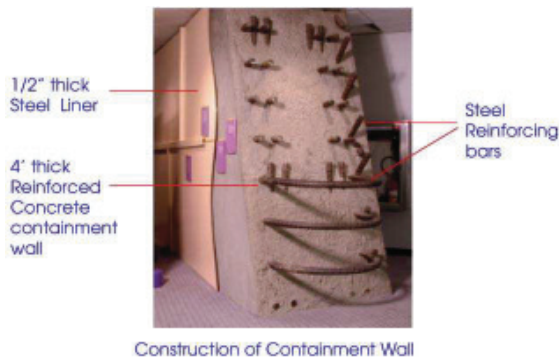


Figure 1 - Containment wall.
(picture source: NEI, Entergy)

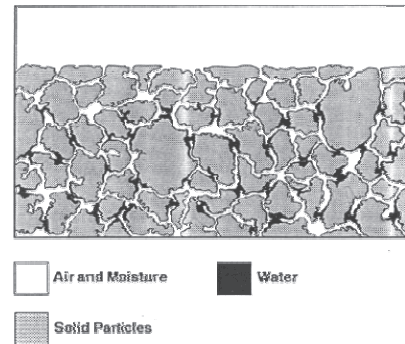


Figure 2 - Concrete Porosity. When excess water evaporates, it leaves voids inside the slab creating capillaries which is directly related to the slab porosity and permeability

Concrete is a construction material composed of mostly cement, aggregate, water, and chemical admixtures. A significant characteristic of concrete is its porosity. It is caused by excess water that evaporates and leaves voids inside the slab (Figure 2). The porosity has to be taken into account for NDT of concrete components; e.g. ultrasonic probes in the frequency range of several megahertz as used to test metals are generally not used for concrete since the resulting short wavelengths would cause the waves to get severely scattered at the air voids and interfaces between the particles. Furthermore, the relatively large thickness of typical concrete components requires probes and methods with high penetration depth.

A major field for the application of concrete related NDT is the condition assessment of bridges and other highway structures. As a result of the research and development conducted in that field, the capabilities of the different methods have been significantly improved. To implement these methods e. g. in aging management programs, their exact capabilities and limitations have to be known and quantified. Significant achievements regarding the validation of concrete related NDT methods have been made at the Federal Institute for Materials Research and testing (BAM), which was the basis for the validation facility initiated at the Florida Department of Transportation. This will be further discussed in the following chapters.

The need for thorough validation of the applied NDT methods becomes evident especially when they are applied to assess the structural integrity of nuclear plants. This has already been addressed in [1], where the quantification of the capabilities of existing NDE techniques along with the qualification of NDE methods for their use in nuclear plants is seen as a priority area for development. The expertise regarding the qualification of NDE systems and personnel in relation to the inspection of mechanical components of nuclear plants as can be found at institutions such as the Swiss qualification body QSt as a part of the Swiss Association for Technical Inspections (SVTI) can be used to expand and adapt this qualification methodology based on ENIQ [2] to the needs of concrete related NDT. The qualification approach has the potential to further improve the reliability of such inspections tremendously.

THE FDOT VALIDATION CENTER

Based on the achievements made by BAM, efforts regarding validation and quantification of the capabilities of concrete related NDT methods have been made by the Florida Department of Transportation (FDOT). Aiming at longer life spans for bridges in Florida, the FDOT decided to move towards the implementation of nondestructive test and evaluation (NDT/NDE) technologies to assess the structural condition of existing bridges. Prior to implementation of such methods, their effectiveness must be proven. Toward this aim, the FDOT funded a project conducted by the University of Florida, which had the primary objective to design, construct and implement a first-stage facility at the FDOT State Materials Office in Gainesville, FL for calibrating and validating methodologies for the NDT/NDE of structural concrete materials and members [3]. Especially to ensure the repeatability of the measurements, an automated test frame was designed, allowing automated use of sensors for various NDT methods (Figure 3).

Once the capabilities and limitations of the different methods to solve a certain testing problem are known, the efficient application of NDT can lead to improved quality and durability and significant cost savings for the state of Florida.

Very similar considerations are applicable to the structural condition assessment of the concrete components of nuclear plants as well.

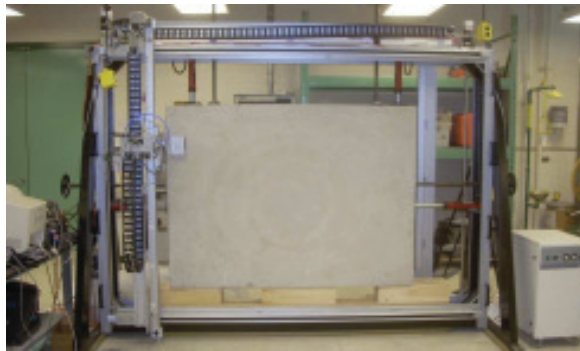


Figure 3 - Automated NDT scanning system at the FDOT Validation Facility in Gainesville, FL

TESTING PROBLEMS

Among others, testing problems of concrete related NDT are:

- Thickness measurements
- Finding Flaws, cracks, delaminations
- Measuring the concrete cover
- Locating steel, anchors, tendon ducts in concrete
- Measuring material properties

The above-named are testing problems that are typical not only for bridges, they are also relevant for nuclear plants as can be seen in [1].

Within the FDOT project it was decided to focus on these testing problems as a first step.

NDT METHODS FOR TESTING CONCRETE COMPONENTS

A brief description of the methods used so far at the FDOT validation center is given as follows.

Ultrasonic Echo: In recent years, ultrasonic echo has been successfully applied in various inspections of concrete bridges ([4], [5], [6]). The porosity and inhomogeneity of the material makes it necessary to use wavelengths in the centimeter range, resulting in frequencies of 100 kHz and lower. Especially the development of a dry-coupled ultrasound sensor (Figure 4) working with shear waves generated by an array of transducers and measured by another array of six transducers [7] has made this method very practical. In combination with a signal processing technique referred to as SAFT (Synthetic Aperture Focusing Technique, [8], [9]) it is highly suitable for concrete scanning and imaging. Its field of applications comprises thickness measurements, flaw detection, and inspection of tendon ducts ([10], [11]).



Figure 4 - Ultrasonic Sensor Eyecon by ACSys. Dry-coupled sensor with a center frequency of 55 kHz, designed for measurements on concrete
Left: Probe with handheld controller Right: Probe mounted on scanning system for automated use

Impact-Echo: Impact-Echo has been successfully applied for thickness measurements and for the localization of defects inside concrete structures. Its principle is based on the analysis of multiple reflections after mechanical impact excitation ([12], [13]). A small steel ball or hammer is tapped on the surface of a concrete structure and creates stress waves propagating through the material. The multiple reflections are analyzed in the frequency spectrum using the Fast Fourier Transform (FFT). There is a direct relation between the measured frequency and the depth of a reflector:

$$2d = c_L \cdot T = \frac{c_L}{f} \quad \Leftrightarrow \quad d = \frac{c}{2f}$$

c_L : Longitudinal wave velocity

d : Depth of the reflector

T : Period

f : Frequency

Its application as a scanning method in combination with a visualization technique for the analysis has definitely improved the possibilities of the method.

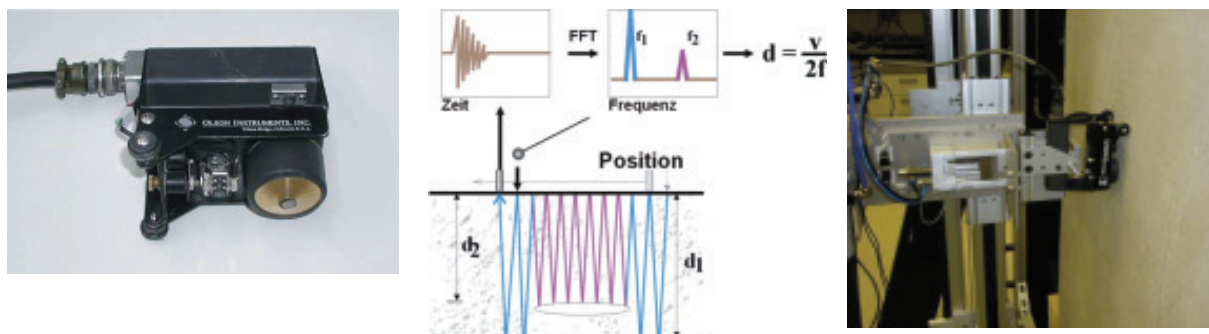


Figure 5 - Impact-Echo
Left: Sensor head used in this study, IE1 by Olson Instruments
Center: Principle of Impact-Echo
Right: Sensor head mounted on scanning system

Covermeter: The principle of the covermeter is based on the use of the pulse-induction method (Figure 6, left). After briefly magnetizing the reinforcement bars the fading magnetic field is measured. The two important parameters that influence the strength of the induced field are the size of the bar and its depth below the search head ([14][15][16]). For an accurate depth measurement, the diameter of the rebar has to be known and vice versa.

The eddy-current echo from the reinforcing bar also depends strongly on the orientation with respect to the bar. If reinforcement running in two perpendicular directions (horizontal and vertical reinforcement) is to be located, the measurements have to be carried out with two different orientations of the search head.

Covermeter measurements can be conducted in a continuous scan. The search head is slid along scan lines at the surface of the test object (Figure 6, center and right).



Figure 6 - Covermeter

Left: The principle of the pulse induction technique

Center: The covermeter used in this study, Profometer 5+ by Proceq

Right: Covermeter mounted on the scanner for automated use

Ground Penetrating Radar (GPR): As an electromagnetic method it is very sensitive to metallic reflectors in the concrete, e.g. reinforcement and metal tendon ducts. The spacing of the reinforcement right below the measurement surface has a major effect on the maximum depth that can be assessed with this method, since dense reinforcement will reflect almost all of the energy and will make it hardly possible to measure below it. For tendon duct inspections GPR is used to determine the exact location of the duct. However, since the electromagnetic waves are reflected almost completely at the metal duct, it is not possible to measure inside the duct to detect a possible void in the grout. It will therefore be used in combination with acoustic methods like ultrasonic echo or impact echo.

Laser Profilometer: Laser profilometers are scanned contactless along a surface and measure the distance to the surface, thus providing a surface profile of the scan area **Fout! Verwijzingsbron niet gevonden**. This can be useful to adjust other sensors (e.g. impact-echo sensor) according to the profile to guarantee good coupling.

STUDY ON THE CAPABILITIES OF NDT

To study the different NDT methods under defined conditions regarding their capabilities to solve the different testing problems, test blocks were made in the laboratory. They were given dimensions that are large enough to minimize geometrical effects on the measurements, but that would still allow to handle the blocks with a forklift in the laboratory.

Some of the testing problems implemented in the different blocks will be discussed in the following sections.

Measurements of the Concrete Cover

The concrete cover is crucial for the durability of the reinforcing steel. This becomes clear in Figure 7, which describes carbonation as one of many failure modes for reinforced concrete.

The reinforcing steel in healthy concrete is protected from corrosion through the highly alkaline cement in which the embedded steel is passivated and therefore protected from corrosion. However, the carbon dioxide in the air starts to carbonate the cement in the concrete from the moment the object is made. This carbonation process starts at the surface, then slowly moves deeper and deeper into the concrete. Based on the environmental conditions, the carbonation rate can be estimated. To protect the steel, the concrete cover needs to be sufficient to ensure that carbonation will not reach the steel over the entire design lifetime of the respective component. In other words, insufficient cover is a durability issue because it reduces the lifetime of a structure.

In the particular case described by carbonation rate graph in Figure 7, the rebar with a concrete cover of 20 mm would be protected for 50 years. However, a reduction of the concrete cover by only 2 mm would reduce this time span by 10 years. Measurements of the concrete cover are therefore important to ensure the durability of the structure.

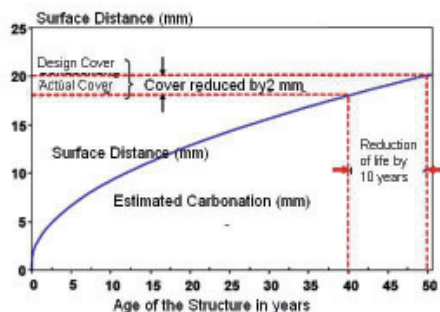


Figure 7 - Carbonation Depth. Under unfavorable conditions, a reduction of the concrete cover by only 2 mm can reduce the durability of the respective component by 10 years



Figure 8 - Rebar Specimen before the concrete was poured (left) and during automated covermeter testing in the test frame (right)

Figure 8 shows the rebar specimen used for the study on concrete cover measurements. There are layers of reinforcement in x- and y-direction and at the front as well as at the back of the block. The bars vary in diameter, depth and spacing.

The results obtained from covermeter measurements along the top and the bottom of the block are given in Figure 9 and Figure 10. The measured depth is given in a color scale. To locate rebars running in x as well as in y-direction, measurements were carried out in two perpendicular scan directions x and y for each side of the block.

At the front of the block the rebars with spacing (position 20-29) not too dense show up very clearly, although the measurement is obviously affected by the crossing rebars (especially positions 33-39). However, even the bars at positions 33-39 with an extremely small spacing can be separated quite well.

Figure 10 gives the results from the back, where the concrete cover is slightly larger than at the front. Here the effect of the crossing rebars becomes even more evident.

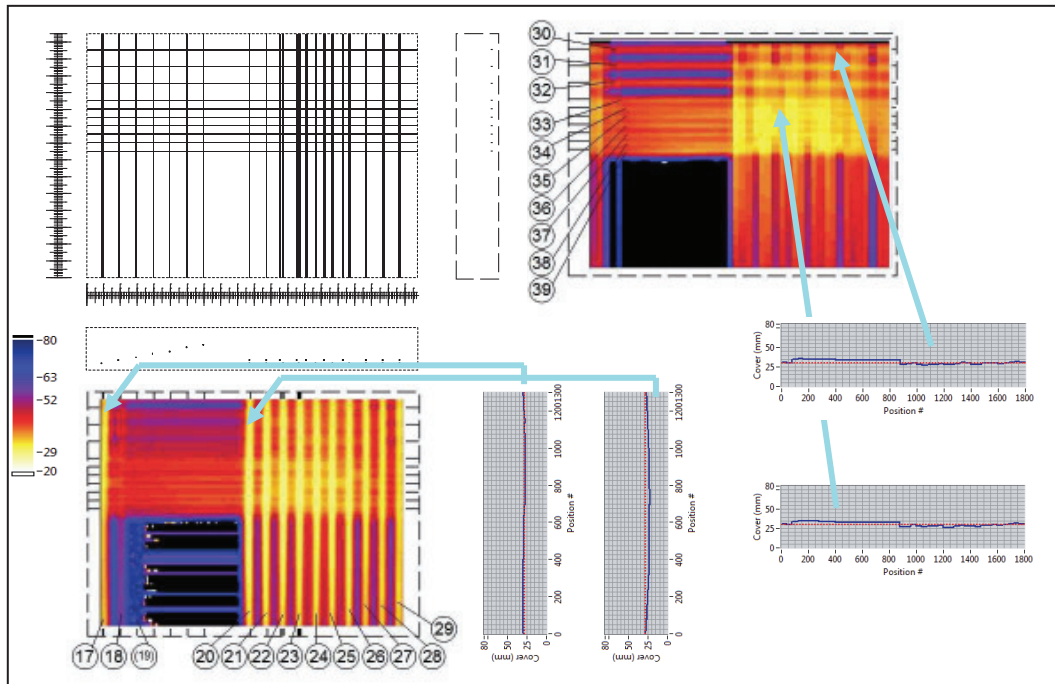


Figure 9 - Results obtained from covermeter measurements on the front of the block
 The C-scan images give a color scaled representation of the measured concrete cover over the measurement area. Additional graphs give the measured concrete cover along a selected rebar, in which the blue curve shows the measured cover and the red curve gives the actual depth of the rebar according to the design plan

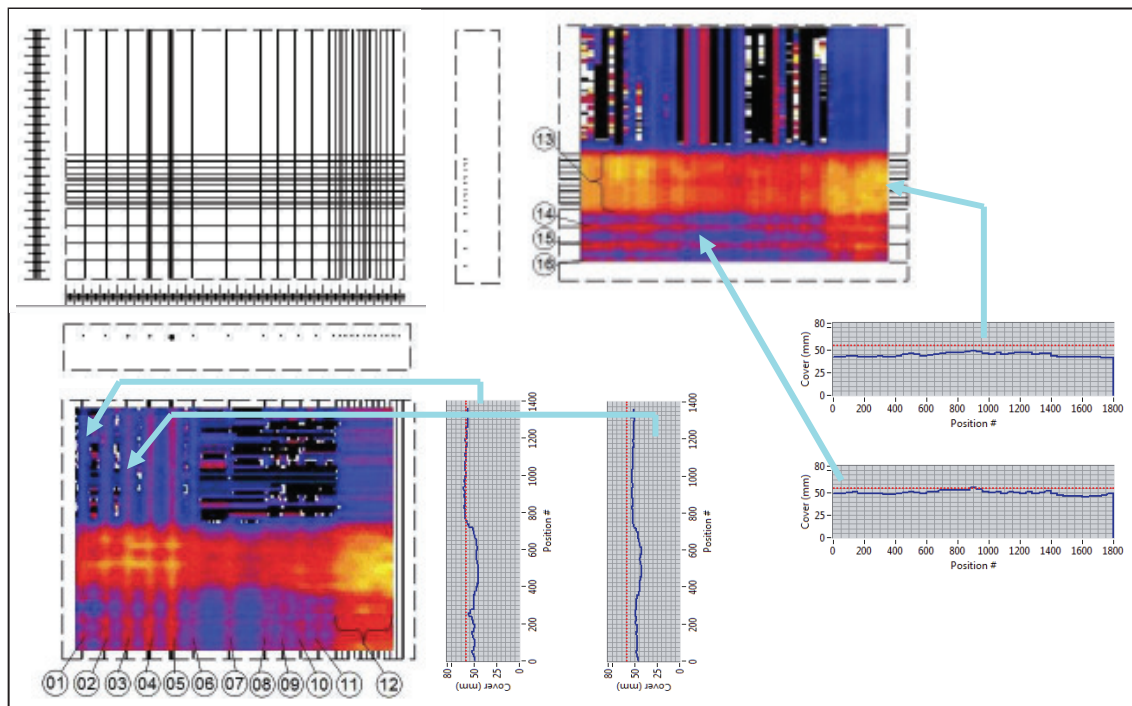


Figure 10 - Results obtained from covermeter measurements on the back of the block
 The C-scan images give a color scaled representation of the measured concrete cover over the measurement area. Additional graphs give the measured concrete cover along a selected rebar, where the blue curve shows the measured cover and the red curve gives the actual depth of the rebar according to the design plan

While covermeters are limited to depths up to 150 mm or less and can only locate the first layer of reinforcement in the respective measurement direction, ultrasonics can provide more detailed information about the rebar locations. Figure 11 shows a cross-sectional view (B-Scan) of the reinforcement running in the y-direction after postprocessing the data with the SAFT (Synthetic Aperture Focussing Technique) algorithm. The rebars can be identified as discrete dots. Not only is the spatial resolution better than in the case of the covermeter measurements, the accuracy in depth with which the rebars is also better because the measurements are not as much affected by crossing rebars as was the case with the covermeter. Furthermore, multiple layers of reinforcement can be detected, even those at the opposite side of the measurement surface.

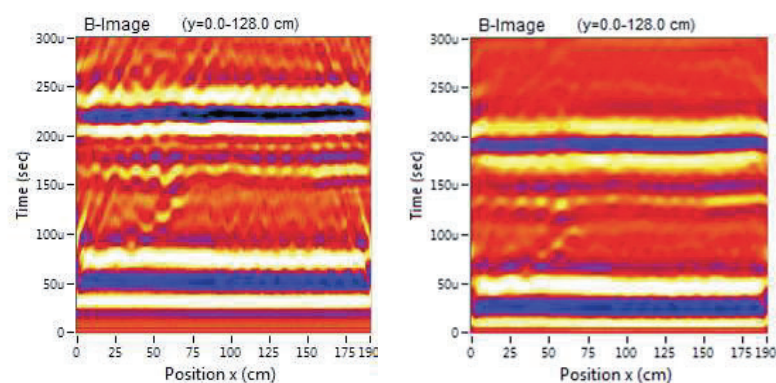


Figure 11 - Ultrasonic B-Scan image obtained from measurements on the rebar specimen before (left) and after (right) post-processing with the SAFT algorithm

Thickness Measurements

The measurements carried out on the block with varying thicknesses (Figure 12) served to evaluate the capabilities of the different methods, especially in combination with complex geometries (steps), and furthermore, in detecting minor thicknesses or voids near the backwall. All measurements were carried out from the top (flat side) of the block in a grid of 20 mm by 20 mm. Ultrasonics as well as impact-echo were used, but due to the challenging block geometry (relatively small areas with different thicknesses) ultrasonic-echo proved to be significantly better suited for this task than impact-echo. Therefore, only the ultrasonic-echo results are shown in Figure 12. The different thicknesses of all areas including the small areas with minor thicknesses can be clearly distinguished.

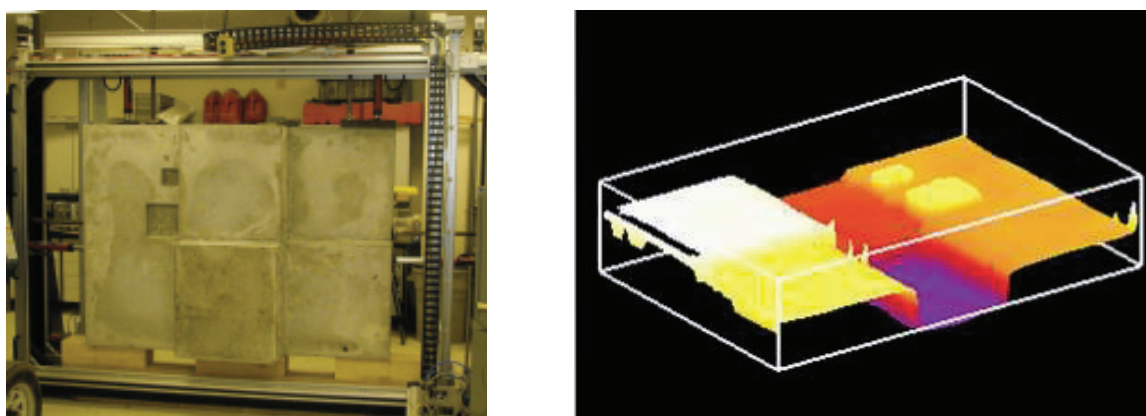


Figure 12 - Thickness Block

Left: Placed in the test frame for automated scanning. View of the back of the block showing the different thicknesses of the block. Measurements are performed from the front
 Right: Results obtained from ultrasonic measurements, 3D representation of the measured thicknesses

Tendon Ducts

The focus of the measurements carried out on the tendon duct block (Figure 13, left) was to see how precisely the tendon ducts can be located in the block and if the different areas with different grouting states (empty, fully or half-grouted) can be identified. Therefore, ultrasonic-echo and impact-echo were used.

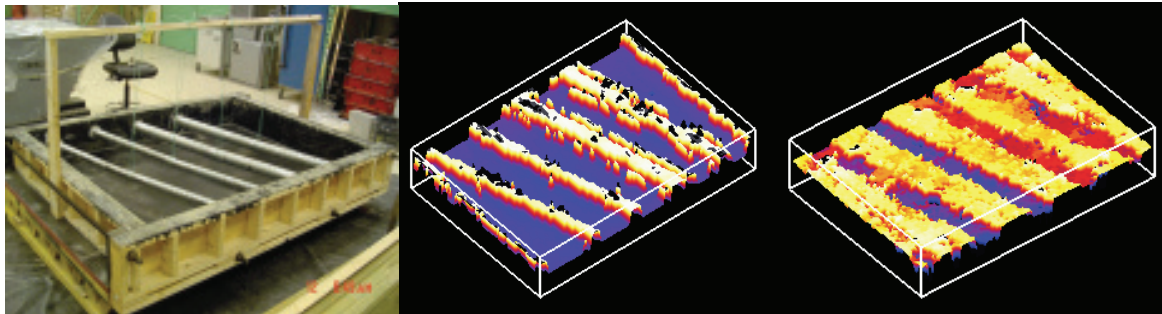


Figure 13 - Tendon Duct Block
Left: Block before the concrete was poured
Middle: 3D representation of the ultrasonic results
Right: 3D representation of the impact-echo results

Ultrasonic-echo (Figure 13, center) successfully located the ducts in their lateral position as well as in depth. Even the different sizes of the ducts (first two ducts from the left are smaller in diameter than the two on the right) can be estimated from the results.

In the impact-echo data, the lateral positions of the ducts can be determined based on a shift of the measured thickness towards an apparently increased thickness at the location of the duct. However, this means that the duct cannot be located in depth. This effect is very typical for impact-echo. In a simplified way, it can be explained as a diffraction phenomenon that increases the time of flight, thus resulting in a lower frequency indication when the data is transformed into the frequency domain.

Due to the large wave-length as well as the interference of the waves with reflections at the geometrical boundaries of the block, it was hardly possible to measure a direct reflection of the waves at the duct with impact-echo.

All four ducts are partly filled with grout, i.e. there are sections that are completely filled with grout and others that are only half-filled or completely empty. This serves to simulate voids in the grout, as they can occur during construction and represent a durability problem for the tendons, since they are no longer protected by the alkaline grout and exposed to the air in the void. Although in Figure 13 there are certain indications in the ultrasonic as well as in the impact-echo data that are somehow correlated to the actual position of the ducts (actual position is not provided in the figures), the indications are rather vague, so that it was not possible to locate the voids in this case. Very likely this is due to a fabrication issue; the grout debonded from the wall of the duct thus making it impossible to distinguish between grouted and ungrouted parts of the duct.

Measuring Elastic Parameters

Material properties such as the elastic parameters can be derived from NDT measurements. For example, if the thickness of a concrete component at a certain position is known, impact-echo measurements can determine the longitudinal wave velocity c_L and ultrasonic-echo using shear waves can determine the shear wave velocity c_s . Based on these two parameters, the Poisson's ratio ν can be calculated as shown in Figure 14. Furthermore, if the density ρ is known, the modulus of elasticity E and the shear wave modulus G can be determined too.

<p>Measured:</p> $c_L = \sqrt{\frac{E}{\rho} \cdot \frac{1-\nu}{(1+\nu)(1-2\nu)}} \quad , \quad c_s = \sqrt{\frac{E}{\rho} \cdot \frac{1}{2(1+\nu)}}$
<p>Calculated:</p> $\nu = \frac{\frac{1}{2} - \left(\frac{c_s}{c_L}\right)^2}{1 - \left(\frac{c_s}{c_L}\right)^2} \quad , \quad E = 4\rho \frac{3/4 c_L^2 - c_s^2}{\left(\frac{c_L}{c_s}\right) - 1} \quad , \quad G = \rho \cdot c_s^2$

Figure 14 - Summary of the equations to calculate Possion's ratio, modulus of elasticity and shear modulus from the longitudinal and shear wave velocity, which can be measured with impact-echo and ultrasonic-echo

CONCLUSION

Especially with regard to the ongoing discussion about the service life extension of nuclear power plants, the demonstration of the structural integrity of the concrete components can become relevant, in which case the application of advanced concrete NDT methods can be very helpful.

Such methods can supplement visual inspections in terms of detecting internal flaws, or they can also be used to determine the as-built details, such as mapping the reinforcing steel or measuring the thickness profile. If feasible, the complimentary information obtained from a combination of different methods can help to increase the efficiency of the inspection.

The experience gained from practical application as well as the research and development effort made especially in the transportation sector should be of great value.

The quantification of the existing capabilities as well as the qualification of inspection systems and personnel will be essential to ensure the reliability of the inspections especially in the nuclear field.

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