NDE for corrosion detection in reinforced concrete structures – a benchmark approach

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Abstract

Corrosion of steel reinforcements is the main cause of damage and early failure of reinforced concrete structures in civil engineering, leading to enormous costs for inspection, maintenance, restoration and replacement of the infrastructure worldwide. Conventional methods for detecting corrosion are based on electrochemical techniques such as half-cell potential and linear polarization. These methods can be affected by a number of factors and require direct contact with the concrete. To overcome difficulties with conventional inspection techniques a benchmark project using and evaluating state-of-the-art NDE methods is set up at FHWA's Turner-Fairbank Highway Research Center. The aim is to devise a test protocol for structural health monitoring (and asset management) of concrete structures by performing periodic baseline NDE surveys. For this a typical bridge deck specimen is cast, corroded and cyclic loaded. The benchmark project incorporates the latest developments in NDE inspection methodologies. A special focus lies on the promising technique of time-resolved thermography with induction heating combined with 3-D microwave imaging—a research cosponsored by the US National Research Council NRC.

Résumé

La corrosion des armatures d'acier est la principale cause de pathologies et de défaillances prématurées des structures en béton armé en génie civil, entrainant des coûts énormes pour l'inspection, l'entretien, la restauration et le remplacement d'infrastructures dans le monde. Les méthodes conventionnelles pour la détection de la corrosion électrochimique sont basées sur des techniques telles que la demi-cellule et le potentiel de polarisation linéaire. Ces méthodes peuvent être affectées par un certain nombre de facteurs et nécessitent un contact direct avec le béton. Afin de surmonter les difficultés des techniques d'inspection conventionnelles, un projet utilisant des méthodes avancées NDE est développé au Turner-Fairbank Highway Research Center de la FHWA. L'objectif est de mettre au point un protocole d'essai pour la surveillance et l'évaluation structurelle des ouvrages en béton en effectuant des enquêtes périodiques de référence NDE. Pour cela un modèle de tablier de pont type est coulé, corrodé et chargé de manière cyclique. Le projet intègre les derniers développements dans les méthodes d'inspection NDE. Un accent est mis sur la technique prometteuse de la thermographie en temps résolu avec chauffage par induction, combinée avec la micro-imagerie 3-D. Cette recherche est parrainée par le US National Research Council NRC.

Keywords

Automation, bridge decks, data fusion, multi sensors, nde monitoring

1   Introduction

Being the main cause for inspection, maintenance and repair of infrastructures worldwide [1] a recent study commissioned by the Federal Highway Administration states that the cost of corrosion in the USA consumes about $286 billion per year (published at

www.corrosioncost.com). In this study the average costs for corrosion control methods and services alone are estimated to be \$121.41 billion per year of which only <0.1 % is spent for research and development. The human consequences of not dealing with corrosion in time is shown by the recent collapse of a concrete highway bridge in Laval, Canada due to rebar corrosion in which five lives were lost [2]. Apart from these spectacular collapses of reinforced concrete structures the main problem remains that of spalling (i.e. Broomfield reports of a man getting killed by a concrete slab [3]).

Consequently, an objective, spatially resolved, and rapid corrosion inspection method could lead to cost savings of billions of dollars worldwide by the detection of corroded reinforcement in concrete at an early stage. Damaged areas could then be targeted for strengthening or repair at the appropriate stage of the lifecycle of the investigated structure. However conventional inspection methods for detecting corrosion all have their limitations and drawbacks (compare section 3 or i.e. [3, 4]). To overcome these difficulties with conventional inspection techniques a benchmark project using and evaluating state of the art NDE methods is set up at the Turner-Fairbank Highway Research Center of FHWA. This not only makes use of the existing equipment at the FHWA NDE Center but also incorporates latest developments in NDE inspection methodologies including the novel approach of *microwave thrmoreflecometry* [5].

2   Corrosion of reinforced concrete structures
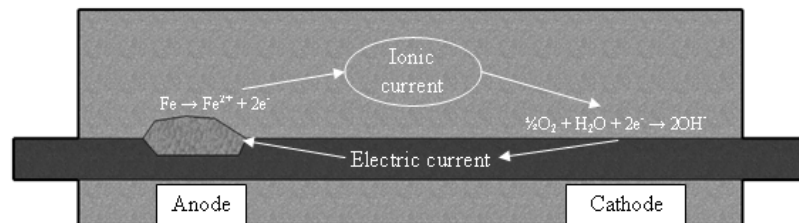
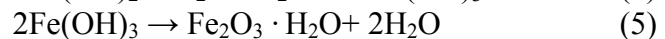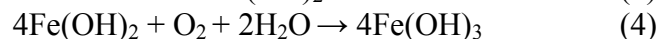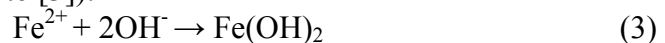### 2.1   Corrosion of steel in concrete

Reinforced concrete structures perform well as long as the alkaline environment is intact. Not until the passivating effect of the concrete with pH 10 – 12 is penetrated, corrosion of steel in concrete can occur. If oxygen (cracks) and water (pore water) are present the chemical reactions for corrosion of steel in concrete can be described on the anode as:

$$\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^- \tag{1}$$

And at the cathode as (compare also fig.1):

$$2\text{e}^- + \text{H}_2\text{O} + \tfrac{1}{2}\text{O}_2 \rightarrow 2\text{OH}^- \tag{2}$$

For the development of *hydrated ferric oxid* ($\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$) or *rust* several other steps through Fe(OH)_2 (*ferrous hydroxide*) and Fe(OH)_3 (*ferric hydroxide*) are necessary as documented in equations 3 to 5 (according to [3]):

$$\text{Fe}^{2+} + 2\text{OH}^- \rightarrow \text{Fe(OH)}_2 \tag{3}$$
$$4\text{Fe(OH)}_2 + \text{O}_2 + 2\text{H}_2\text{O} \rightarrow 4\text{Fe(OH)}_3 \tag{4}$$
$$2\text{Fe(OH)}_3 \rightarrow \text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O} + 2\text{H}_2\text{O} \tag{5}$$

Anodic and cathodic reactions of reinforcing steel in concrete [3]

The main reasons for depassivating concrete are carbonation of concrete and chloride penetration. Carbonation induced corrosion is a problem where concrete cover is small or the concrete of bad quality with well connected open pores and a low cement ratio with poor

curing. It is rarity on US highway and civil structures, chloride induced corrosion is a far greater problem [3].

2.2 Deterioration of concrete embedding corroding steel

According to focus it can be distinguished between different chloride induced corrosion phases. Taking into account the marine environment Melchers and Li [6] distinguish between 5 phases of marine corrosion; phase D1: diffusion of chloride into the concrete without corrosion; phase D2: diffusion of chloride with minor amounts of corrosion; phase C1: increasing corrosion with radial stresses, building of longitudinal cracks and finally spalling; phase C2: increasing longitudinal cracking and spalling and enhanced oxygen inflow and phase C3: anaerobic corrosion resulting in *black rust*. On the other hand according to Weyers et al. [7] there are especially 5 phases of (chloride induced) corrosion that are of interest for estimating the service life of bridges; phase1: early structural damage; phase 2: diffusion of chloride and corrosion initiation; phase 3: 2.5 % steel corrosion and spalling; phase 4: spalling and delaminations and phase 5: cumulative damage till the end of service life. And Chen and Mehadravan [8] describe 3 phases respective 3 times of interest for the numerical simulation of chloride-induced reinforcement corrosion and concrete cracking: phase1: chloride penetration ending with $t_{initiation}$ of corrosion initiation; phase 2: free rust expansion ending with t_{stress} and stress initiation and phase 3: concrete cracking ending with $t_{spelling}$ (compare fig. 2).
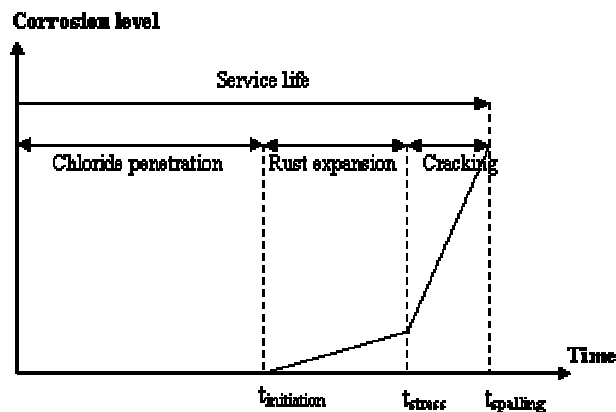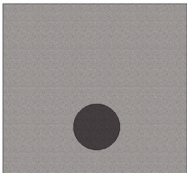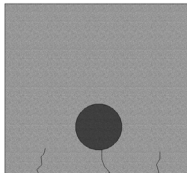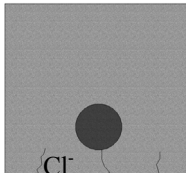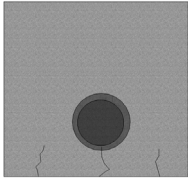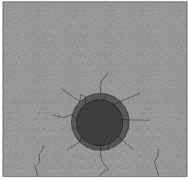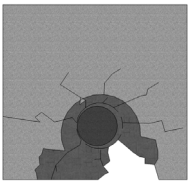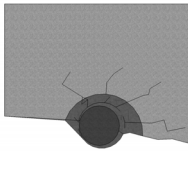

Figure 2. *Chloride induced reinforcement corrosion process according to Chen and Mehadravan [8]*

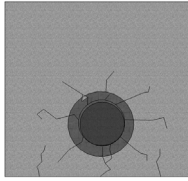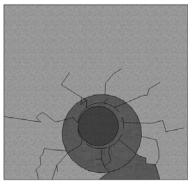Considering these positions and taking the view point of a modern highway-bridge assessment 9 differing phases of the concrete corrosion process can be targeted for this cyclic NDE monitoring as shown in table 1:

Chloride induced corrosion and cracking

| 0) Fresh cast and hardening concrete | 1) Early local structural, thermal and fatigue cracking | 2) Migration of chloride; no corrosion |

3) Initial corrosion of steel and formation of corrosion products; no stresses (t_{init})	4) Radial hoop stresses with formation of cracks and starting chemical alteration of concrete	5) Increased cracking around steel and starting concrete spalling
6) Enhanced oxygen, moisture and chloride inflow; development of radial macro-cracks, spalling and delaminations	7) Cumulating damage	8) End of life performance

3 NDE for corrosion detection in reinforced concrete structures

3.1 Corrosion assessment and monitoring

The assessment of bridge decks is an essential part of modern bridge management. To monitor the performance or the effectiveness of maintenance and repair measures sensors can be embedded in concrete for permanent or temporary monitoring to give early warning of deterioration by measuring especially the concrete resistivity, the reference electrode potential or the corrosion rate. In addition to these there are several techniques in the toolbox of corrosion assessment (for a more detailed description compare the manifold literature, i.e. [3, 4]):

Visual inspection is the most common method but is highly dependent on the expertise of the operator and by definition cannot detect hidden corrosion. *Chain/ hammer drag* is commonly used method for detecting delaminations with two drawbacks: 1. the localization of damaged areas is rather rough, 2. the damage has to be already significant (phases 6/7 ff of table 1). *Drill cores* in combination with *chemical analysis* and / or *petrography* give only local information and extensive sampling can weaken the structure. Minimal invasive *electrochemical potential* measurements do not indicate the rate of corrosion, are complicated in the handling and have difficulties making reliable quantitative measurements. The factors influencing *half-cell potential* measurements are affected by the resistance of the concrete and the pH of the pore solution (carbonation). *Resistance* measurements of concrete can provide an indication of the presence, and possible the amount, of moisture and salt in a concrete structure and therefore evaluate the extent and rate of corrosion of reinforcement indirectly. However they are sensitive to the configuration of the reinforcements, so for the assessment of the condition of a structure and the likelihood of corrosion accurate knowledge of its built construction is necessary [4]. Better results can always be achieved if more than one inspection-method is applied simultaneously, but the larger the number of methods the higher the costs.

There are also NDT methods used with some success on bridge decks: *radiography* measures density changes with high accuracy but needs access to both sides of a structure and

certain safety requirements. *Impact-echo* is able to detect and quantify the degree of delaminations (phase 7) and *ultrasonic* detects defects in concrete [9]. *Radar* detects corrosion induced bridge deck deterioration in an earlier stage (at least phase 6 of table 1) [10] and is very effective especially in combination with *thermography* [11].

3.2   The benchmark approach

As mentioned before, the main objective of this research is to evaluate NDT methods for their aptitude to detect differing phases of corrosion progression in concrete as outlined in table 1. This task will be accomplished by performing automated multi-sensor periodic NDE inspection of a typical concrete deck specimen in the laboratory followed by the analyses of the time-resolved images. Therefore, the aim is to devise a test protocol for structural health monitoring (and asset management) of concrete structures by performing periodic baseline NDE surveys. For this a typical bridge deck specimen is cast, corroded and cyclic loaded to create all above mentioned phases of corrosion (compare table 1). To monitor the corrosion process sensors are embedded to monitor voltage, current, resistance and temperature with an Anode-ladder system (www.sensortec.de). In addition half-cell measurements are carried out.

The methods used for NDE structural health monitoring will consist inter alia of an advanced *ultrasonic's* linear array for early crack detection [12} (www.germann.org), commercial GPR, infrared thermography with induction heating and a new *microwave* camera (www.newportsensors.com).

A special focus lies on the promising technique of *time-resolved thermography with induction heating* [13] combined with *3D microwave imaging* [5, 14] - a subtask co-sponsored by the US National Research Council: A corroded steel bar that has been heated above ambient temperature will cool down more slowly than an uncorroded one, and the difference in rate of cooling can be used to detect the corrosion. The rebar can be heated in the concrete by using an AC (alternating current) electrical induction heater, external to the concrete structure. The temperature at the surface of the rebar can be detected nondestructively by the reflectance of a microwave beam, since the reflectivity is temperature dependent. The induction heater can be cycled on and off to produce temperature pulses in the rebar, and thus the heating and cooling can be cycled repeatedly. By scanning the microwave beam over the rebar it is possible to image the corrosion layer.

4   Conclusions

Corrosion of reinforcement in bridge decks is a major problem for United States infrastructure. A rapid, non-contact, spatially resolved and objective inspection tool for detecting corrosion of reinforcement in concrete at an early stage could lead to planning reliability and a saving of billions of US-Dollars in the public and private budgets. But traditional methods and even the increasingly used NDE methods all have there limits. In addition the used NDE methods are mostly expensive expert's methods and the clients, mostly the State DOTs, have to rely on their expertise. Here FHWA NDE Center is trying to fill the gap by setting up a benchmark project by following its own guideline for the evaluation of NDE methods for infrastructures assessment. The first goal is to use and evaluate state of the art NDT methods for NDE corrosion monitoring. The final goal is to give guidelines to the DOTs which method can be expected which results. To realize this ambitious plan an expert's committee is founded, involving corrosion specialists and NDE experts from the US and Europe. The focus of this collaborative effort is to design and build concrete test specimens, artificially induce and monitor corrosion, periodically load it and perform automated multi-sensor NDE inspections, followed by 3D imaging and destructive validations. First results are to be presented in the oral presentation.

Acknowledgements

References

1. Elsener, B., Klinghoffer, O., Frolund, T., Rislund, E., Schiegg, Y., Böhni, H. (1997) "Assessment of reinforcement Corrosion by Means of Galvanostatic Pulse Technique", *Proc. of the Int. Conf. Repair of Concrete Structures*, 1997, Svolvaer, Norway.
2. Rapoport, I. (2006) "Corroded Steel Reinforcing Bars Likely Culprit", *Daily Commercial News and Construction Record*, Oct. 4, 2006, http://www.dailycommercialnews.com /article/2006100475.
3. Broomfield, J. P. (2007) "Corrosion of Steel in Concrete: Understanding, Investigation and Repair", E&FN Spon, London, Great Britain, 277p.
4. Naumann, J., Haardt, P. (2003) " NDT Methods for the inspection of highway structures", *Proc. of the Int. Symp. NDT-CE,* Sept. 2003, Berlin, Germany.
5. Spicer, J. W. M., Osiander R., Aamodt L. C., Givens R. B. (1998) " Microwave thermoreflectometry for detection of rebar corrosion ", *Proc. of the 3rd Int. Conf. Structural Materials Technology* of SPIE, San Antonio, United States, 1998, pp.402-409.
6. Melchers, R. E., Li, C. Q. "Phenomenological Modeling of Reinforcement Corrosion in Marine Environments", *ACI Materials Journal*, Vol**.**103, No.1 Jan.-Feb. 2006, pp.25-32.
7. Weyers, R. E., Fitch, M. G., Larsen, E. P., Al-Qadi, I. L., Chemberlin, W. P., Hoffman, P. C. (1994) "Concrete Bridge Protection and Rehabilitation : Chemical and Physical Techniques", SHRP-S-668, Strategic Highway Research Program, National Research Council, Washington Dc, United States, 357p.
8. Chen, D., Mahadevan, S. "Chloride-induced reinforcement corrosion and concrete cracking simulation", *Cement & Concrete Composites,* Vol. 30, 2008, pp. 227-238.
9. Gucunski, N., Wang, Z., Fang, T., Chen, Y., Rascoe, C. (2008), "Automated Interpretation of Bridge Deck Impact Echo Data Using Three-Dimensional Visualization", *Proc. of Symp. NDE / NDT for Highways and Bridges, SMT*, Sept. 2008, Oakland, United States, pp.33-41.
10. Gucunski, N., Rascoe, C., Parrillo, R., Roberts, R. (2008), "Comparative Study of Bridge Deck Condition Assessment by High Frequency GPR", *Proc. of Symp. NDE / NDT for Highways and Bridges, SMT*, Sept. 2008, Oakland, United States, pp.58-66.
11. Maser, K. (2008), "Integration of Ground Penetrating Radar and Infrared Thermography for Bridge Deck Condition Evaluation", *Proc. of Symp. NDE / NDT for Highways and Bridges, SMT*, Sept. 2008, Oakland, United States, pp.67-74.
12. Friese, M., Wiggenhauser, H. (2008), "New NDT Technique for Concrete Structures: Ultrasonic Linear Array and Advanced Imaging Methods", *Proc. of Symp. NDE / NDT for Highways and Bridges, SMT*, Sept. 2008, Oakland, United States, pp.287-294.
13. Hillemeier, B. (1984) "Location of Reinforcement by Induction-Thermography", *Proc. of SPIE - The International Society of Optical Engineers*, *Thermosense VII*, Vol. 520, 1984, pp. 197-206.
14. Feng, M., Kim, Y. J., Park K. (2006) "Microwave NDE of Fiber Reinforced Polymer Wrapped Concrete Structures", Proc. Int. Conf. NDE-CE, 2006, St. Louis, United States.