

INSTRUMENTATION AND MONITORING OF CONCRETE STRUCTURES IN NUCLEAR POWER PLANTS

REPORT 2016:306



CONCRETE RESEARCH PROGRAM
NUCLEAR



Instrumentation and Monitoring of Concrete Structures in nuclear Power Plants

Summary of seminar

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ISBN 978-91-7673-306-6 | © 2016 ENERGIFORSK

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Preface

The Energiforsk Concrete Research Program Nuclear arranged a seminar on Instrumentation and Monitoring of Concrete Structures in Nuclear Power Plants in Stockholm on March 15, 2016. The seminar was held as a first step in a process to develop new research activities within this area.

Documentation from the seminar is found on www.energiforsk.se. PhD Peter Lundqvist at Vattenfall is the technical expert of the Energiforsk Nuclear Concrete research program, and has summarized the findings of the seminar in this report.

The aim of the Energiforsk Nuclear Concrete research program is to conduct research and development that will contribute to a safe and cost effective long term operation of Swedish and Finnish nuclear power. The program is financed by Vattenfall, Uniper, Fortum, Skellefteå Kraft, Karlstads Energi, Strålsäkerhetsmyndigheten (SSM) and Teollisuuden Voima Oy (TVO).

Sammanfattning

Föreliggande rapport är en sammanfattning av seminariet "Instrumentation and Monitoring of Concrete Structures in Nuclear Power Plants" vilket anordnades av Energiforsks betongtekniska program inom kärnkraft den 15/3 2016.

Syftet med seminariet var att öka kunskapen inom området övervakning av främst kärntekniska betongkonstruktioner samt att utgöra en grund för diskussioner om framtida forsknings- och utvecklingsbehov inom området. Under seminariet hölls ett flertal presentationer inom följande tre kategorier:

- Reaktorinneslutningar med cementinjekterade spännkablar
- Reaktorinneslutningar med icke-injekterade spännkablar
- Mätning och övervakning av betongens fysikaliska egenskaper

Summary

This report is a summary of the seminar "Instrumentation and Monitoring of Concrete Structures in Nuclear Power Plants" which was organized by the Energiforsk concrete research program nuclear on the 15th of March 2016. The purpose of the seminar was to widen the knowledge within the nuclear industry regarding instrumentation and monitoring of nuclear concrete structures and also to provide a basis for discussion of further research within this field. Presentations covering several topics within monitoring and instrumentation of concrete structures were given divided into three categories:

- Reactor containments with bonded tendons
- Reactor containments with unbonded tendons
- Monitoring of physical properties in concrete structures

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1 Introduction

1.1 BACKGROUND

This report is a summary of the seminar "Instrumentation and Monitoring of Concrete Structures in nuclear Power Plants" which was organized by the Energiforsk concrete research program nuclear on the 15th of March 2016. The purpose of the seminar was to widen the knowledge within the industry regarding instrumentation and monitoring of nuclear concrete structures and also to provide a basis for discussion of further research within this field. The full documentation including all presentations are available at the Energiforsk webpage: <http://www.energiforsk.se/program/betongtekniskt-program-karnkraft/seminarier/instrumentation-and-monitoring-of-concrete-containments/>

1.2 PROGRAM

Below is the program for the seminar given.

12:00 Registration

Introduction

12:30 Introduction, Monika Adsten, Energiforsk

12:35 Monitoring and instrumentation of concrete structures, Christian Bernstone, Vattenfall

Reactor containments with bonded tendons

12:55 Measurements during initial pressure test of the reactor containment at Ringhals unit 1, Johan Klasson, Ringhals/Vattenfall

13:10 Instrumentation of the containment at Oskarshamn unit 1, Ulrik Brandin, OKG

13:25 Surveillance systems in Olkiluoto NPP, Olli Tiirola, TVO

13:45 Modelling of long-term effects in reactor containments, Manouchehr Hassanzadeh, Sweco

14:10 Coffee

Reactor containments with unbonded tendons

14:40 Monitoring strategies of containments in the U.S., Abdul H. Sheikh

15:05 Monitoring of tendon forces in Swedish containments, Peter Lundqvist, Vattenfall/Energiforsk

Monitoring of physical properties in concrete structures

15:25 Electrochemical corrosion measurements in concrete structures, Bror Sederholm/Johan Ahlström, Swerea Kimab

15:45 Surveillance of concrete structures in cooling water ways, Peter Ulriksen, Engineering geology, Lund University

16:05 Structural health monitoring of large concrete structures, Patrik Fröjd,
Engineering geology, Lund University

16.25 Concluding remarks, Christian Bernstone, Vattenfall

16:30 End of seminar

2 Introductory session

2.1 INTRODUCTION

Energiforsk, the Swedish energy research center, is a company facilitating research within electricity, heat and gas. Six research programs are being conducted within the nuclear area, one of these is the concrete research program nuclear. It is jointly financed by Vattenfall, Uniper (formerly known as E.ON), Fortum, Skellefteå Kraft, Karlstads Energi, Swedish Radiation Safety Authority and Teollisuuden Voima Oy (TVO) in Finland. The vision of the nuclear concrete research program is to ensure having civil works that support safe operation of nuclear power plants throughout the life-length of the power plants, and to ensure that the license holders and the regulator stay well informed on civil works aspects of permits and long-term operation. Over the next program period 2016-2018 the research within the program will focus on three areas:

- Investigation of local environments of the reactor containment that could cause degradation affecting its leak-tightness,
- Develop tools for the assessment of the reactor containment pre-stressed tendons and liners,
- Validity of advanced calculation tools applied to the reactor containment.

2.2 MONITORING AND INSTRUMENTATION OF CONCRETE STRUCTURES

All of the Swedish nuclear power plants have reached their designed service life of 30 years and several have also reached the age of 40 years. A number of the reactors are currently being planned for long-term operation (LTO) potentially up to 60 years. LTO is defined by IAEA as: operation beyond an established time frame set forth by, for example, license terms, design, standards license and/or regulations, which has been justified by safety assessment, with consideration given to life limiting processes and features of systems, structures and components. Regarding the LTO conditions in Sweden it must be shown, according to the Swedish radiation safety authority, SSM, that the plant with its different structures, systems, and components can be used / operated beyond the time and with the assumptions which were made during design or make the necessary replacements. Further, prior to and during long-term operation special attention needs to be given to e.g.:

- The condition of tendons and steel liners in reactor containments,
- Degradation mechanisms that can influence reactor containments concrete and metal parts,
- Possibilities for reliable inspections and testing of reactor containments.

In addition to these requirements from the authorities the power plants have demands on high availability of energy production which means that non-planned stops of the turbines must be avoided and planned stops for maintenance work must be few and have short durations. There is also a huge flow of information within nuclear power plants either linked directly to the operation for the reactor or related to maintenance, e.g. for assessing the status of machinery, equipment or structures. All this combined is a challenge for the maintenance organization and to facilitate the maintenance longer premonition times on potential problems must be obtained. Through monitoring of a structure against a baseline condition the premonition time for degradations of the structure may be prolonged compared to objective or subjective condition assessments

since small changes in the structures condition may be detected early, see Figure 1. However, for effective baseline monitoring the conditions after the completion of the structure must be known, i.e. the baseline. This is usually not known for the concrete structures in nuclear power plants, however, the design basis is known. Results from the monitoring of the structures should thus be evaluated against the design basis. Within dam safety this is e.g. performed using control charts where the condition of the structure is evaluated against the expected condition from the design. In case of deviations from the design basis different actions are required based on the severity of the deviation.

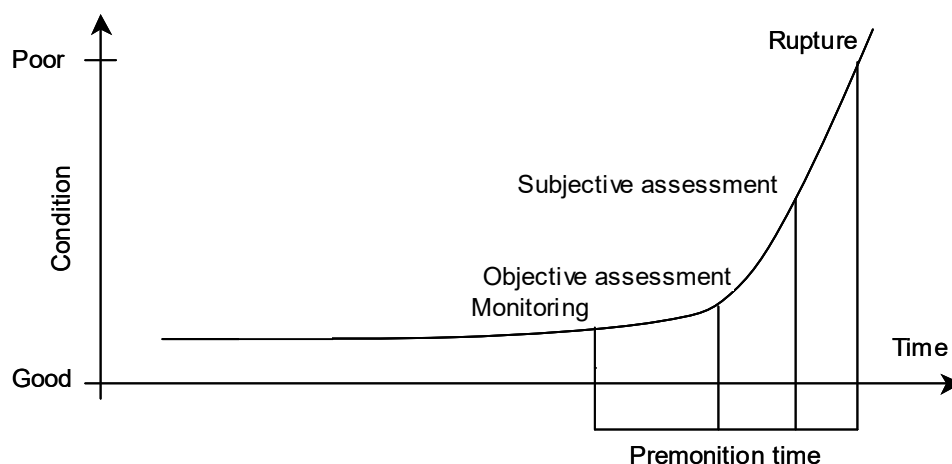


Figure 1. Difference in premonition time between monitoring and condition assessment.

3 Containments with bonded tendons

3.1 MEASUREMENTS DURING INITIAL PRESSURE TEST OF THE REACTOR CONTAINMENT AT RINGHALS UNIT 1

During the initial structural integrity test (ISIT) of the reactor containment of Ringhals unit 1 (R1) in the summer of 1972 measurements of the structures mechanical behavior were performed. The duration of the ISIT was fifteen days during which the internal pressure was increased to a maximum value of 4.2 bar excessive (e), which was maintained for a period 1.5 days. The purpose of the measurements was to verify that the containments behavior when subjected to the design pressure was in agreement with the results from the design calculations. The measurements which were conducted are:

1. Deformation measurements between different structural parts, e.g. movements of the cylinder wall in relation to the bottom slab,
2. Strain measurements in both horizontal and vertical direction on the cylinder wall,
3. Strain measurements at the top of the cylinder wall, 100 mm below the connection to the top slab,
4. Strain measurements in the steel liner at the toroid,
5. Crack indicators were cast in the concrete of the bottom slab, which would indicate if cracks exceeding 0.2 mm would develop in the concrete,
6. Temperature and moisture measurements.

Measurements in 1 and 2 above was conducted through the application of specially designed deformation gauges which measured the deformation along a length of 5000 mm. The measurements in 3 and 4 above was conducted by applying strain gauges directly to the concrete surface of the cylinder wall and steel liner, respectively. In Figure 2 the positions of all the gauges are presented. Generally, the results from the measurements during the ISIT showed that the design calculations overestimated the containments behavior during over pressurization. None of the crack indicators were triggered, which means that no crack exceeding 0.2 mm occurred during the ISIT. All instrumentation was dismantled after the ISIT and no measurements have been conducted since.

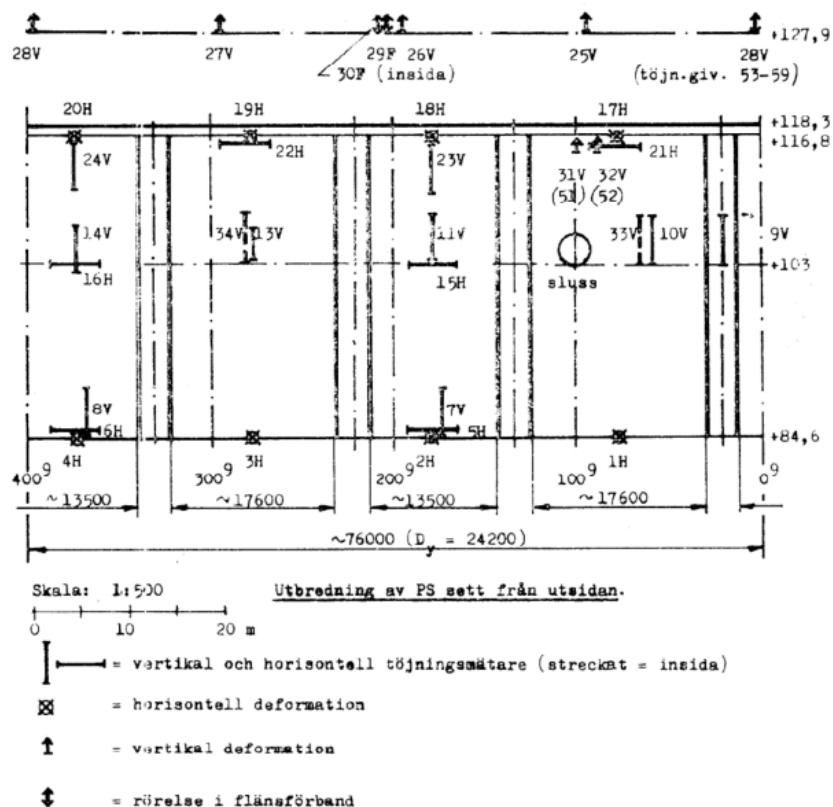


Figure 2. Positions of the strain gauges during the ISIT of R1.

3.2 INSTRUMENTATION OF THE CONTAINMENT AT OSKARSHAMN UNIT 1

Similarly as for the containment of R1, measurements were performed during the ISIT of Oskarshamn unit 1 (O1) in 1968. During the ISIT the inner pressure in the containment was increased in increments of 0.5 bar up to a maximum pressure of 4.5 bar(e). At each step measurements of the containments mechanical behavior were conducted. In total 44 strain gauges were installed at various positions on the containment. Unfortunately, no detailed information is currently available from the performed test except that the measured behavior was in good agreement with the design calculations.

Similar measurements were performed during a periodical structural integrity test (SIT) in 1995. 11 strain gauges were installed on the containment, 8 of these measured strains in the tangential direction and 3 gauges measured strains in the vertical direction, the positions of the strain gauges are shown in Figure 3. The pressure was increased to 3.25 bar absolute (a). In order to estimate the tendon forces the modulus of elasticity of the structure was determined from the results of the measurements, i.e. the relation between pressure and strain. The results showed that the calculations of the containments behavior overestimated the containments behavior, i.e. the measured deformations were smaller than the calculated strains. This indicates that the development of the prestress losses has been slower than what was assumed during the design phase.

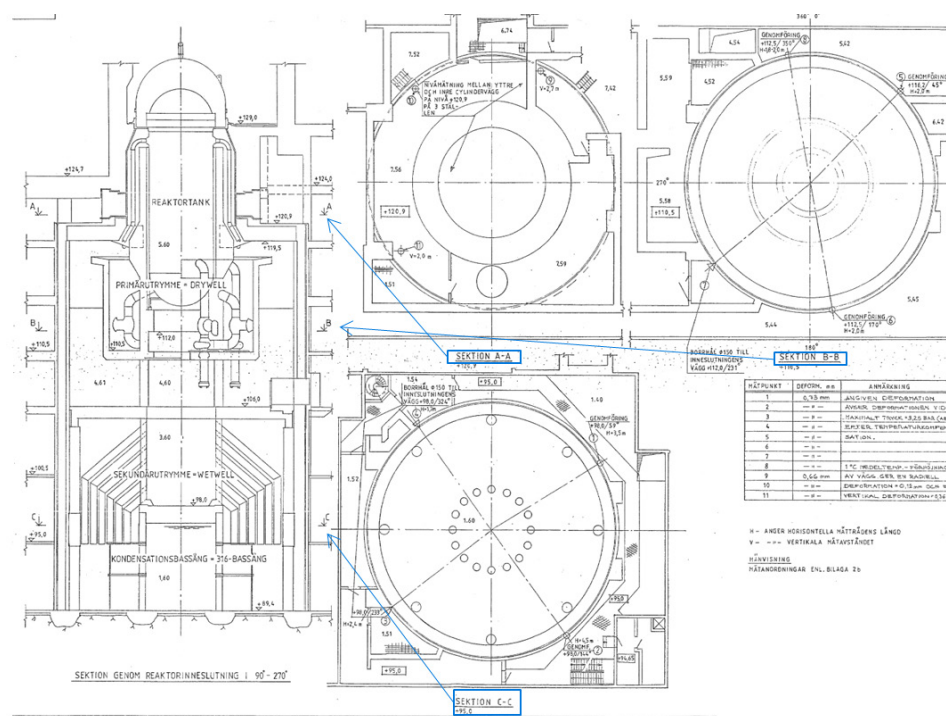


Figure 3. Positions of the strain gauges during the SIT in 1995 at O1.

3.3 SURVEILLANCE SYSTEMS IN OLKILUOTO NPP

The new reactor, unit 3 (OL3), currently under construction in Olkiluoto in Finland has been instrumented with a vast number of sensors. General outline of the containment is shown in Figure 4, the height of the containment is approximately 70 m with an inner diameter of 47 m. As can be seen, the design is a double-walled containment where the inner cylinder is prestressed and supplied with an internal steel liner. All tendons except for four vertical reference tendons are cement grouted. The outer cylinder is around 2 m thick and heavily reinforced but not prestressed.

In total 350 strain gauges have been embedded in the concrete at various positions in the containment. Three strain gauges measuring strains in radial, tangential and vertical directions are installed in each position. In addition, temperature probes have been installed at each position in order to estimate the influence of temperature on the strain gauges. A number of direct pendulums are used for the measurements of the global displacements of the containment. The pendulums consists of a wire suspended along the height of the containment, a reading station is placed at the bottom of the wire measuring displacement of the containment in three directions relative to the stretched wire. In order to monitor the tendon forces the four non-grouted reference tendons are instrumented with load cells at the upper anchorages continuously measuring the tendon forces. 10 fiber optical sensors, 7 in the horizontal direction covering the entire circumference of the containment and 3 vertical sensors covering both cylinder wall and dome, are installed and measuring strains in the steel liner. Examples of other types of sensors which have been installed are humidity sensors embedded in the concrete, monitoring of existing cracks with strain gauges and strain gauges on the steel liner measuring local strains. Furthermore, during pressure tests displacements in the dome and local deformations in the steel liner are measured using laser scanning.

Measurements have been performed since early in the construction phase and are planned to be performed continuously during the entire service life of the reactor. The prestressing of the tendons was completed in late 2010 and the measurements performed directly after this was used as the reference level against which all subsequent measurements are evaluated. During the ISIT of the containment the internal pressure was increased in steps of 1 bar up to a maximum pressure of 4.9 bars(a) and subsequently decreased in similar steps. At each step measurements were performed. The behavior of the containment was in good agreement with the numerically estimated behavior. Subsequent measurements performed continuously since the ISIT have generally been in good agreement with the estimated behavior.

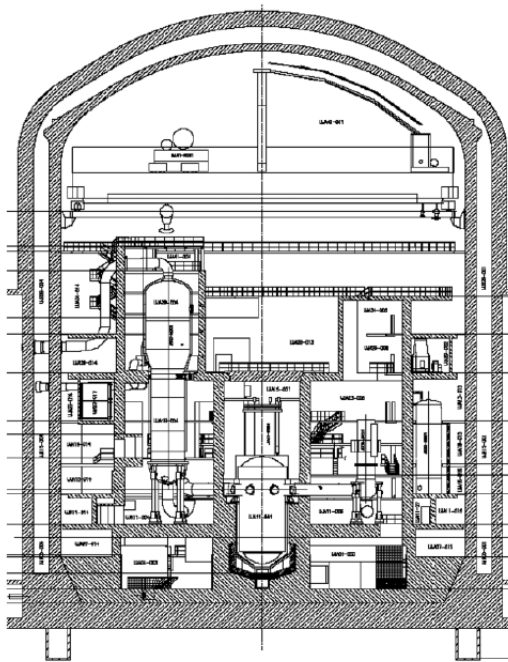


Figure 4. General outline of the containment of OL3.

3.4 MODELLING OF LONG-TERM EFFECTS IN REACTOR CONTAINMENTS

In an European research project regarding ageing of prestressed nuclear reactor containments the long-term behavior of a pressurized water reactor (PWR) was modelled using both analytical and numerical methods. As a first step in the project analytical calculations of the containments behavior was conducted which later were used as basis for an axisymmetric finite element (FE) analysis. In order to estimate the long-term effects in the structure, models for predicting creep and shrinkage of concrete and relaxation of the prestressing steel were applied. The second step in the analysis was a detailed 3D FE-analysis of the containments behavior during the entire service life. This included long-term effects and also investigations of the risk for cracking in the concrete. In addition, in the 3D-model the moisture and temperature conditions in the containment were modelled and included in the analysis in order to improve the accuracy of the prediction model for shrinkage of concrete. The results from the modelling were verified against performed strain and deformation measurements. From the results it could be concluded that both axisymmetric and 3D non-linear analyses are applicable for determining overall stresses, strains and displacements due to relaxation of tendons, creep and shrinkage of the drying concrete

and temperature variations. In addition, all condition assessments and analysis of long-term behavior regarding stress and strain conditions of reactor containments must include analysis of the moisture and temperature distributions. It is also crucial to have the possibility to calibrate and verify both the models and input data in order to make reliable predictions of the structural behavior of reactor containments. Thus it must be possible to perform measurements on the studied structure but also to take samples from the structure and monitor different physical and mechanical properties of the materials on site. A short summary of this project is provided in [1].

4 Reactor containments with unbonded tendons

4.1 CONTAINMENT MONITORING STRATEGIES IN THE USA

In the USA a total of 99 nuclear power plants are currently in operation, the majority of the containments are prestressed using unbonded tendons. The monitoring of tendon forces in the containments is regulated by the US Nuclear regulatory commission (USNRC). In their regulatory guide 1.35 the basic inspection requirements for nuclear reactor containments are given. For containments with unbonded tendons the remaining tendon forces shall be measured in 4 % of the tendons within each tendon group, e.g. vertical and horizontal tendons in the cylinder wall, every 5th year. One tendon in each tendon group should be detensioned and inspected for corrosion and damages. In addition, the entire containment should be visually inspected, which includes all concrete parts, steel liner and other steel parts. For containments with grouted tendons the monitoring could be performed in two different ways; either using instrumentation during pressure test in order to estimate the response of the structure, in this case the pressure tests should be performed every 10th year. In the other option only pressure tests are required, however, in this case the pressure tests should be performed more frequently, every 5th year. The procedure for calculating prestress losses for containments in the USA is also provided in the regulatory guide along with instructions for trending analysis of the prestress losses, which is required when evaluating results from consecutive tendon force measurements.

In the regulation the procedure for testing of the leak tightness of containments in the USA is also provided. Two different options for the testing with different testing frequency are given. Both options include testing of the leak tightness of the containment, penetrations and isolation valves. The option with lower testing frequency requires testing at higher internal pressures.

Some examples of observed degradations are anchor head corrosion, high relaxation of wires and leakage of corrosion protection grease. For the concrete part of the containments damages due to alkali silica reactions and delaminations of large concrete surfaces have been reported. For the steel liner different cases of corrosion damages have been observed. For more information regarding containments in the USA see [2].

4.2 MONITORING OF TENDON FORCES IN SWEDISH CONTAINMENTS

Monitoring of the remaining tendon forces in the Swedish containments with unbonded tendons, i.e. Forsmark unit 1-3 and Ringhals unit 2-4, is performed with measurements with hydraulic jacks during certain periodical in-service inspections (ISI). For the units at Ringhals the testing is performed in accordance with the USNRC described in section 4.1. The monitoring of tendon forces in Forsmark is performed according to a modified version of the USNRC where e.g. the number of tested tendons are based on statistical evaluation from earlier performed measurements. A number of horizontal and vertical tendons in the cylinder wall of Forsmark 1 were instrumented with load cells during the original tensioning of the tendons. The experience of these load cells is good and the results are in good agreement with the results from measurements with hydraulic jacks.

In an Energiforsk project [3], three tendons were instrumented in Forsmark 2. During the ISI in 2014 three old tendons were de-tensioned and replaced with new ones; one vertical and one horizontal tendon in the cylinder wall and one horizontal tendon in the wall of the spent fuel pool. The new tendons were instrumented with load cells in the active ends and 5 strands in each tendon were instrumented with strain gauges. Measurements were performed during the entire post-tensioning process. Long-term measurements are being performed continuously. From the conducted measurements the following results were obtained:

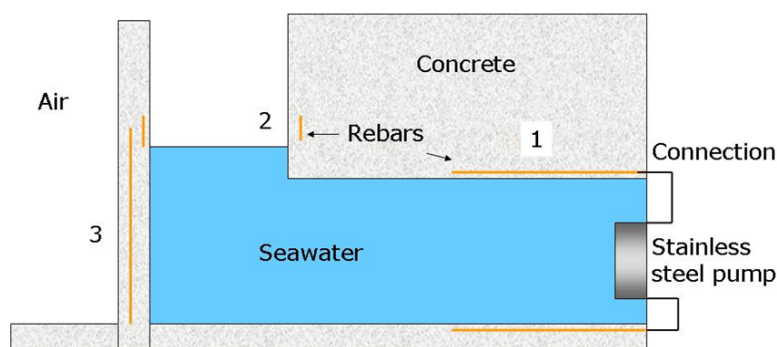
- The anchor set losses and the subsequent tensioning in order to compensate for the anchor set losses were measured and quantified.
- In order to estimate the friction properties of the ducts for the horizontal tendons the post-tensioning of these tendons were initially only performed from one of the anchorages while measurements were conducted at both ends. From these measurements the friction coefficients could be calculated.
- The measurements with the load cells during the post-tensioning indicated that the tendon force measurements with hydraulic jacks tend to overestimate the tendon forces in the horizontal tendons by approximately 5 %. For the vertical tendon the measurement with the hydraulic jack was in relatively good agreement with the results from the load cells.
- Long-term measurements of the prestress losses during the first year after the tensioning of the tendons showed that the prestress losses were somewhat higher than those estimated theoretically. More than 85 % of the losses developed during the first 20 to 30 days after tensioning.
- The ambient temperature affects the load cells during long-term measurements and is thus an important parameter to measure along with the tendon forces.

The results from the short-term measurements of the anchor set losses, the compensation for these losses and the frictional properties of the ducts, provide valuable information for the tensioning of new tendons.

5 Monitoring of physical properties in concrete structures

5.1 ELECTROCHEMICAL CORROSION MEASUREMENTS IN CONCRETE STRUCTURES

In nuclear power plants the main problem with corrosion is damages on the reinforcement in the cooling water ways. Different causes for corrosion of steel in concrete structures, in this case reinforcement in the cooling water ways, are shown in Figure 5. The corrosion process may be initiated by galvanic corrosion, high chloride levels in the concrete and through the influence of stray currents.



- 1: Rebar connected with a more noble material
→ Galvanic corrosion
- 2-3: Optimum moisture condition for corrosion
- 4: Stray current corrosion

Figure 5. Different causes for corrosion of reinforcement in cooling water ways.

Galvanic corrosion occurs when two metals with differences in corrosion potential are connected electrically. The risk for galvanic corrosion increases with the difference in potentials of the materials. Other factors which are decisive for the initiation of corrosion are the oxygen concentration and the electric conductivity of the electrolyte, in this case sea water. In positions 2 and 3 in Figure 5 the corrosion process will be initiated by the high chloride content in the concrete due to the use of sea water in the cooling water ways. In these two positions the conditions for propagating corrosion are optimal due to favorable moisture conditions, i.e. relative humidity in the concrete of around 95 %.

Stray current corrosion is caused by “leakage” of current from a direct current source. This leakage can be caused by some unbalance in the electric circuit which means that some of the current returns to the power source through a nearby structure instead of through the components of the circuit. The point where the current leaves the structure will act as anode and thus corrode. In order to produce a large enough difference in potential to initiate corrosion the affected structure needs to be of sufficient length. One hypothesis is that the cooling water ways may be affected by stray currents from nearby high voltage direct current (HVDC) transfer. Measurements of stray currents conducted around Forsmark showed a difference of approximately 0.4 volts per

kilometer along the distance from a HVDC transfer [4]. However, no corrosion damages due to stray currents have yet been identified.

Two different methods are available for monitoring or measuring corrosion or to estimate the risk of corrosion, i.e. measure the corrosion potential or measure the corrosion current. Measurements of the corrosion potential are performed using reference electrodes which measure the corrosion potential in relation to a specific reference material, e.g. zinc. This method is also the one that has been used for the concrete structures in the cooling water ways. Corrosion currents can be measured using two different methods, the linear polarization resistance method (LPR) and using a zero resistance ampere meter (ZRA). The LPR method is based on a polarized material which is polarized in relation to a certain reference level where no current is flowing in the material. During measurements the potential of the material will change due to a current flow initiated by the corrosion process. By measuring the potential and current the materials resistance to polarization can be estimated and from this information the corrosion rate can be calculated. In ZRA measurements the measuring device produces an output of the voltage which is proportional to the produced current flowing in the internal circuit. The ZRA device is connected to a structure and imposes no drop in voltage on the external circuit. ZRA are mostly used for measuring the galvanic coupling current between two electrically connected materials.

In a previous project [5] within the Energiforsk concrete program corrosion potentials were measured in the cooling water ways of Ringhals in order to investigate the reason for the high consumption rate of sacrificial anodes. The results from the measurements showed that the high consumption was due to large potential differences between the sacrificial anodes and the reinforcement and stainless steel pumps. The measurements did not indicate galvanic corrosion. A new project is currently being performed where corrosion potential loggers are planned to be installed in the cooling water ways of all the Swedish reactors. The purpose of the project is to determine the risk for galvanic and stray current corrosion.

5.2 SURVEILLANCE OF CONCRETE STRUCTURES IN COOLING WATER WAYS

Several studies regarding non-destructive testing (NDT) methods for application to nuclear concrete structures have been conducted within the Energiforsk concrete program in nuclear, [6] - [10]. A literature review [6] of possible NDT methods suitable for application in concrete structures showed that the methods based on propagation of mechanical waves are most suitable and should be developed further. The reason is that several of mechanical properties of concrete are related to the propagational properties of mechanical waves, e.g. strength and modulus of elasticity. For application in the cooling water ways a number of methods were further investigated in [7]. This included a close study of a Russian built ultrasonic instrument (ACSYS A1220), investigating profiling with parametric sonar in water, vibration measurements with water jet and impedance measurements. Of these methods only the parametric sonar can be used in water filled water ways, i.e. during operation of the reactor. In laboratory studies the Russian ultrasonic instrument was able to detect manufactured delaminations and other simulated degradations in a concrete slab. Parametric sonar devices are commercially available and may be suitable for detecting delaminations in the concrete in water filled cooling water ways. In this case the sonar must be mounted on some type of underwater vehicle. Laboratory tests of a water jet showed that it was possible to excite the concrete surface and record its response through measurements in the water jet.

The impulse response method was further investigated in [8] and was considered to be of particular interest since it resembles the simple and well established investigation method bowing. Three different setups of different exciting and recording sensors were tested: a vibrator with a hand held impedance head, an instrumented hammer and hand held impedance head and hammer with hand held impedance head. The results from the tests showed that all three setups were suitable for detecting delaminations in concrete and that delaminations could be detected down to a depth of 180 mm from the concrete surface, this was also the maximum depth that was investigated. Further, the results showed that the simplest parameter to measure for detecting delamination is the impedance, i.e. the force of the impact divided by the recorded velocity of the mechanical waves in the material. As a continuation of this investigation the tested methods were applied to the concrete structures in the cooling water ways at Ringhals [9]. Four different setups were tested: the earlier used impedance head combined with a dead blow hammer, same as previous method with the addition of a microphone, a modally tuned hammer with microphone and a carpenter hammer with a microphone. The results showed that the modally tuned hammer in combination with a microphone was the most suitable for detecting delaminations in real concrete structures. The method with impedance head and dead blow hammer also gave reliable results.

In [10] a system for detecting, quantifying and documenting delamination in concrete structures was developed. It consists of a video projector, laptop computer, digital camera and for the measurements either an impedance head or an instrumented hammer and a geophone. The system projects a measuring grid on the concrete surface that will be investigated and also provides the impact points for the hand held sensors. Except for quantification of the delamination the results from the measurements can thus be documented and the position of the delaminations registered.

5.3 STRUCTURAL HEALTH MONITORING OF LARGE CONCRETE STRUCTURES

In structural health monitoring (SHM) different NDT methods are used for continuously monitoring the status of structures with the aim of detecting damages and defects. In the PhD-project "Structural health monitoring of large concrete structures" [11] the aim is to implement and investigate different methods for SHM, with focus on application for large concrete structures. In a laboratory study measurements were performed on a concrete specimen subjected to cyclically increased load using two different methods for detecting the imposed damage of the concrete. In concrete structures signals are attenuated relatively quickly and after having travelled a certain distance be obscured by the noise in the signal. This means that a relatively dense network of transducers may be needed to be able to accurately measure the signals. A lock-in amplifier which measures a signal with a certain frequency with high accuracy even if the signal is below the signal to noise ratio was used in order to increase the sensitivity of the measurements. It was thus possible to increase the transmission of mechanical waves in concrete structures, which means that the distance between transducers can be kept relatively large. The results from this study showed that it was possible to transmit a continuous wave in a concrete structure over relatively large distances and that the resulting continuous wave field showed a high sensitivity to damages. This method is thus suitable for SHM.

In the following study the measurement method from the earlier study was applied on a concrete slab in order to investigate if damages could be detected using a network of transducers and whether the relatively large transmission length from the earlier study

could be used on larger structures. A network of 30 transducers was mounted on an 8 x 2 m concrete slab, see Figure 6. Measurements were performed on the undamaged slab in order to obtain a baseline level. Progressive local damage was induced in the concrete using impact hits. Measurements were performed during the entire procedure. The results showed that the imposed damages could be detected by comparing the obtained signal with the earlier obtained baseline measurements. The deviation from the baseline was measured in number of standard deviations. In addition, the location of the induced damage could be identified within less than 1 m². In Figure 6 the results from the measurements are shown and as can be seen the damaged area could be identified since it displayed the biggest deviation from the baseline.

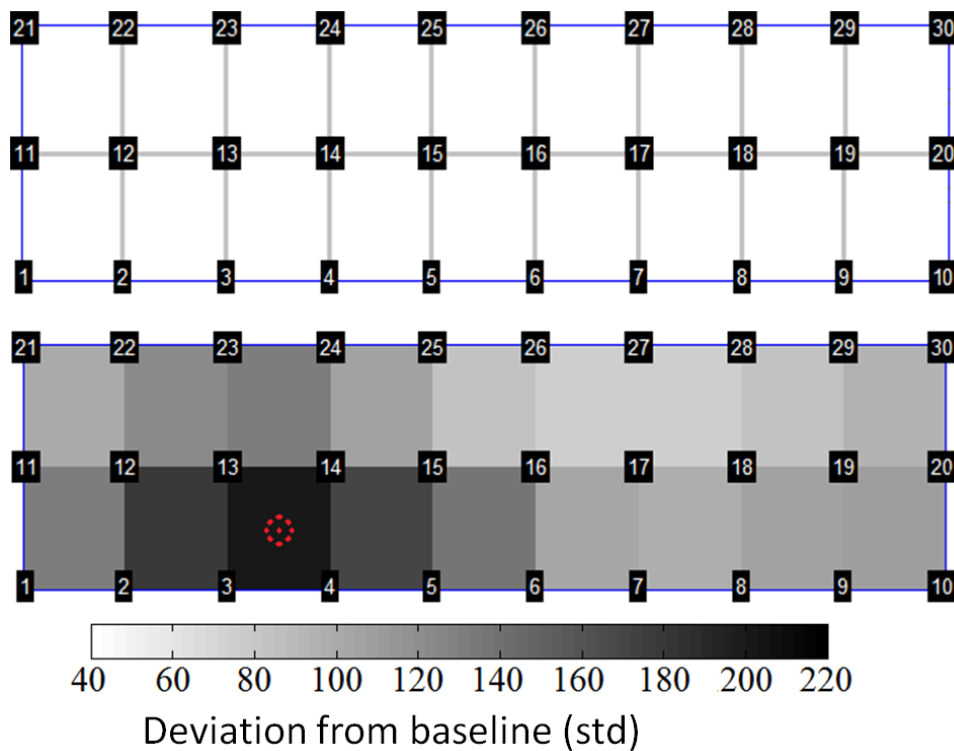


Figure 6. Upper figure shows the network of transducers on the concrete slab. Lower figure shows the results from the measurements after induced damages (red circle).

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INSTRUMENTATION AND MONITORING OF CONCRETE STRUCTURES IN NUCLEAR POWER PLANTS

This report is a summary of the seminar "Instrumentation and Monitoring of Concrete Structures in Nuclear Power Plants" organized by the Energiforsk concrete research program nuclear in March 2016.

The purpose of the seminar was to widen the knowledge within the nuclear industry regarding instrumentation and monitoring of nuclear concrete structures and also to provide a basis for discussion of further research within this field.

Presentations covering several topics within monitoring and instrumentation of concrete structures were given divided into three categories:

- Reactor containments with bonded tendons
- Reactor containments with unbonded tendons
- Monitoring of physical properties in concrete structures

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