NONDESTRUCTIVE EVALUATION AND STRUCTURAL HEALTH MONITORING

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ABSTRACT: The European project *Smart Management of the Sustainable Human Environment* (SmartEN) aims at developing and planning of early proactive measures to reduce the environmental impact of human actions, the influence of climate changes and to protect infrastructure as well as the environment. The work of SmartEN is organised in an initial training network (ITN) of early stage researchers (ESRs) in European universities, research institutes and in industry. The participation of specialists from different disciplines as structural engineering, structural health monitoring, non-destructive testing, computational techniques and telecommunication allows a cross-themes cooperation. The cooperation between young engineers and scientists from different disciplines aims at improving the career perspectives of early stage researchers in both public and private sectors and enables them to create multidisciplinary networks in the field of structural monitoring. The project is structured into four thematic work programmes: Wireless sensor networks, sensor signal processing, non-destructive evaluation and smart proactive management. Besides an in-depth theme about corrosion mapping with ground penetration radar (GPR) in work programme 3, BAM is involved in specifying the links between NDE, inspection and SHM in structural engineering, including small and medium span bridges. The Work programmes considers multidisciplinary tasks besides the PhDs that solve a specific open task in the defects detection. Multidisciplinary tasks to be considered in the field of NDE are the limitation and applicability of methods for the intended use for detection of the most critical parameter considering (1) Implementation of NDE in structural health monitoring, (2) Requirements on non-destructive evaluation, (3) Optimum sensor placement in infrastructure with special focus on small and medium span bridges and (4) Combined monitoring and inspection systems. In Smarten Work programme 3, we studied the contribution of NDE to monitoring from a civil engineering point of view. An example presents NDE requirements from laboratory tests on demonstration specimens for ground penetration radar.

KEYWORDS: Non-destructive testing, requirements for NDE, reinforced concrete bridges, corrosion detection, ground penetrating radar, chloride contamination

1. INTRODUCTION

The objective of the European project Smart Management of the Human Environment (SmartEN), funded in the 7th framework programme, People action, is to develop and to plan proactive measures to reduce the environmental impact of human actions, environmental impact and to protect both, the human infrastructure and the environment.

The work of SmartEN is organized as an Initial Training Network in the Marie Curie programme [1]. Early stage researchers (PhD-students) and experienced researchers (postdoc) form the backbone of the projects. The PhD-students and experienced young researchers from all over the world originate from different related fields of science. They are employed in seven European academic research institutes, two governmental research and testing centres and six industrial enterprises. The project aims on creating a multidisciplinary research training network. Specialists from civil engineering and electro- technical disciplines provide training and organise transnational networking n.

The project is structured into four thematic work programmes: (1) Wireless sensor networks, (2) sensor signal processing, (3) non-destructive evaluation and (4) smart proactive management [2]. The topics of the PhD-thesis provide contributions to four work programmes. The participation of specialists from different disciplines as structural engineering, structural health monitoring, non-

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destructive testing, computational techniques and telecommunication allows a cross-themes cooperation.

Besides an in depth theme about corrosion mapping with ground penetration radar (GPR) in work programme 3, BAM is involved in discussing the possible links between NDE, inspection and SHM with special attention to bridge infrastructure, e.g. applicable to small and medium span bridges.

For the prediction of the future performance of the deteriorating concrete bridges, updated knowledge about the condition of the bridge is required to update the input and reduce uncertainties of models for the prediction of the remaining service life. Uncertainties in the input of deterioration models have a significant influence on predicted remaining service life. In-situ measured corrosion can proof the actual level of corrosion and reduces the uncertainties of the results from deterioration calculation and helps decision makers as infrastructure owners or authorities to upgrade their maintenance plans. None the less, non-destructive testing methods for corrosion detection do not have the level for a quantitative estimate of e.g. cross section reduction. Current tasks are focussing on mapping of corrosion before the corrosion induced cracks reach the concrete surface. Unfortunately, the signals of many methods are influenced by the presence of chlorides and humidity in the specimens or in the field. The signals of the non-destructive test methods, as mentioned in the withdrawn ASTM-standard for half-cell potential measurements, show the response to all influencing parameters, chlorides, humidity and corrosion. In the project Smarten, a PhD we investigate the possibility to separate the influence of corrosion and humidity from influences such as free chloride ions and humidity.

Parallel horizontal topics aim to link the work in several work programmes. The Work programme has claimed the following special multidisciplinary tasks in the field of NDE:

- Requirements on non-destructive evaluation,
- Implementation of NDE in structural health monitoring,
- Optimum sensor placement in infrastructure with special attention to corrosion in bridges
- Combined monitoring and inspection systems.

The project SmartEN considers the influence of proactive measures on the infrastructure performance. BAM is involved in the Work programme 3 Non-destructive evaluation. The topic of the PhD thesis is the development of a methodology for GPR-based corrosion mapping by performing demonstration tests in the laboratory.

2. NON-DESTRUCTIVE EVALUATION AND STRUCTURAL HEALTH MONITORING

2.1 Implementation of NDE in SHM

Traditional Structural Health Monitoring systems are applied to continuously measure dynamic or quasi static parameters of the structure, as local strains, inclinations, differential settlement or displacement in order to measure a deviation of the structure from the basic stage. The measurement must be carried out as a minimum performed at a minimum twice, once to get information about the system as-built and the second to get information of the data of interest at the time of the second measurement. To get an early alert for changing parameters of the structure, the frequency of the measurement is increased in case of doubts that arise e.g. during regular inspection. Early signs about arising changes of the properties of a structure or a material allow taking measures in a maintenance procedure. The more frequent or even continuous data was collected the more early an initiated degradation process can be identified. Once the degradation is found, measures can be applied to stop it or to undertake measures to keep the safety level of a structure or to upgrade it. It is characteristic for SHM that the sensors for the survey of material or structural parameters are permanently attached to the surface or embedded in the structure. This allows for developing smart systems with wireless sensing and multiple-node data transfer systems.

Examples of a SHM system is the construction process monitoring of the Berlin Main station. During construction between 2001 and 2006, 128 sensors remained in place. Changes in sensible cross sections measured absolute values during all construction phases. Permanent attachment of sensors allows the monitoring at any time. A real-time transferred the absolute values into changes and visualized them in an on-line system. The on-line data were accessible for the measurement group and the infrastructure owners could read.

2.2 Requirements on NDE

Industrial non-destructive testing (NDT) is embedded in standardised requirements on non-destructive evaluation (NDE) processes. In industrial processes NDT is often addressing fatigue problems. Thus, the requirements for NDE are best formulated for the implementation of NDT for crack detection, e.g. in [3]. Aim of the NDE requirements is to guaranty a high level of reliability and safety of their aerospace flight systems by early detection of crack-like flaws during screening.

In case of fatigue, the parameter to measure as input in an assessment is the minimum detectable crack size a_0. Either a detected crack size or if not detected, an assumed crack length a_0 that may be missed during the non-destructive inspection of the most critical details is then used as input into deterioration prediction models. Such a model would be in the case of fatigue, e.g. the Paris law, to estimate a save service interval. Before a measurement in the field is performed, must be clarified, that the method is appropriate for the given task to solve. If, e.g., the choice of a surface method as colour penetration test is appropriate for a thin plate, it may not be appropriate for a thick structural element (t > 10 mm). The crack may appear on one side of the surface longer, but appear much shorter on the other side. Figure 1 shows the surfaces of a disassembled crack after full scale test of truss girders. The fatigue crack can be clearly distinguished from the brittle fracture during disassembling under liquid nitrogen. For this reason, radiography would be the better method to measure the real crack length, even if the crack is accessible from one side. The applied method must guarantee the detection of the real crack length. A NDE procedure would be necessary to show the limits of the applied methods and conditions for usage in the intended test details. For this purpose, standard test specimens with crack-like defects shall serve to test the methods for their applicability.

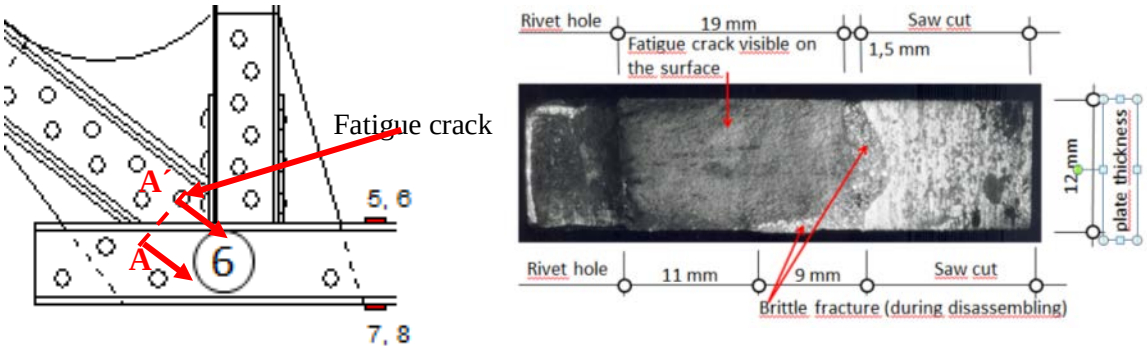


Figure 1. Fatigue crack after full scale test. Left: Location of the crack in a gusset plate, right: Crack surface after dissembling. The fatigue crack between A-A´ is 19 mm long on one surface and 11 mm on the other [5]

A measure for the quality assessment of a method is the Probability of detection (POD). The POD-curve for a given detail like proves that the chosen method is appropriate to detect a certain crack length with a probability of 95 %. For this purpose, capability demonstration specimens may be designed that have the same properties and characteristic flaws to detect as the structure as a fracture critical bridge detail or bridge slabdetail to assess in reality.

The applicability of POD to NDT-problems in concrete engineering was shown by Feistkorn in 2012 [4]. He has used GPR for the detection of reinforcing bars, located in different depth below the concrete cover and compared two different radar systems regarding their appropriateness for the intended task to test. By applying POD he was able to show, the GPR equipment with higher

frequencies are more appropriate testing equipment for reinforcing bars near the surface and lower frequencies proved to measure more exacts in deeper sections.

So far, some standard procedures for NDT-methods for concrete structures in civil engineering applications were recommended by RILEM. The TC 154, Electrochemical measurement methods [9], has issued recommendations for the half-cell potential measurement. The German society for Non-destructive testing has published a leaflet for GPR-applications to concrete structures. New applications as e.g. for corrosion detection by means of GPR are still under development and not standardised, yet. A comprehensive procedure for NDE in civil engineering is still missing. The NDE requirements must insure that an NDE method is able to detect a minimum acceptable damage when applying specific equipment and when all requirements are fulfilled.

NDE requirements must incorporate far more information than the application of a selected method and the analysis of the results. Requirements for NDE in civil engineering have to consider the following fields, e.g. for corrosion:

(1) Reference to available standards/ RILEM recommendations for the selected method
(2) Make a statement about the required level of training of NDT-specialists.
(3) Showing the appropriateness of the selected method over alternative methods on capability demonstration specimens.
(4) The capability demonstration specimens must have the same typical defects and material properties as expected in the field. Artificial defects, e.g. extend of corrosion, can be designed for this purpose. Proof that the demonstration specimens have the same parameters (same concrete, same depth and diameters of reinforcing bars, level of corrosion),
(5) Chose an appropriate NDT-method to demonstrate the precision of the artificial defects detection, e.g. by using Probability of detection (POD), as by following the procedure proposed by Feistkorn in [4]

In case of corrosion measurements in civil engineering there is no available NDE procedure so far that is fixing these requirements.

2.3 Optimum sensor placement

Sensor placement depends on individual factors on any bridge type. Both, any structural health monitoring system and any NDE examination must be planned individually. Local (and lost) sensors make sense in case of extreme changes of the loading conditions of a structure, e.g. to monitor a structure sensitive to vertical changes of their bearings, like a glass roof during the construction phase with traditional strain and displacement sensors [6], see figure 2. After the construction phases were finished, the SHM-system was not further maintained.

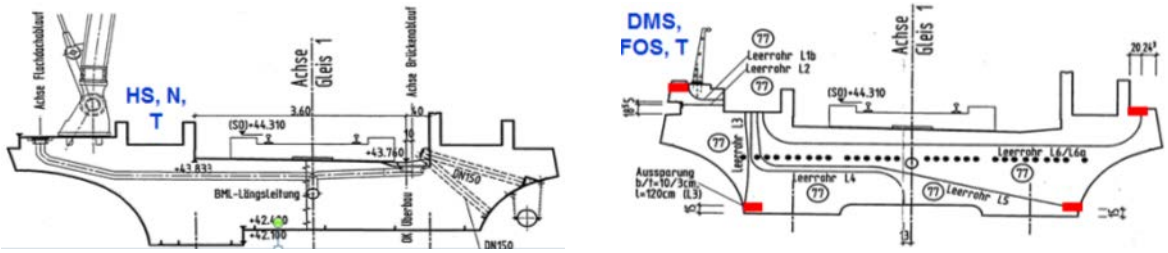


Figure 2: Sensor positions in a partially prestressed bridge carrying a glass roof along one edge (hydrostatic levelling), left, and supported by two columns (strain measurements by strain gauges (DMS) and Fibre Optical Sensors(FOS), right, at the Berlin Main station between 2001 and 2006 [6]

The decision about the sensor placement depends on the type of the structure (steel structure or concrete structure), type of task to answer (find early cracks from scour or fatigue, location detection

of reinforcing bars or corrosion detection) and on the type of deterioration process. A monitoring engineer cannot answer the individual tasks alone, thus specialists for NDT shall cooperate with him and the infrastructure owners. NDT will be not be applied for the whole structure. Indications from regular inspections lead to called-in special inspections (SI) or s.c. object-related damage analysis, as recommended by the German Highway Association (OSA). The sensor set-up and measurements in a SI or OSA is then planned by specialized and trained NDT teams with the representative of the owner or administration.

In most cases the most cost effective solution for a non-destructive monitoring of deterioration will be performed as a periodic measurement. Expensive sensors or e.g. the equipment for radar would be quite cost-intensive to keep it in place. The nature of NDT using GPR antennas is to move the antenna along a predefined grid on the surface for 3D-data acquisition Surface mapping to collect three dimensional data sets means measuring point-wise along a dense grid. . The grid size would depend on the task to solve. Automation was further developed to get a sufficient correlation between surface geometry and measured data (Figure 3).

Figure 3. Automation of NDT echo measurements (here with an ultrasonic sensor) along a defined grid in the laboratory (left) and in the field (right), using an under-bridge unit as base

The automated scanner is here attached to an area that is selected to be representative for the investigated defects. Occasionally, once the scanner is installed, the measurement with several methods can provide more information. In case of corrosion, multiple methods can visualise the location of reinforcing bars (rebars), the concrete cover depth (eddy current measurement), the existence of horizontal cracks in the level of corroded rebars (ultrasonic measurements) active corrosion (half-cell potential) and corrosion (GPR). Often, the data is post-processed to remove noise or other disturbing influences from the effect of interest. The removal of reflections from a back wall can increase the visibility of other reflectors. The measurements and the data analysis require that the campaign must carry out a specialized laboratory.

2.4 Combined Monitoring and Inspection system

Usually a doubt about the integrity of a structure arises during regular inspection. A special inspection is then called in to investigate local changes or inhomogeneities, until the cause was found. This makes sense because deterioration does not affect the whole structure regularly. Because of this reason, NDT-measurements, e.g. for corrosion detection is not appropriate to be regularly incorporated into wireless sensor networks of the civil infrastructure.

3. GPR-BASED CORROSION MONITORING

3.1 Aim of the Smarten-Work progamme 3

As an example NDT-methods, a new procedure for corrosion detection is presented. Within the SmartEN WP 3, corrosion detection is topic of two PhDs. Corrosion is a mayor cost factor in civil engineering. Corrosion is still a cost intensive damage in civil engineering to be considered in condition assessment. According to a study (2001) funded by the FHWA, the direct annual corrosion costs in the US are about $276 billion, i.e. 3.1% of the US-nation´s Gross Domestic Product. The transportation sector contributes 21.5 % or $29.7 billion [7]. The World Corrosion Organization as a NGO of the United Nations has with their white paper (2009) initiated a call for worldwide activity for corrosion knowledge dissemination to fight corrosion and to introduce preventive measures to finally reduce the corrosion costs and maximize asset life [8]. For Europe, no summarized data is accessible.

So far, methods as half-cell potential mapping, differential mapping or GalvaPulse are state of the art. The RILEM TC 154 Electrochemical Techniques for measuring metallic Corrosion has developed recommendations about the main principles and requirements [9]. These methods can document active corrosion (corrosion rate), but neither distinguish the influence on chlorides and humidity from corrosion effects nor measure inactive corrosion, e.g. after a long dry period. For this reason, basic research is carried out within SmartEN. Ring electrodes are able to monitor the chloride penetration into the concrete. They are often embedded into the structure, e.g. after the first cores were taken from existing structures to confirm half-cell potential measurements, at a later stage. Then, the ring electrodes or corrosion ladder is embedded in a different concrete or mortar compared to the original material in a different concrete.

3.2 Methodology of the GRP-based corrosion mapping

The work of Lai [10] and Hong [11], [12] contributes new findings for the application of GPR-methods for corrosion detection in reinforced concrete. The work of Shuxian Hong was one of the PhDs in the initial training Network SmartEN. Her work divides into two main investigations.

The ***mechanism study*** of corrosion effects on the electromagnetic properties of reinforced concrete specimens was found in first laboratory tests. A concrete specimen with four parallel reinforcing bars was immersed into a solution containing chlorides. Additional applied impressed direct current accelerated the corrosion process. The impressed current was connected to the lowest of four reinforcement bars. The corrosion mapping showed a change after 15 days and a significant corrosion after 30 days.

In her ***Parameter study,*** Hong [12] has separated the influence of chloride-solution from corrosion during data processing. The tests for this study were carried out with a series of six specimens with only a low percentage of chlorides. A relatively low percentage of chlorides (2 %) were added into the concrete mixture of four specimens to obtain a regular distribution of chlorides. Two of six specimens were produced from the same

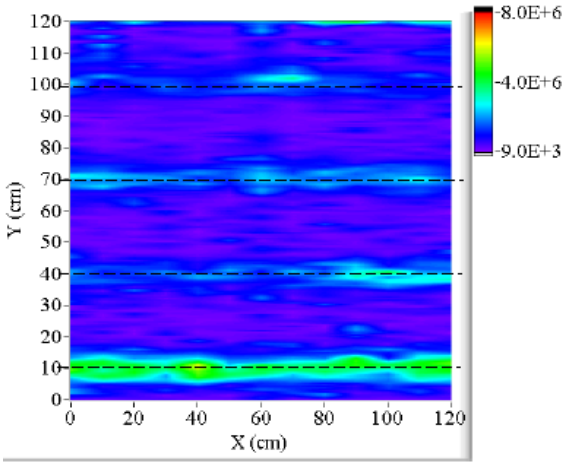
3.3 Data analysis and presentation

The corrosion intensity mapping of radar data requires extensive data processing. Hong [12] has developed a program in labview that allows both, data processing and imaging. The radar data amplitudes effects and the velocity were analysed in the time and frequency domain. The frequency shift was processed as a function of corrosion. By comparison of radar signals from accelerated corrosion in chloride contaminated concrete and concrete without any chlorides, the effect of chloride-containing solution on the concrete properties and thus the radar data was found.

Main finding of the corrosion data analysis is the post processing of data to exclude the influence of chlorides and humidity on the electromagnetic properties. Radar data are strongly influenced by changes of the concrete parameters as The content of chlorides and moisture (pore water) influences

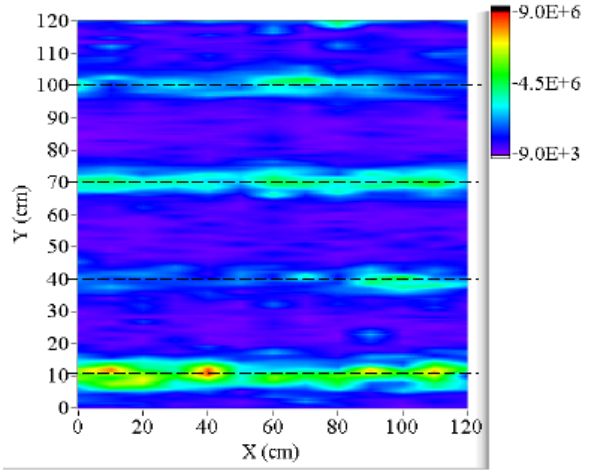
and changes the dielectric constant of the concrete. The electromagnetic properties of the concrete influence then the GPR-waves.

Figure 4 and Figure 5 show. exemplarily the result for corrosion mapping of a specimen during and after artificial corrosion acceleration using impressed current. The anode of the impressed current was the lowest rebar in the images. For further details see [12].



(b) Day 15

Figure 4. Corrosion of the lowest rebar after 15 days impressing direct current, unit of the colour coded imaging: mV^2-ns



(c) Day 30

Figure 5. Corrosion of the lowest rebar after 30 days impressing direct current, unit of the colour coded imaging: mV^2-ns

4. SUMMARY AND OUTLOOK

Deterioration processes influence the performance of infrastructure. Implementation of non-destructive evaluation into the performance prediction process helps to decrease the uncertainty of the prediction models. In the frame of the European Initial Training Network was a developed a method or early corrosion detection and mapping with the separation of the effects from chloride-containing solution fom corrosion on radar signals [10], [11]. The GPR- based method used demonstration specimens with defined chloride content and reference specimens without chloride. Aim was to separate the influence of chlorides and humidity on one side and corrosion on the other side.

The applicability of probability of detection (POD) for quality assessment of NDT procedures in concrete engineering was shown for non-corroded reinforcements [4], so far. In a next step the results from both methodologies shall be merged to create the basic procedure for requirements on NDE in civil engineering. Final goal is than to implement NDT into inspection and SHM-processes to better upgrade models for prediction of the future performance of aging and deteriorating structures. Infrastructure owners and bridge authorities will benefit from more realistic updated models in their decision making processes about maintenance planning.

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