SMAR 2019 – Fifth Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

General aspects on the assessment of reliability of corrosion monitoring systems

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ABSTRACT: The average age of our infrastructure is increasing constantly and with the age increases as well the corrosion probability of the reinforcement. Therefore, regular corrosion condition control plays an important role in the through-life management of existing structures. The most common corrosion inspection method is the half-cell potential measurement but continuous corrosion monitoring becomes more and more important. One substantial contribution to strengthen the use of corrosion monitoring is given by the DGZfP-Specification B12 "corrosion monitoring of reinforced and pre-stressed concrete structures". The specification presents the fundamental measuring principles and shows practical case studies on the application of corrosion monitoring in newly built and existing structures. Thus, the corrosion condition control enables the decision making for further maintenance and undertaking interventions and consequently, these data must be reliable. However, the evaluation of the reliability of corrosion monitoring systems hasn't received any attention in literature up to now – and neither the DGZfP-Specification B12 gives any advice. The evaluation of the reliability of monitoring systems needs to consider some other issues in comparison to inspection methods. Therefore, the objective of this paper is the discussion on the general aspects for the reliability assessment of corrosion monitoring systems in reinforced concrete structures.

1 BACKGROUND

Monitoring is becoming a fundamental tool to control the development of the time-dependent deterioration of our constantly ageing infrastructure. The advantage of monitoring is that it enables a predictive (instead of reactive) assessment of structural behavior including updating of reliability and durability of deteriorating structures.

Most durability problems on reinforced concrete structure are caused by the corrosion of the reinforcement. As soon as a structure is exposed to chloride ions from sources such as seawater or de-icing agents the chloride-induced corrosion becomes more and more likely with time. Other reason of corrosion onset is the carbonation process of the concrete cover leading to carbonation-induced corrosion. Therefore, corrosion testing and monitoring fulfill an important role in the framework of the through life management of existing structures.

The objective of corrosion testing and monitoring is to deliver reliable data on the real corrosion conditions and structural response. Furthermore, monitoring reduces uncertainties in the assessment and in the prediction of the performance of structures, e.g. Matthews et al. (2018). But up to now, there is no comprehensive approach how to assess the reliability of corrosion monitoring systems. Therefore, this paper aims to discuss the fundamental aspects and what to consider before evaluating the reliability of corrosion monitoring in reinforced concrete structures.

1.1 Corrosion Monitoring of Reinforced Concrete Structures

The process of reinforcement corrosion in concrete structures consists of two phases the initiation phase and the propagation phase. The initiation phase is the time period until the critical chloride threshold or the carbonation depth reaches the reinforcement leading to corrosion onset. After depassivation the propagation period starts and the loss of reinforcement cross section evolves based on Faradays Law. Each phase, the initiation and the propagation phase, place other requirements on the corrosion monitoring system. The specification B12 (2018) from the German Society of Non-destructive Testing (DGZfP) provides an overview of the basic measurement principles for corrosion monitoring in the initiation and the propagation phase for new and existing structures.

However, the basic requirement on the monitoring system is the indication of reinforcement corrosion. The outcome is either “indication of corrosion (I)” or “no indication of corrosion ($\overline{\text{I}}$)”. Consequently, the theory of Probability of Detection is feasible to assess the reliability of corrosion monitoring.

1.2 The concept of Probability of Detection

The concept of Probability of Detection (POD) enables the quantification of the capability of non-destructive testing and monitoring systems. The capability of monitoring/ testing systems is the probability of detecting a defect with a particular size under specified conditions and based on a defined procedure. Since the flaw size has major impact on the detectability the POD is usually expressed in its dependence. The corresponding defect size with regard to corrosion monitoring is the anode area. This is the area on the reinforcement where the anodic partial reaction takes place and the loss of cross section progresses.

Several probabilistic methods are available to analyze the POD as a function of flaw size. The most common models are the “HIT/MISS” and the “â vs. a”, see Berens (1989) or MIL-HDBK (2009). The “HIT/MISS”-Model uses the discrete response (flaw is detected or not) of the monitoring system and the “â vs. a”-Model considers the continuous response signals (â). Thus, the POD evaluation is based on the simplified relationship between the maximum signal (â) and the significant defect parameter causing the signal (a).

First POD’s for corrosion detection in reinforced concrete structures are based on corrosion inspection using data from half-cell potential measurement, Kessler et al. (2017). However, the evaluation of the reliability of corrosion inspection shows some similarities but the evaluation of the POD of corrosion monitoring demands additional considerations.

2 CONSIDERATIONS TOWARDS RELIABILITY OF CORROSION MONITORING

The differences between testing and monitoring lead to other prerequisites when assessing its reliability. In contrast to inspection methods monitoring systems are stationary systems providing solely information at one spot. In return monitoring data are able to record data continuously. Both aspects, the spatial constraints and the temporal indication, are discussed in order to evaluate the corrosion monitoring reliability.

2.1 Spatial resolution

The spatial resolution of monitoring systems covers two levels: the reliability of corrosion monitoring systems on the structural level and on the sensor level.

2.1.1 Structure level

Corrosion monitoring on the structural level is the merger of several sensors to a monitoring network. The determination of number of sensors and position of the sensors is of particular importance, Figure 1 left. These decisions depend on several factors such as statics system, hot spots, poor workmanship, age, exposition, used materials and so on. Thus, structural and material engineers shall make these decisions together under the consideration of the theory of value of information (VoI), e.g. Straub (2014).

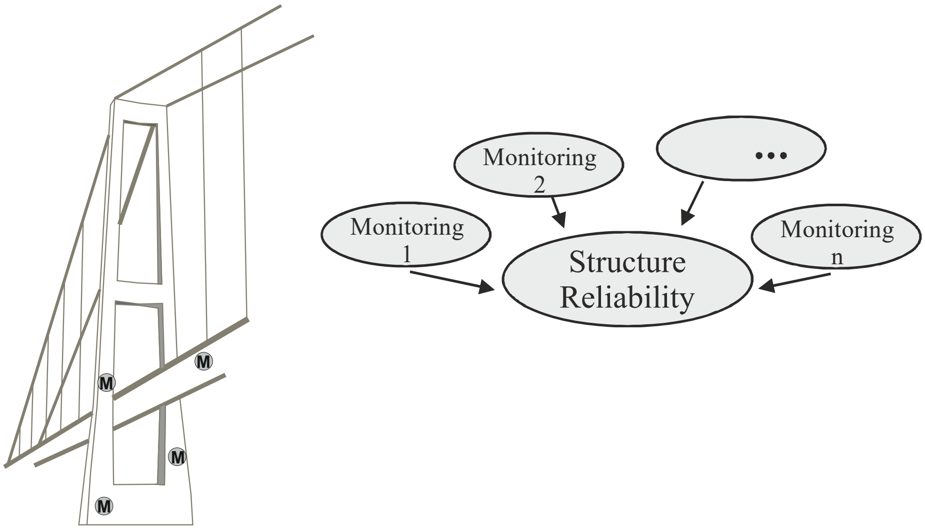

Figure 1. Monitoring on the structural level.

Finally, the evaluation of all sensor data leads to an overview about the corrosion condition in order to estimate the structure reliability, Figure 1 right. Consequently, the reliability of the sensor network as well as the reliability of a single sensor affects the outcome on the structural reliability.

2.1.2 Spatial coverage of a single monitoring spot

On the sensor level counts solely the Probability of Detection of a single sensor. Since the sensor is a stationary system its position is fixed. However, this means that the sensor is not necessarily close to a defect. In case of carbonation-induced corrosion which leads to a homogeneous corrosion of the first reinforcement layer the corrosion sensor is always close to the corrosion process. Whereas, in case of chloride-induced corrosion which is characterized by the formation of macro-cell elements, the position of the sensor has an impact on its detectability, Figure 2.

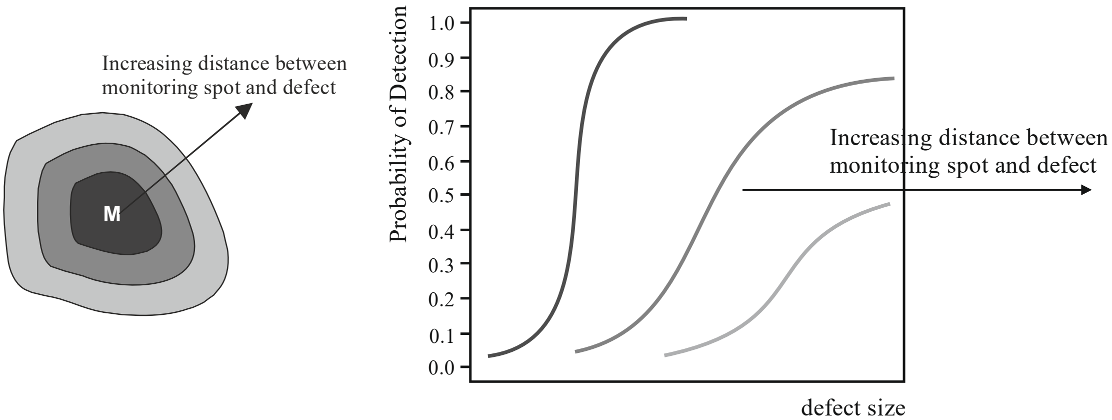

Figure 2. Schematic spatial resolution of a corrosion monitoring spot and corresponding Probability of Detection curve.

It is assumed that with increasing distance of the monitoring sensor to the anode decreases the probability of corrosion detection. As greater the distance as smeared is the anodic signal by the surrounding cathodic areas. Here, the spread of the macro-cell element, Warkus (2012), is of importance which is directly connected to the geometry of the anodic and cathodic areas. The formation of anodic and cathodic areas depends on the available reinforcement surface. Therefore, sensors in different components such as superstructure, columns, abutments, etc., with different percentage of reinforcement show probably different POD's.

2.2 Judging criteria of corrosion sensors

Corrosion monitoring sensors can estimate several parameters, see Figure 3. There is not "The One" corrosion sensor.

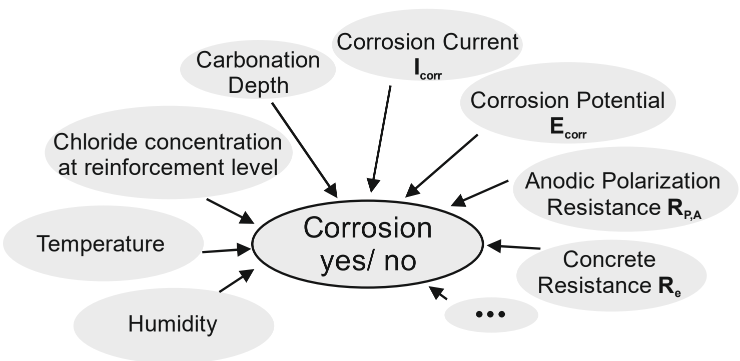

Figure 3. Possible parameters for the indication of corrosion initiation and corrosion activity.

Corrosion monitoring often pursues two objectives:

- The estimation of the time to corrosion initiation
- The information about corrosion activity

For the first objective the monitoring of the chloride concentration and/ or the carbonation depth with regard to the concrete cover is needed. For this case, the reliability of the sensor cannot be expressed by the Probability of Detection, because there is no corrosion and therefore no defect created so far.

As soon as the onset of corrosion or the halt of corrosion is the focus, the reliability of the sensor can be estimated according to the POD theory. For the estimation of the corrosion onset or activity respectively the following parameters are useful:

- I_{corr}: corrosion current [A]
- $R_{P,A}$: polarization resistance of anode [Ωm²]
- E_{corr}: corrosion potential [V]
- R_e: concrete resistance [Ωm²]

All these electrochemical parameters are directly connected via the following relationship, Beck et al. (2011), (equation 1):

$$I_{corr} = I_{\text{macro}} + I_{\text{micro}} = \frac{\Delta E}{R_{p,A}+R_{p,C}+R_e} + I_{\text{micro}} \tag{1}$$

with:

I_{corr}:	corrosion current [A]
I_{micro}:	self-corrosion current [A]
I_{macro}:	macro-cell corrosion current [A]
ΔE:	driving potential [V]
$R_{P,A}$:	polarization resistance of anode [Ωm²]
$R_{P,C}$:	polarization resistance of cathode [Ωm²]
R_e:	concrete resistance [Ωm²]

Consequently, the estimation of at least one or at best all of these parameters shall be considered to perform the corrosion condition assessment; see Hiemer et al. (2018a), Hiemer et al. (2018b).

The cathodic polarization resistance is of minor importance, since the corrosion process is normally not controlled by the cathodic partial reaction. Additionally, each reinforced concrete structure provides more cathodic areas than would be necessary to maintain corrosion activity and the cathodic signal is therefore not very pronounced.

The parameters, I_{corr}, $R_{P,A}$, E_{corr} and R_e correlate with each other, Osterminski (2013), and partially, e.g. E_{corr}, as well with the defect size (anode area), Kessler et al. (2017). Additionally, the temperature and the humidity affects especially the resistances $R_{P,A}$, and R_e leading to misleading results if not considered during evaluation and interpretation, Hiemer et al. (2018a). Since the temperature and the humidity changes due to weather and climate condition they control the corrosion activity. Therefore, reinforcement corrosion in concrete structures is a highly time-dependent process.

The application of the POD theory requires the definition of thresholds to distinguish whether an e.g. measured anodic polarization resistance indicates corrosion activity or not. Information on possible threshold values are partly presented in literature. Andrade and Alonso (1996) studied intensity of corrosion current densities with regard to corrosion activity. Hornbostel (2015) investigated the relationship between macro-cell corrosion and concrete resistivity to clarify under which concrete resistances corrosion activity is possible. However, more research is needed with regard to threshold for the reliability determination of corrosion monitoring systems.

In general the evaluation of corrosion monitoring systems should be accompanied by additional inspections methods such as visual inspection or concrete cover depth measurement at least after the execution of the structure or after the post installation of a sensor. Often the structural engineer asks for the corrosion rate or the loss of cross section. Unfortunately, this information is not deducible out of the monitoring signals.

3 APPROACH TO EVALUATE CORROSION MONITORING WITH POD ANALYSIS

There are two approaches to evaluate a monitoring system according to the two levels, which are mentioned above. An evaluation on the structural level answers the question, if the structure can be used in a reliable way for near future. The evaluation is limited on the evaluated structure. However, the influencing factors are strong and the evaluation will be highly sophisticated.

The second approach is to evaluate the capability of the monitoring system in general. Due to the functionality of the monitoring system different influences should be evaluated and kept in mind. To gain as much information as possible an evaluation of single sensors is the right way, before transferring it to the structure.

The detectability can be affected by more than a simple result. The conventional POD approach is there not useful anymore. Similar to the data-field POD, Pavlović et al. (2008), or the observer threshold POD, Kanzler et al. (2015), a more dimensional signal field needs to be used. It is expected that a correlation of the signal parameter exists and not all the time the knowledge of a parameter will be known. Therefore, an extension of the parameters as statistical distributions is necessary. With unknown parameter each requirement of the conventional POD will not be meet and a new approach is necessary.

Bayesian statistics is able also to include unknown parameters in a statistical model. One possible way might be a Bayesian network with the abovementioned input parameters. Through this approach the typical POD curve might not be the result.

Furthermore, the reliability of corrosion monitoring systems does not depend exclusively on the flaw size. Therefore, the capability of the monitoring system to detect corrosion needs to be expressed with respect to those parameters which determine flaw severity, see Pavlović et al. (2012). As a consequence, the resulting Probability of Detection is a function of all different influencing parameters - a so called multi-parametric Probability of Detection.

There are three major steps to defining the capability of the monitoring system on a structural level. The first step shows the capability of the evaluated sensor, mainly focused on the physics. With the help of a reference part different parameters will be investigated and their influence in the signal parameters will be evaluated. At the second step, a model will be defined. Based on the results of one sensor a general model will be built. Statistical models for the parameter and the knots of the network will be defined. The model should be verified by another reference part, independent from the first part. In the last step the evaluated structure will be in focus, therefore different position for the sensors will be used, and additional testing equipment is necessary to keep control of the influences. With the gaining of data, the amount of control testing will be decrease.

4 CONCLUSIONS

Up to now we do not know the reliability of our corrosion monitoring systems. However, at least we can summarize that reliability of corrosion monitoring systems depends on the following factors

- Spatial variability on the structural level
- Spatial variability on the sensor level
- The correlation structure of the measured parameters
- The frequency of data recorded since corrosion parameters are highly moisture and temperature dependent

Only after the determination of the Probability of Corrosion Detection we are able to determine which monitoring data are decisive and which are sufficient.

All the discussion above deals mostly with the Intrinsic Capability of the monitoring systems. The effect of the Application Factors, e.g. such as the coupling of the sensors, or the Human Factors and the Organizational Factor on the monitoring system has to be regarded as well, see Müller et al. (2016).

5 REFERENCES

Andrade C., Alonso, C. 1996. Corrosion rate monitoring in the laboratory and on-site. *Construction and Building Materials,* 10, 5. https://doi.org/10.1016/0950-0618(95)00044-5

Beck, M., Burkert, A., Harnisch, J., Isecke, B., Osterminski, K., Raupach, M., Schießl, P., Tian, W., Warkus, J. 2013. Deterioration model and input parameters for reinforcement corrosion. *Structural Concrete* 13 (3), pp. 145–155. https://doi.org/10.1002/suco.201200004

Berens, AP. 1989. NDE reliability analysis. *Metals Handbook*, Vol. 17, 9th Ed., Univ. of Dayton Research Institute, Dayton, OH.

German Society for Non-Destructive Testing (DGZfP). 2018. *Specification B12 - Korrosionsmonitoring von Stahl- und Spannbetonbauwerken*, Berlin, (German).

Hiemer, F., Wich, F., Gehlen, C., Keßler, S., Mayer, T. 2018a. Monitoring von Bewehrungskorrosion in Rissbereichen von Stahlbetonbauwerken. Special Issue *Messtechnik im Bauwesen*, 35-43, Ernst & Sohn Special (German).

Hiemer, F.; Jakob, D.; Keßler, S.; Gehlen, C. 2018b. Chloride induced reinforcement corrosion in cracked and coated concrete: From experimental studies to time-dependent numerical modeling. *Materials and Corrosion*, 69(11), pp.1526-1538. https://doi.org/10.1002/maco.201810148

Hornbostel, K. 2015. The role of concrete resistivity in chloride-induced macro cell. *PhD thesis*, Norwegian University of Science and Technology.

Kanzler, D., Ewert, U., Müller, C., Pitkänen, J. 2015. Observer POD for radiographic testing. *AIP Conference Proceedings* 1650, pp. 562–570.

Kessler, S.; Gehlen, C. 2017. Reliability evaluation of half-cell potential measurement using POD. *Journal of Infrastructure Systems* 23 (2). http://dx.doi.org/10.1061/(ASCE)IS.1943-555X.0000334

Matthews, S., Bigaj-van Vliet, A., Walraven, J., Mancini, G., Dieteren, G. 2018. fib Model Code 2020: Towards a general code for both new and existing concrete structures. *Structural Concrete* 19 (4), 969-979. https://doi.org/10.1002/suco.201700198

MIL-HDBK (Military Handbook). 2009. *Department of defence handbook*: Nondestructive evaluation system reliability assessment. MIL-HDBK-1823A, DoD, VA.

Müller, C., et al. 2016. Conclusions of the 6th European American Workshop on reliability of NDE. *AIP Conference Proceedings*. Vol. 1706. No. 1. AIP Publishing.

Osterminski, K. 2013. Zur voll-probabilistischen Modellierung der Korrosion von Stahl in Beton - Ein Beitrag zur Dauerhaftigkeitsbemessung von Stahlbetonbauteilen, TU München Dissertation, (German).

Pavlović, M., Takahashi, K., Müller, C., Böhm, R., Ronneteg, U. (2008). *NDT reliability - Final report Reliability in non-destructive testing (NDT) of the canister components*. R- 08-129. Technical Report. Sweden: Svensk kärnebränslehantering AB.

Pavlović, M., Takahashi, K., Müller, C. 2012. Probability of detection as a function of multiple influencing parameters. *Insight* 54, 11.

Straub, D. 2014. Value of Information Analysis with Structural Reliability Methods. *Journal of Structural Safety* (49), 75-86. http://doi.org/http://dx.doi.org/10.1016/j.strusafe.2013.08.006

Warkus, J. 2012. Einfluss der Bauteilgeometrie auf die Korrosionsgeschwindigkeit von Stahl in Beton bei Makroelementbildung. *Dissertation*, RWTH Aachen, (German).