Monitoring steel corrosion in reinforced concrete beams with variable crack widths under sustained load

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Summary

This work reports on the investigation of steel corrosion behavior in 1000 mm in length reinforced concrete beams under sustained load, aiming to define a feasible experimental protocol for corrosion monitoring. The beams were subjected to wetting (5% NaCl for corroding cases and tap water for control ones) and drying cycles. Generally applied lab electrochemical techniques as Electrochemical impedance spectroscopy (EIS) and Potentio-dynamic polarization (PDP) were employed and results correlated to commonly used, for both lab and field assessment, methods as Open circuit potential (OCP) monitoring and Linear polarization resistance (LPR). EIS provided useful information for the effects of concrete bulk properties and cement hydration on steel corrosion monitoring. The polarization resistance (Rp) values recorded via EIS and LPR were in a very good agreement and were used for deriving corrosion current densities, applying the Stern-Geary equation. The results from the commonly used in practice “spot” measuring approach were found to be in good agreement with the records in saturated concrete cover conditions (during wet cycles). However, meaningful results can only be at hand when measurements in time are performed in exactly the same manner and in equal environmental conditions. In contrary conditions, the effect of various factors is even more pronounced, resulting in under- or overestimation of corrosion rates.

1 Introduction

Steel corrosion in reinforced concrete is well recognised to be the major cause for structures’ degradation. For a good quality concrete and within the absence of detrimental external influence, the steel reinforcement is in a passive state. Passivity is maintained as long as the concrete bulk matrix maintains high alkalinity (i.e. buffer to corrosion initiation) and performs as a sound physical barrier against penetration of aggressive substances. Concrete, however, is a porous material and e.g. penetration of chloride ions can initiate steel corrosion even at high pH (12.9 – 13.5). Logically, the process of Cl-induced corrosion would have a faster onset and will be further more pronounced when except porosity, concrete cracking is at hand. Cracks are unavoidable in civil structures, ranging from micro to macro level. Therefore, standards are applicable for permissible crack width within engineering applications [1].

The application of electrochemical techniques, general (as OCP, LPR) or more sophisticated (as EIS, Cyclic voltammetry (CVA), etc.) is well accepted for deriving corrosion rates of steel in reinforced concrete. Monitoring and data interpretation for steel corrosion in reinforced concrete structures, however, can be challenging in many ways when lab approaches and techniques for controlled environment are to be employed in practical applications. Next to that, various purely structural parameters (as concrete cover thickness, crack frequency and width, loads, etc.) logically exert additional impact, which needs to be considered in case the electrochemical behaviour of the steel reinforcement is to be assessed. To this end, an experimental
program was designed for monitoring steel corrosion in comparatively large (>1000 mm in length) reinforced concrete beams, considering the effect of the aforementioned various structural parameters on steel corrosion rate with time. 32 beams of 1500 x 100 x 150 mm were cast, where the following parameters were varied: crack width, crack frequency, total (summed) crack width, concrete cover and type of loading. The experimental set-up is as reported in detail in [2]. In order to account for the effect of the above variables and to determine the most suitable and reliable approach for monitoring steel corrosion in large specimens, a preliminary study on the applicability of electrochemical methods was performed and reported in this work.

2 Experimental materials and methods

2.1 Materials

For this preliminary study, two reinforced concrete beams of 1000×125×125 mm were cast with one ribbed bar and one stainless steel bar which were embedded at the desired position (Figure 1a). High yield ribbed cold rolled reinforcing bars B500A were used, diameter of 16 mm and length of 960 mm. Before casting, the bars were degreased and sealed by epoxy at both ends; the exposed surface area was 200 cm². The stainless steel bar (Fig.1a) was embedded at a larger depth in order to act as a counter electrode. Ordinary Portland cement was used as a binder; the concrete was vibrated in three layers. After casting, the beams were covered with plastic sheets for 72 hours under laboratory conditions. Subsequently, all specimens were cured in a climate-controlled (fog) room (20±2°C and 95±5% RH) until the age of 28 days. The reinforced concrete beams (A and B) were exposed to air drying under laboratory conditions for additional 10 and 160 days respectively. After that, 4-point bending was applied to induce cracks. In the experiments, pile B was subjected to 4-point bending at 38 days of age, whereas pile A – at 188 days. Pile B was exposed to alternating wetting and drying cycles once a week for 2 days ponding (5 % NaCl solution) and a 5 days drying phase to simulate aggressive environment. Pile A was control beam which was exposed under the same regime to tap water.

2.2 Methods

The electrochemical methods involved were EIS, LPR and PDP. Open circuit potentials (OCP) were recorded in all relevant conditions through “spot” measurements (wet sponge for ensuring concrete conductivity) above sound (non-cracked) and cracked regions (schematically shown in Fig.1a) or when the concrete was in a “wetting cycle” (as above specified). All electrochemical tests were performed after OCP stabilization. EIS and LPR were performed on time intervals throughout the test, PDP was performed at the end of the tests. For LPR and PDP a polarization window of ± 20 mV and -0.15 V to +0.15 V respectively at a scan rate of 0.1 mV/s for the former and 0.5 mV/s for the latter were used. EIS was carried out in the frequency range of 1 MHz to 10 mHz by superimposing an AC voltage of 10 mV (rms). The execution and data interpretation of all electrochemical measurements was as previously reported for steel in reinforced concrete systems [3-5]. All potential values were recorded vs Ag/AgCl (for an easier comparison with standards/criteria, some figures present these values re-calculated vs standard calomel electrode (SCE)). The used equipment was Autolab PGSTAT302N (FRA2 module) and NOVA interface.
3 Results and discussion

3.1 OCP readings

For both lab and field conditions, recording the OCP values for the steel reinforcement in time is a well accepted practice, indicating the time to corrosion initiation. For reinforced concrete, the steel surface is considered passive if OCP is equal or more anodic than -270 mV (SCE). In lab-conditions a well defined geometry of the electro-chemical cells apply, where the reference electrode (embedded or external) is positioned in the cell itself, accounting for minimal influence of IR drops and other factors i.e. a three-electrode cell arrangement is used [6]. For field conditions, the OCP monitoring is similarly performed through embedded pseudo-reference cells (e.g. Mn/MnO₂, Pt/Ti) or externally via Cu/CuSO₄ or Ag/AgCl electrodes. In the former case an average OCP (for the total exposed steel surface) is recorded. In the latter case, local measurements could be also recorded. For external measurements, the tip of the electrode is pressed on a wet sponge on the concrete cover for minimising the contact resistance i.e. the “spot” method applies. Logically, RH (especially for sound or aged concrete) has a significant impact on the recorded values.

In this study, two methods were employed: the “spot” measurement was executed immediately after the “wetting” cycles (i.e. with still saturated concrete cover), during the drying cycles, as well as above sound (not-cracked) concrete cover and above cracks (schematically depicted in Fig.1a). OCP was also recorded during wet-cycles by simply positioning the reference cell in the solution above the reinforced concrete cover i.e. average OCP readings were recorded. The motivation behind these two techniques was to possibly differentiate “active” surface underneath the various cracks, and compare results to all other records. Figures 1b) present the OCP readings for the “control” beam A and “corroding” beam B, recorded via local “spot” measurement. The values indicate passive behavior, as expected, for beam A, irrelevant of crack width and/or sound concrete; OCP values were not exceeding -50 mV also within the wetting cycles. Alteration of values within drying and wetting was as
expected, OCPs ennoblement was recorded on later stages, reflecting stabilization of the passive layer on the steel surface with time. In contrast, the OCP values for beam B vary more significantly with wetting and drying, presenting more noble values in the former and more cathodic values in the latter case (all values, despite fluctuations were in the activity region). This is also as expected, denoted to Cl-ions penetration and steel active behavior within the wetting cycles. A general trend of more cathodic potentials, recorded for the locations of larger crack widths (0.22 – 0.25mm) was expected, but not really observed for all crack locations in this test; e.g. for the middle of the beam – crack width 0.17mm, more anodic values were recorded, possibly due to wider sound concrete areas i.e. less damaged concrete-steel interface on both sides of this crack. Clearly, OCP readings can only give an indication for the corrosion state of the steel reinforcement and are significantly affected by electrical properties of the bulk matrix and relevant interfaces.

3.2 Electrochemical Impedance Spectroscopy (EIS)

EIS is applied for in-depth characterization of steel/concrete systems as it provides information for both the steel surface (electrochemical response) and the concrete bulk matrix (concrete bulk and pore network properties) [7-8]. EIS is particularly useful when a non-destructive evaluation of changing bulk microstructure is to be studied.

Figure 2 depicts an overlay of the response for piles A and B (during wet-to-dry regime), the derived $R_p$ values (Fig. 2b) and the equivalent electrical circuit, Fig.2c, used for interpretation and data fitting of the experimental EIS response (the circuit is based on previously used and reported such for reinforced cement-based systems [9-10], including additional parameters to account for bulk matrix properties [11], considering the frequency range hereby used of 1MHz to 10mHz. The elements of the equivalent circuit present the following physical meaning: the first part of the circuit i.e. the high frequency (HF) domain (inlet in Fig.2a) is presented by time constants.
$C_RC_p$ and $C_{pn}R_{pn}$, attributed to the properties of the concrete matrix in terms of solid phase, disconnected pore pathways and continuous connected pores. The second part of the circuit i.e. middle (MF) and low frequency (LF) domains (time constants $R_{ct,Cdl}$ and $R_{pr,l}C_{pr,l}$) deals with the electrochemical reaction on the steel surface including the contribution of redox processes and product layer transformation. The HF response corresponds to the concrete bulk resistance, including the contribution of electrolyte resistance (electrolyte resistance was in the range of 4 ohm for the 5% NaCl solution (pile B) and 10 ohm for water (pile A). For deriving polarization resistance ($R_p$) from EIS measurements in reinforced concrete (($R_{ct}$ and $R_{pr,l}$ respectively), the medium-low and LF limits are generally considered [11-12].

**Overall observations:** as common for EIS in reinforced concrete, a clear differentiation between active and passive steel is possible, based on the shape of the curves in the MF to LF domain: as seen from Fig.2a), the response for pile A (control) is with a significantly larger magnitude of impedance $|Z|$ compared to that for pile B. For pile A here, a slight transformation of the product/passive layer on the steel surface with altering drying-to-wetting regimes was observed (Fig.3) but passivity was maintained as seen by the high charge transfer resistance values in the range of 8 to 10 kOhm cm$^2$ at the end of the test (Fig.5). In contrast, the MF to LF domain for pile B clearly shows active behavior, with response strongly inclined to the real axis (here already denoted to chloride ions presence at the steel surface [6], significantly lower magnitude of impedance (charge transfer resistance in the range of 0.5 to 1.5 kOhm cm$^2$, Figs. 2,4,5). The charge transfer resistance and product layer characteristics determine the significantly higher global $R_p$ values for pile A throughout the test, compared to those recorded for pile B (summarized in Fig.2b).

**Fig.3:** EIS response in the MF- LF domain for beam A (control) in wetting, wet-to-dry and drying regimes: (a) complex plane Nyquist and (b) Bode plots

**HF response and bulk matrix properties:** Except the corrosion state of the embedded steel and product layers transformation, the EIS response clearly differentiates the bulk matrix properties in both A and B piles. The HF domain (magnified also as inlet in Fig.2a) depicts the semi-circle capacitive arcs, attributed to the properties of the concrete bulk matrix. As seen form the plot, the bulk matrix resistance for pile A is actually lower than that for pile B, despite the chloride-containing environment (which would result in lower resistivity of the connected pore network for pile B). The result is
attributed to the fact that although A and B were at equal cement hydration (concrete) age, loading conditions and cracks were induced for pile A five months earlier than for pile B. Therefore, the bulk matrix in pile A was already significantly altered, whereas the crack patterns in pile B were induced just before the hereby employed electrochemical tests. The result is higher global bulk matrix resistance for pile B compared to pile A in wet-to-dry conditions.

**MF to LF response:** An overlay of the MF to LF response (frequency window 50 kHz to 10 mHz) is presented for beam A in Fig. 3 and for beam B in Fig.4. As seen from Fig.3, the wetting and drying cycles do not exert a significant influence on the electrochemical behavior of the steel reinforcement, which was as observed via the OCP readings (Fig.1b). The steel reinforcement in beam A is in passive state throughout the experiment, reflected by the higher $|Z|$ and phase angle of more than 60 degrees.

![Fig.4](image)

**Fig.4:** EIS response in the MF- LF domain for beam B (corroding) in wetting, wet-to-dry and drying regimes: (a) complex plane Nyquist and (b) Bode plots

The influence of the wetting regimes is only in terms of pore network properties, partially seen in this response (inlet in Fig.3), where a shift towards lower real $|Z|$ values was observed with wetting. As far as electrochemical behavior is concerned, a slight drop of the phase angle was recorded within the wetting regimes (Fig. 3b), which does not have an effect on the passive state. All these are seen in the derived charge transfer resistance, which maintains high values irrelevant of the conditioning regime. Further the range of similar capacitance values (around 0.35 to 0.45 mF/cm²) for both double layer and redox capacitance (Fig.5) determines the passive state of the steel reinforcement in beam A [13]. In contrast, for beam B, a larger significance of altered environmental conditions was observed with regard to electrochemical state of the steel reinforcement. As seen from Fig.4, except the already commented influence on bulk matrix properties (Fig.4, inlet), the MF-LF response presents an inclination to the real axis when wetting regime is at hand. This is denoted to both chloride ions penetration and activation of the steel surface. The active state of the steel reinforcement is also reflected by a significant drop of phase angle to below 30 degrees, which is in line with the previously discussed OCP readings (Fig.1b). The sequence of wetting and drying exerts alternating changes in the capacitive values for both product layer and double layers capacitances, Fig.5a)b). Higher capacitance and lower resistance of the product layer were recorded during or at the end of the wetting regime (Fig.5a), attributed to both re-structuring of the layers and active corrosion within Cl-ions pene-
The charge transfer resistance values (Fig.5b) are significantly lower for beam B, compared to beam A, which accounts for the active corrosion state in beam B. The increasing (and significantly larger) double layer capacitance in the wetting cycles corresponds to the lowest charge transfer resistance values i.e. enhanced steel corrosion process. The increase in double layer capacitance, accompanied by higher and increasing charge transfer resistance for the transition form wetting to wet-dry regime (Fig.8b) is attributed to spreading of the corrosion damage on a larger surface, which is the case when drying out of the specimen allows oxygen penetration to a larger extent, thus catalyzing the anodic process of steel dissolution by enhancing the cathodic reaction.

![Graph](image1.png)

**Fig.5:** Summarized electrochemical parameters for beams A and B in all tested regime

The summarized $R_p$ values (based on $R_{ct}$ and $R_{pl}$), derived from EIS were correlated to those derived from LPR. A very good agreement was observed (Fig.2b) with a slight variation in magnitude which is attributed to the manner of executing these measurements: AC perturbation and no DC polarization within EIS and DC cathodic/anodic polarization within LPR, resulting in slightly lower absolute $R_p$ values from the LPR tests.

### 3.3 DC electrochemical tests (LPR and PD) and correlation to EIS results

As previously introduced, this work aimed at clarifying the suitability of electrochemical tests to corrosion monitoring in large reinforced concrete beams. EIS proved to be very useful and informative, revealing information for both electrochemical response and bulk matrix alterations. However, EIS is a rather sophisticated approach when a more rapid quali- and quantification of the steel corrosion state in large-scale experimental set-ups is to be achieved. Therefore, except the OCP records (which are also not sufficient with respect to quantitative results, but just indicative), the commonly accepted LPR technique was employed. In order to account for concrete age and the variation of structural parameters, LPR was supported by PDP meas-
urements, performed at the end of this test. The aim of the PDP tests was to perform Tafel slope analysis for the steel response in both beams A and B and thus experimentally derive all necessary parameters for the calculation of corrosion current densities (e.g. through the Stern-Geary equation). Figure 6 depicts the recorded LPR curves for beam A (left) and B (right) in consecutive wetting regimes with drying cycles in between. In other words, the first response (curves 1) refer to measurements in the middle of the first wetting cycle; the second response (curves 2) refer to measurements, taken at the end of wetting cycle, which was preceded by a dry cycle of 5 days; the third response refers to measurements taken in the middle of a third wetting. For both A and B beams a slight cathodic shift of corrosion potential was observed within wetting, which for both beams is related to limiting oxygen access to the steel surface, but accompanied by chloride penetration (increased rate of Cl-induced corrosion) for beam B. As expected the relevant corrosion current densities stabilize over time for beam A and are at least one order of magnitude lower reflecting passive state( Fig. 9a), compared to the values for beam B, which increase over time (Fig. 9b ) and alterations from more to less active behavior is observed. The result is consistent with the EIS tests, supporting the previously discussed observations for limited or none effects on wetting/drying regimes on steel electrochemical behaviour for beam A (Fig.3) and larger effect of the environmental conditions on the steel response in beam B, Fig.4 (mainly chloride ions penetration and subsequent chloride binding).

Fig. 6: LPR curves for beam A (left) and B (right) in wetting cycles (average response)

As aforementioned, PDP curves were recorded for both beams in wetting and drying regimes (the former present average response, the latter was recorded also as an average for the total exposed surface via a “spot” measurement over a sound (un-cracked) location in the middle of the beam). As seen from Fig.7, the wetting cycles increase corrosion and anodic currents for both beams A and B. However, only a very small variation of these is relevant for the control beam A (due to already discussed phenomena), where environmental changes do not effect the electrochemical response (already discussed and supported from EIS results). In contrast, larger variation and enhanced corrosion activity within altered external environment is relevant for beam B, where the effect governing corrosion behavior is chloride penetration in the wetting cycles. As expected, the recorded corrosion current densities for beam A are at least one order of magnitude lower than those for beam B. The PDP served for performing of Tafel slope analysis in a polarization window of -50 mV to +50 mV around corrosion potential, following standard for reinforced concrete procedures and considerations [7].
The aim was to experimentally derive B constants for the calculation of corrosion current densities, since well-known are the large deviations in these with respect to the steel response in concrete of different hydration age and environmental conditions. The calculated values (based on $R_p$ derived from LPR) are summarized in Fig. 9, including the relevant OCP potentials before LPR tests. As already commented, the corrosion current densities for beam A are in the range of passivity (0.1 μA/cm$^2$ accepted as a threshold value), whereas the derived current densities for beam B fall in the active corrosion region. What can be also observed from Fig.9 is the variation of currents and potentials with the different conditioning regimes, which is far more pronounced for beam B, compared to beam A.

**4 Conclusion**

In conclusion, this work reported on the applicability of electrochemical measurements as EIS, LPR and PDP to monitoring corrosion of steel in large reinforced concrete beams. The tests and data interpretation took into consideration variable structural parameters as crack widths, crack frequency and load. The generally employed (both lab and field tests) OCP monitoring can only serve as an indication of corrosion initiation and propagation and even in this case, the contribution of cracks, oxygen and humidity levels respectively, need to be taken into account to avoid misinterpretation. Next to that, a meaningful and reliable electrochemical measurement can be only obtained when equal environmental conditions are at hand, especially for the “spot” method. Even then, knowledge on bulk matrix properties is very important in order to account for observed fluctuations or discrepancies in response. To that end, EIS is a very useful technique, providing information for the whole system as a global and at different (desired) levels. Being, however, a more sophisticated approach, continuous EIS measurements are possibly not entirely applicable for large test setups. LPR tests provide meaningful results, however additional measurements (at
start, middle and end time intervals) as EIS and PDP will increase the level of reliability of the LPR tests. In all cases, trends in observed behavior and response are more accurate to be presented and discussed, rather than absolute values, especially when only one technique is employed for corrosion monitoring.

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6 References


