AUTOMATIC DEGRADATION DETECTION DURING A DYNAMIC LOADED BEAM TEST

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ABSTRACT

The remaining service life of concrete structures strongly depends on the corrosion level of the reinforcement bars. It explains that measuring the corrosion rate is a key issue in monitoring the structural health of concrete structures. A common and appropriate technique used to evaluate the instantaneous corrosion rate of steel reinforcement is by Linear Polarization Resistance (LPR). A dynamic loaded, four-point-bending test on a reinforced concrete (RC) beam was developed to measure dynamic responses and stiffness changes due to corrosion. The test setup can load two beams with a comparable structural behaviour simultaneously, while exposed to the same ambient conditions. To expedite corrosion in one of the beams, a water-chloride solution bath was mounted on top of it. As a reference, a tap water bath was placed on top of the other beam. A wetting cycle of two days wet and five days dry was carried out to simulate real-time situations and to accelerate the corrosion process. During this test, the responses of both beams were measured by Linear Variable Differential Transformers (LVDTs) and results were filed automatically. Furthermore, the corrosion rates of both RC beams were automatically measured by LPR every day. The results of these measurements show differences in corrosion rate between both beams with time. After beam failure, brief forensic engineering was executed to analyse the corrosion of the reinforcement bars. Visual observations show a good correlation with the corrosion behaviour measured by the LPR method.

Keywords: Corrosion, Chemical degradation, Dynamic load, Linear Polarization Resistance, Structural Health Monitoring

INTRODUCTION

Structural health monitoring (SHM) systems provides information about the health, safety and remaining service-life of infrastructures. Corrosion of steel reinforcement is one of the most important durability issues on reinforced concrete (RC) structures. For this reason, corrosion measurements can be a key-element in SHM systems. However, corrosion sensors do not provide information automatically and are no common tools in SHM systems.
There are several ways to measure corrosion in RC structures. Most reliable methods are destructive, in which the corroded reinforcement will be compared with the original reinforcement. Differences are assumed to be caused by corrosion activity. Since these destructive measurement techniques cannot be used in real-time monitoring of structures, non-destructive methods are the only possibility to measure the actual performance of structures. Only two of these methods, the Half-cell Potential (HCP) method and the Linear Polarisation Resistance (LPR) method, are commercially used and available in practice. However, these methods need to be controlled and operated manually to provide information about the corrosion location and corrosion rate. Therefore, in order to gain more insight in the possibilities of automatic measuring of degradation processes, a lab-scale experimental setup has been developed, which will be discussed in more detail in this paper. Emphasis is on the automatic detection of the global corrosion data measured by HCP and LPR. Furthermore, some forensic engineering was executed to check the automatic HCP and LPR measurements and its correlation with the deterioration of the specimens.

EXPERIMENT PROGRAMME

Concrete specimens
A lab experiment was developed to better understand the impact of corrosion on the structural response of a dynamically loaded RC beam. The beam design and embedded instrumentation necessary to measure the electrical properties with the HCP or LPR method were taken similar to the original work of Blagojevic [1]. Four beams with comparable dimensions (Table 1) and similar reinforcement (Table 2) were cast in one go and hardened under the same climate conditions, which make the test results of the beams comparable. One of the beams is used to determine the static failure load. Two other beams are used for the dynamically loaded four–point-bending test. The last beam is just used as a backup beam.

After 28 days of hardening (3 days moulded, 18 days in a fog room with RH=100% and T=20 ºC, and 7 days in a climate room with RH=50% and T=20 ºC), the compressive strength and the tensile splitting strength are tested using three specimens for both compression and tension tests. The results can be found in Table 3.

<table>
<thead>
<tr>
<th>Length</th>
<th>Height</th>
<th>Width</th>
<th>Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500 mm</td>
<td>150 mm</td>
<td>100 mm</td>
<td>30 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Steel quality</th>
<th>Yield stress</th>
<th>Modulus of Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 mm</td>
<td>FEB 500</td>
<td>500 N mm⁻²</td>
<td>200000 N mm⁻²</td>
</tr>
<tr>
<td></td>
<td>HKN</td>
<td></td>
<td></td>
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</tbody>
</table>
Table 3 – Concrete material properties

<table>
<thead>
<tr>
<th>Compressive strength</th>
<th>Tensile splitting strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$: 35.4 N mm$^{-2}$</td>
<td>$\sigma$: 0.21 N mm$^{-2}$</td>
</tr>
<tr>
<td>$\mu$: 2.92 N mm$^{-2}$</td>
<td>$\sigma$: 0.17 N mm$^{-2}$</td>
</tr>
</tbody>
</table>

Setup frame
The beams are tested up-side-down, which means that the rebar is positioned at the top side of the cross-section and that the load will be applied at the bottom side of the specimen, acting in upward direction. A ridged steel frame was used for the experimental setup with an oil-pressure cylinder to apply the dynamic force and a pressure cell to measure it, and both are situated in line with the beams (Figure 1). The gap between the pressure cell and the top support of the setup is large enough to install the two RC beams on top of each other, separated with a steel beam (Figure 1). The setup was also used for testing the static failure load of the beam. In this case, one beam and the steel supporting beam were replaced by an additional steel support spacer. The deformations of the beam are measured with LVDT gauges and the whole experimental setup is controlled automatically using an Instron controller and a PC with control software.

Figure 1 – Experimental setup

The failure load of the two dynamically loaded beams was assumed to be similar to the one that was tested statically in a deflection controlled four-point-bending mode. The result was used as reference for the calculation of the dynamic load of the experiment.

Traffic loads on real time bridges have a dynamic nature, and are randomly distributed. During the design of a bridge, in general, a safety factor is used to calculate the dimensions and structural properties, which also includes the load distribution. Similar perception was performed to calculate the load for the beam test, in which the load distribution was calculated as function of the failure condition. A dynamic impact of 70% of the failure load and a frequency of 0.5 Hz was chosen for this experiment.

First, the beams were loaded statically up to 70% of the failure load, to initiate cracks. This is done to avoid instabilities in the control system during hook-up of the system.
Similarities with “real life” situations can be visualized by for instance a heavy asphalt truck, which drives slowly over the bridge before first use.

After that, the beams are loaded dynamically. On one of the beams, a bath with a 10% chloride-water solution was mounted on top to initiate corrosion. On the other beam, which is used as reference, a bath with tap water was applied on top. Since a cyclic drying-wetting condition was identified as the most feasible environmental condition for RC structures [2], a wetting–drying cycle of two days wet and five days dry was used during this experiment. According to the measurements, which will be discussed later, the five days drying period turned out to be enough to restore potential equilibrium.

After failure of the chloride-affected beam, the reinforcement bar (rebar) was removed from the concrete matrix for forensic analysis and to investigate the corrosion visually. It was observed that the rebar was locally corroded at every spot of crack occurrence. Some corrosion activity was also predicted by the automatic potential measurements.

MEASURING METHODS

Different methods can be applied to measure the actual corrosion activity of an embedded rebar. One of the most basic methods is a destructive measuring method where the corroded rebars have to be removed from the RC structure in order to be investigated. The mass difference between the corroded rebar and the original rebar can be used to identify the corrosion rate [3]. Although this method will result in proper corrosion rate values, destructive measuring techniques will always weaken the structure and can, therefore, not be used for real time infrastructure monitoring. A better solution would be to apply a non-destructive corrosion activity method that provides actual information about the corrosion rate of the structure while in service. In the past, many researchers have investigated non-destructive methods for in-service conditions [4]. At present, six non-destructive methods could be identified. These methods are: Galvonostatic Pulse Method, Time Domain reflectometry, Ultrasonic Guided Waves, X-ray Diffraction and Atomic Absorption, Half-cell Potention, and Linear Polarization Resistance [5]. Only the last two methods are commonly used and commercially available [6]. The principle of these methods is briefly discussed in this section.

Half-cell potential (HCP)

The principle of the HCP method is to measure the voltage potential, which is present around rebars in RC structures. The theory of this method is to embed a reference electrode close to the rebar and to measure the voltage difference between the rebar and the reference electrode due to the concrete around the rebar. The measured potential difference indicates if there is presence of corrosion activity. However, the potential difference depends also on type of reference, concrete material properties, and moisture condition. In dry conditions, there is a 10% corrosion probability at a potential measurement of -200 mV, while there is a 90% corrosion probability at a potential measurement at -350 mV [6]. Since the bandwidth is quite high, HCP might result in incorrect conclusions. Furthermore, HCP gives no information about the corrosion level.
**Linear Polarisation Resistance (LPR)**

LPR provides a relation between the voltage potential and the electric current density of the concrete matrix. In LPR measurements, the potential decreases with a constant (normally 5-20 mV). After several minutes stabilization, a constant is added to this rebar potential [7]. A too short stationary period could lead to significant measurement errors. The polarization resistance is the first derivative of the electric current intensity to the potential at I=0. For LPR measurements, some reference electrodes need to be connected to the beam and the rebar. Real bridges, therefore, need to be damaged locally to connect these electrodes [8].

Electrical resistance depends on many properties, such as corrosion state of the rebar, concrete cover, concrete resistivity, rebar diameter, and counter electrode diameter. Measurements are affected by temperature and humidity as well. Because of all these dependencies, LPR does not result in corrosion constants. The measurements should be considered accurate within a factor of two [8]; however, the beams, used in this experiment, were cast and loaded under the same conditions, which means that the differences between the resistance of both beams should be limited.

Corrosion can be considered as an electric circuit, in which lower electrical resistance electrodes can move more freely and corrosion can develop in a shorter time period [4]. The resistance provides information about the corrosion rate; if the resistance is low, free electrodes can move easily and the corrosion rate is higher [9].

The electrical resistance (Rp) can be used to indicate the current variation using Equation 1 [10].

\[
I_t := \frac{\Delta E}{R_e (R_e + R_p)} \left[ R_e + R_p \exp \left[ -t \frac{C R_e R_p}{R_e + R_p} \right] \right] 
\]

(Equation 1)

The voltage sweet rate with time can be calculated by Equation 2 [10].

\[
\frac{dI}{dt} = \frac{k}{R_e + R_p} + \frac{R_p k}{R_e (R_e + R_p)} \exp \left[ -t \frac{C R_e R_p}{R_e + R_p} \right] 
\]

(Equation 2)

A major limitation of LPR is that, while it gives a reasonable estimation of the corrosion rate at the time of measurement, it gives no indication about the amount of steel that is already corroded [11].

**AUTOMATIC LINEAR POLARIZATION RESISTANCE**

To measure corrosion in the RC beam by HCP or LPR, some internal electrodes are needed. The working principle of the applied beam layout with the electrodes was already investigated by Blagojevic [1]. In this, the electrodes are preinstalled in the beam formwork before casting. Besides this, the rebar is also connected with an electrical wire and operates as a working electrode. Furthermore a Pt/Ti reference electrode is connected
to the rebar as well. As counter electrode, a titanium mesh was immersed in the liquid concrete during casting, 20 mm from the surface.

The electrodes were connected to a computer using an analog-to-digital converter (ADC). This ADC converts the measured potentials into digital signals and prepares the potentials for computer input. The potential between the working electrode (rebar) and the reference electrode (Pt/Ti electrode), called U₁, as well as the potential between the working electrode (rebar) and the counter electrode (titanium mesh), called U₂, were measured automatically with a frequency of 100 Hz. Since the corrosion data does not change that much, the average data was stored every minute.

Measuring U₁ provides information about the average potential losses around the rebar (global HCP), which represents a global indication of the corrosion activity. The actual location where the corrosion happens cannot be measured with this method. By measuring over time, some fluctuations can be observed, e.g. differences caused by changing the moisture content in the beam. In additional, the changes in the potential can be used to detect differences in the properties, which indicate a probability of corrosion. An absolute level of corrosion cannot be quantified by this method.

For measuring the actual electrical resistance, the potential of U₂ was lowered by 20 mV, followed by ten minutes of stabilization. The potential was then increased by small steps (0.15 mV per second) until U₂ + 10 mV. The potential U₂ and the electric current intensity (I) were then measured with a frequency of 100 Hz and recorded with a frequency of 2 Hz. Since the potential in the beam was disturbed by the LPR measurement, this potential could not be monitored with a high frequency. Therefore, the LPR measurement was conducted once a day, and generating as such an average electrical resistance flow with time. Besides this, it is still part of discussion whether LPR could also accelerate corrosion due to the input of free electrons. This was also one of the reasons that the number of measurements was limited to one per day. The validity of this principle is also part of this research project.

**RESULTS**

During hook-up of the experimental setup the LPR sensors were tested on their performance. It turned out that some sensors showed initially irregularities in their readings and had to be reinstalled and recalibrated. This incorrect data was removed from the file which is the reason for the gaps that show up in the figures presented in this section.

**Half-Cell Potential (HCP)**

During the testing phase of the potentials sensors, measurements were repeated every hour. When the results showed a stable repetitive pattern, the time between two measurements was slowly increased to twenty-four hours. The data show that the potentials of both beams were not equal, but did had the same shape, which corresponds well with the expectation [8]. In addition, the data also show that the potential needed time to stabilize during the initial testing phase. From the data recorded during this testing period, it was observed that
stabilization of the potential in the concrete specimens, after starting the recording of the electrical resistance, takes approximately four to six hours. Because of this instability of the potential, the measurements during the initial testing phase are not representative and are omitted in further analysis. The potentials of both beams during the testing phase are shown in Figure 2.

![Figure 2 – Potential of RC beams over time. Beam 2 will be affected by chloride-solution; Beam 1 is the reference beam.](image)

After one week of dynamic loading under dry conditions, the beams were wetted with both tap water and a chloride-water solution. Beam 1 was wetted with tap water to act as a reference, and Beam 2 was wetted with a chloride-water solution to generate corrosion. After the first time wetting, leakage was observed caused by the connection between the plastic bath strips and concrete surface. To prevent this leakage, the water was removed, some tiny gaps were closed, and the beams were wetted again, which happened within twenty-four hours. After two days of wet and dynamic loading, the water was removed and beams could dry. Within one week after first wetting, Beam 2 broke and a second wetting cycle could not be conducted.

Figure 3 shows the measured potential of the beams over the loading time. After first wetting (± 280 hrs), the potentials of both beams show a strong decline. The potential of Beam 2 dropped below the critical value (-350 mV, [6]), which indicates a probability of corrosion of over 90%. In addition, data observations show also that it took three days before the potential of the beam was re-stabilized under dry conditions. A second point of attention is the gap in the data between 170 hours and 266 hours. During this period, the experiment was stopped because of loss of oil pressure, caused by technical problems. This means that the data in this period was not recorded.
Linear Polarization Resistance (LPR)
The electrical resistance was automatically measured every twenty-four hours. Since these measurements are independent of the deflections and the oil pressure, there are no gaps in the data. During the testing phase, the resistance was measured more frequently. As discussed before, the potentials of these measurements were not reliable. The data of the testing period was, therefore, neglected from the data file. Figure 4 shows the LPR measurements for twelve days of testing. Interesting observations from Figure 4 are the resistance drop between 278 and 326 hours, and the stabilization after 326 hours. This decreased resistance was caused by wetting of the beams. This observation was also noticed from the potential measurements. After re-stabilization, in dry conditions, the resistance of Beam 1 was larger than that of Beam 2, which indicates a higher corrosion rate in Beam 2 compared with Beam 1. These observations correspond to the expectations.

Forensic engineering
After 480,000 loading cycles and 425 hours of testing, the rebar of the chloride-affected beam broke without showing any clear warnings before. It was discovered that the main cause of failure was fatigue. However, Beam 1 had more cracks, more deflection and, had, therefore, the highest probability for fatigue failure. Furthermore, some corrosion was observed at the cracking surface (see Figure 5). This means also that some corrosion was decreasing the strength of the structure.
Figure 4 – Electrical resistance of RC beams over time. Beam 1 was wetted with tap water and Beam 2 with chloride-water solution.

Figure 5 – The RC beam directly after failure. Some corrosion can be observed on the rebar.

After failure, the beams were demolished and the rebars were checked for corrosion. By reading the HCP and LPR measurement data, some corrosion was expected. It was discovered that the rebar of Beam 2 showed local corrosion at every crack. In addition to that, Beam 1 showed a limited amount of corrosion as well. However, the amount of corrosion in Beam 1 was less than in Beam 2, which was also predicted by the measurements. The corrosion observations are shown in Figure 6.
The hypothesis that corrosion fatigue was the reason for failure was analysed by examining the rebar-crack interface under microscope. It could be confirmed that fatigue and corrosion were both contributing to the cause of beam failure. Both corrosion as well as micro-cracks are observed by microscopic analysis (see Figure 7).

**CONCLUSION**

Half-cell Potential (HCP) and Linear Polarization Resistance (LPR) were automatically measured during a dynamic four-point-bending test with two reinforced concrete (RC) beams. Automatic measurements are necessary to understand the development with time, which is valuable in structural health monitoring.
The experiment started with testing the setup and the sensors. When the setup was stable and the sensors were tested, the beams were loaded dynamically and under dry conditions. During this period, the potential and the electric resistance were stable. Furthermore, the differences between both beams were small. The beams were wetted for two days. One beam was wetted with tap water and the other with chloride-water solution. This wetting had a direct influence on both corrosion measurements. The potential and the electrical resistance stabilized within three days after wetting. At the end of the experiment, one beam failed and both beams were demolished for investigating the rebars. The broken bar, which came from the chloride-affected beam specimen, showed partial corrosion on every crack location. Failure was, therefore, expected to be caused by mainly fatigue and partially corrosion. Furthermore, at the tap-water affected beam, a very limited amount of corrosion was observed. Visual observations also showed good agreement with the results of the automatic corrosion measurements. Although further research is necessary to confirm the applicability of automatic HCP and LPR sensors for real time corrosion monitoring, the results of this paper show that they might be valid indicators for Structural Health Monitoring systems.

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REFERENCES