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NDE of Thick and Highly Reinforced Concrete Structures: State of the Art

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Abstract

The objective of the report is to present the state-of-the art of non-destructive testing methods and technologies for the inspection of thick, heavily-reinforced structures, (e.g. found in nuclear power plants). Wall thicknesses can be in excess of one meter and the structures often have increased steel reinforcement density. The accessibility for any testing method may be limited due to the presence of liners and other components such as cast-in-place items. Testing methods have to provide solutions for tasks such as locating failure (inclusions, corrosion, voids, delaminations) in the structures or the assessment of the condition of the structure in general.

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1. Introduction

Nuclear Power Plants have been in operation for ca. 50 years. Concrete is a very durable material and any natural deterioration processes may take a long time to become critical to the structure. The experience of more than 50 years of service shows that there are testing tasks for which good solutions can be provided by the application of NDT and a few others for which reliable methods have not yet been developed.

The performance based service life extension of existing NPPs needs a measurement based decision to support continuing the service of the concrete part of the installations. Non-destructive testing tasks specific to thick and highly reinforced nuclear containment structures have been developed and can partly be applied successfully for certain, well-defined testing tasks. The inspection of nuclear power plant concrete structures presents challenges

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different from conventional civil engineering structures. Wall thicknesses can be in excess of one meter and the structures often have increased steel reinforcement density with more complex detailing. The accessibility for any testing method may be limited due to the presence of liners and other components and there can be a number of penetrations or cast-in-place items present [2, 3].

2. State of the Art Report

A comprehensive state of the art report was compiled in cooperation with the Oak Ridge National Laboratory (ORNL) [1]. This report is summarizing available data and information on non-destructive testing methods and technologies for application to nuclear power plant safety-related concrete structures.

A number of parameters which distinguish the subsets of such testing problems must be defined before searching for a solution. In the following, the most obvious parameters for the general NDE tasks are listed. Since the parameters for the tasks are not sharply defined, the state-of -the-art and the recommendations are more general and could be quite different in special cases. The following test scenarios are discussed in detail in the report where also the main findings are summarized in subchapters:

Locating Steel Reinforcement and Identification of Its Cover Depth

In NPPs the reinforced concrete structures are commonly described as highly reinforced. There is no common definition of this term. For NDE it may be important to define this situation to be able to select the test method. The measurement of the lateral position, diameter and concrete cover for near surface reinforcement is a standard testing task for which a number of commercial systems are available. In order to locate reinforcement beyond the first two layers or with a large concrete cover, test methods and strategies have to be developed.

Locating steel reinforcement and the determination of its cover depth is possible within certain limits. Depending on the accessibility (one-sided or double sided) different methods or combinations of methods can be applied in a range between 0,03 – 2,0m. Concrete properties like aggregate size and distribution, W/C ratio, porosity and moisture content play a role for the quality of the results that can be gained. The inductive method with low or high (eddy-current) frequency excitation, Radar (GPR) can be considered to be standard methods for the described task.

In very special, strictly defined cases further methods allow at least the localization of reinforcement and the measurement of cover depth from a physical point of view: Ultrasonic, Active thermography, Radiography (multi-angle technique) and Magnetic Flux Leakage. However, these methods are no standard testing procedures and can only be applied to get initial information. Magnetic and inductive methods are well established since the 1980ies when cover depth became an issue for durability and devices became available on the market.

The inductive methods, both with high or low frequency excitation as well as the Radar method have to be validated to a large extent. Although commercial devices are available, the application is still not well established for the described tasks and particularly not in the needed thickness range. Active thermography and Radiography are only applicable under very specific conditions and it is not likely that they can be further developed to meet the requirements of testing of thick concrete members. For radiography (e.g. Betatron) the time consumption is very high and safety precautions have to be strictly followed.

Locating Tendon Ducts and Identification of the Condition of the Grout Materials

Remark on grouting defects: grouting defects may have geometrical properties which support or obstruct their discovery.

Locating tendon ducts and the identification of the condition of the grout materials is possible within certain limits [4]. Depending on the accessibility (one-sided, double sided or from the edge) different methods or combinations of methods can be applied in a range between 0,1 – 2,0m. Concrete properties like aggregate size and distribution, W/C ratio, porosity and moisture content play a role for the quality of the results that can be gained.

For locating the tendon ducts, it has to be considered, whether they are metallic (single or overlap at joints) or plastic. Furthermore their size (diameter) and the number of strands play a role for the selection of the proper method. The concrete and reinforcement cover, as well as the presence of tendon layers/crossings are further variables.

The target parameters of the grouting defects are grout material, size, shape, orientation, length and density. Most applications concerning non-destructive testing of tendon ducts deal with metal ducts. Because of the shielding of electromagnetic waves of metal surfaces, GPR is principally not applicable for this task. It can however be used in a first step, to locate the ducts on which other methods are applied. Radiography applying X- and Gamma Radiation is the oldest method to investigate the interior of steel and concrete structures. They still play an important role for NDT of post tensioned concrete bridges because of the capability of penetrating thick concrete elements up to 1 m. When digital imaging plates instead of films are used these methods have become much more sensitive during the last decade. Principally the method requires that the building element is accessible from both sides. Using radioactive radiation sources the thickness is limited to about 0.7 m. If betatrons are applied, even a thickness up to 1 m is feasible, but this requires up to 1 h exposure time.

The first applicable ultrasonic wave method applied for this purpose was Impact Echo, developed at the end of 1980s. The equipment is not too complex and rather easy to handle. Impact-Echo was widely applied in the 1990s and had the advantage of dry coupling on concrete surfaces. Even though evaluation in the frequency domain works best for planar slabs, the method was also applied for post tensioned structures with more complicated geometry. Since mid-1990s, several commercial equipments came into the market and numerous applications were reported with partially verified results.

Commercially available imaging with a linear array should be tested in comprehensive experiments at new specimen. It should be adapted for new dimensions of tendon ducts and test specimen of more than 1m thickness. These elements should feature large diameter tendon ducts and heavy reinforcement. Further research should go into the improvement of the ultrasonic echo imaging technique with SAFT including phase evaluation.

Detection of Cracking, Voids, Delamination, and Honeycombing In Concrete Structures

Cracks have a wide variety of structure. It is mandatory to give a definition, which kind of voids are to be found. The term voids is used in a more general way as defect, especially in the case of an air defect. Delaminations can be defined as a crack parallel to the surface. Honeycomb is a voided area which is still connected through cement and/or aggregates. Its structure can vary at large scales.

The detection of cracks, voids, delaminations and honeycombing in concrete structures is possible within certain limits. Depending on the accessibility (one-sided, double sided or edge) different methods or combinations of methods can be applied in a range between 0,5 – 2,0m. Concrete properties like aggregate size and distribution, W/C ratio, porosity and moisture content play a role for the quality of the results that can be gained.

For the detection of cracks it has to be considered to which type (Single, multiple, microcracking, water filled/dry) they belong and if they are closed, open or partially closed. Cracks may have different orientations (perpendicular to surface, parallel to surface (= delamination, if open crack; = debonding if closed), random orientation) and thus the selection of the proper method has to be adapted. For the determination of voids regarding their type and location, the presence of reinforcement or tendon ducts is crucial and if a void is crossed by rebars or eventually located behind it. The targeted variables for any measurement are: Density, shape, homogeneity, size, orientation.

On short term it would be beneficial to do a comprehensive analysis of inspection records to collect information about the most typical defects in containments and related NPP-structures. Following this, the design of a mock-up for the typical NPP-containments with typical artificial defects (vertical cracks surface, near surface crack, irregular crack or deep delamination, honeycombing) can be made. With this specimen, a validation of current methods with available equipment can be carried out, eventually in Round Robin tests.

Further research should cover the identification of gaps in methodologies for measurements and for equipment. To cover larger areas, faster measurements with optimised equipment are required, this has to include data analysis using data fusion. In the long term the application of embedded optical and acoustic (active and passive) sensors should be considered already during the design and construction phase.

Detection of Inclusions of Different Materials or Voids Adjacent to the Concrete Side of the Containment Liner

The testing task considers access through the concrete, not from the liner side. The ratio between the diameter of the object and the concrete cover may be very small. The detection of inclusions of different materials or voids adjacent to the concrete side of the containment liner in a range between 0,5 – 2,0m and an accessibility from only one side is principially possible, but methods with the potential of identifying such objects with a concrete cover of more than 0,5 m are very rare. Concrete properties like aggregate size and distribution, W/C ratio, porosity and moisture content have to be considered for the selection of the testing method.

Depending on the object material (non-metallic, metallic, air, water), interaction between the object and the containment liner might occur, like corrosion following moisture transport. Size, shape and orientation of included objects might be determined.

Several cases have been reported, where inclusions of foreign material have caused severe corrosion with partially complete thickness loss of the steel liner. So far there have been no systematic studies on early stage detection of these inclusions by NDT. However, these inclusions might be detectable by ultrasonic echo and other techniques described above. Depending on the details of the scenario the contrast to undisturbed parts of the structure might be less than with voids or delaminations. The size of inclusions is small. Thus the probability of detection is limited. To assess the ability of the techniques mentioned above to detect inclusions of anomalous material properties it is recommended to perform a series of test at full scale mockups, including all scenarios described above.

Methods Capable of Identification of Corrosion Occurrence on the Concrete Side of the Containment Liner

There are no known methods which could (under standard conditions) directly address the corrosion through a steel liner or with a concrete cover exceeding approximately 10 cm. In this task it is necessary to know, if there is active corrosion, corrosion with debonding or if liner thickness loss has already occurred [5]. However, this is not directly measurable, only indirect measurements can eventually point out that corrosion in one of the above described forms has happened. While ultrasound echo with large aperture might be able to identify delaminations (which might be an indication for corrosion and loss of contact near the liner), ultrasound echo high frequency can measure the remaining liner thickness. If there is a lower value as expected, again, it can be concluded that corrosion has happened. Acoustic emission has some potential to monitor active corrosion.

In case of access only from the concrete side research would be needed to apply voltmeters with a much higher resistance than voltmeters for classical potential mapping. In addition simulation could help to find out if measurable gradients of the potentials may occur at the concrete surface. For both measures, intense R+D would be necessary.

The following table summarises the applicability of different NDT methods for the testing tasks as described above:

	Suitability of methods for the described task		
Task	**very well suited**	**well suited**	**partially suited**
Locating steel reinforcement and identification of its cover depth	inductive method with low frequency excitation (<10 cm cover max 2 layers) inductive method with high frequency excitation (eddy-current) (<10 cm cover max 2 layers) radar (<30 cm cover diameter not measurable)	Ultrasonic (>5 cm cover) radiography (multi-angle technique) (< 60 cm two sided access) magnetic flux leakage (<20 cm)	active thermography (<10 cm cover n/a for depth > 10 cm)
Locating tendon ducts and identification of the condition of the grout materials	ultrasound echo imaging (MIRA) locate (< 80 cm), cover (< 80 cm), grouting radar locate (< 50 cm) cover (< 50 cm)	ultrasound echo (A-scan) locate (< 50 cm), cover (< 50 cm) radiography (x-ray, gamma, betatron, linear accelerator), locate: (< 60 cm), cover: (< 60 cm), grouting ultrasound transmission, locate (< 10 cm)	radiography (x-ray, gamma, betatron, linear accelerator), cover: + (< 60 cm) ultrasound echo (A-scan) grouting
Detection of cracking, voids, delamination, and honeycombing in concrete structures		imaging ultrasonic echo (delaminations, cracks, voids) in a depth range < 100cm impact echo (delaminations) in a depth range < 50 cm	imaging ultrasonic echo (honeycombs) in a depth range < 100cm ultrasound, surface+lamb+ diffracted waves (delaminations, cracks, voids) in a depth range < 50 cm impact echo (cracks, voids) in a depth range < 50 cm
Detection of inclusions of different materials or voids adjacent to the concrete side of the containment liner			imaging ultrasound with large aperture (location, material), depth range ~ 2 m
Methods capable of identification of corrosion occurrence on the concrete side of the containment liner			ultrasound echo large aperture (delamination) ultrasound echo high frequency (indirect measurement of corrosion by determination of liner thickness) acoustic emission (active corrosion)

Table1. Suitability of NDT methods for the described tasks

Imaging ultrasonic pulse echo methods have the highest potential for progress in the non-destructive evaluation of structural discontinuities in thick and highly reinforced concrete. Existing commercially available equipment has been optimized for a concrete thickness up to 50 cm. This technology may be up-scaled and optimized for thick NPP concrete elements. To overcome the intrinsic scattering and attenuation of mechanical waves propagating in concrete, additional properties of acoustical waves (phase, frequency bands, modes) can be utilized to improve results. Array techniques are powerful technical solutions for many NDE testing tasks. Ultrasonic and GPR equipment is already available, other testing scenarios may benefit from multi-sensor testing equipment as well.

GPR has shown its potential in reinforced concrete structures like bridges. The high reinforcing level typical to NPP structures prevents the use of GPR in most cases. Nevertheless, there is a potential for GPR testing in selected cases where speed is a major concern, e. g. cooling towers. Detection of corrosion of steel deeply embedded in concrete is an unsolved testing issue. Basic research has to be carried out to find an approach to a solution of this important topic.

3. Summary and Conclusion

Research in NDT of concrete structures is performed by many research institutions all over the world with different technical and systematic approaches. Results are mainly obtained on laboratory specimen, sometimes additional field studies are reported. This research takes place independently without coordination and as a result, the outcomes mostly lack full comparability. But the validation (by definition the proof that customer´s requirements in the test are being met by the testing solution) of NDE solutions is becoming a critical part in concrete structure testing. This includes equipment, personnel qualification and data analysis. In general, a validation methodology for NDE solutions for concrete testing in itself needs to be researched and established.

Comparability of research also needs an accepted and easily accessible reference. From experience, it is almost impossible to manufacture exact copies of test specimens at different locations. Round Robin tests are therefore needed to evaluate the performance of a test. Reference specimens and validation are key elements for a streamlined research effort. Independent of the individual research group, their location and equipment used, comparability of experiments and results should be assured.

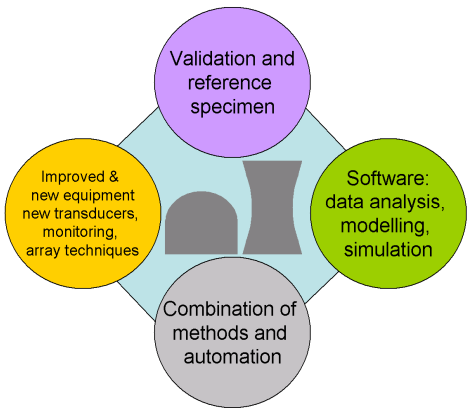

Figure 1. Action and research areas for improved NDE of NPPs.

The biggest impact on research into NPP related NDE of reinforced concrete structures may be found in improvement of the research infrastructure and support of synergy effects.

Automation and scanning is vital for producing high quality data which is the basis for any subsequent data analysis. Software for data analysis has become indispensable and very powerful. This part of testing needs more attention when it comes to evaluate test results. An in-depth evaluation needs to address the comparability and validation of software used for data analysis and evaluation. The vision of a unified software pool for NDE investigations would undoubtedly support research tremendously.

Quantitative NDE is mostly recommended to assess the condition of a structure. However, qualitative data can be very useful, especially for processes which change the material properties or deteriorate the structure (e.g. corrosion of reinforcement). The need for reliable baseline data is a key factor for such monitoring tasks.

Another major aspect in any research is software for modeling, simulation and data analysis. It is necessary to be able to simulate a testing scenario as close as possible to reality to be able to choose the appropriate equipment and parameters for the test and the subsequent data analysis. A common data format would be a significant step towards more collaboration between research groups and comparability of results. A software pool with dedicated numerical routines for data analysis, visualization, modeling, simulation and validation - as it is common in other areas of research, e.g. geophysics or medicine - would be very supportive for any NDE research and application.

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