MODELLING OF REINFORCEMENT CORROSION
- MACRO CELLS AND TIME DEPENDENCE –

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Abstract

As part of the joint research group DFG - FOR 537 “Modelling of reinforcement corrosion” /1/ this subproject investigates macro cell formation with a main emphasis on geometrical influences. Another important aspect that will be investigated within the next years is the time dependence of the anodic activity and the macro cell current. Hence, this subproject provides key data for the final design model. The investigations on macro cells were carried out by laboratory experiments and additionally by numerical analyses to increase the available database especially with respect to geometrical influences. Chloride induced corrosion of real structures, however, is influenced by many time-dependent factors, e.g. the temperature and the polarisation behaviour of depassivated reinforcement. In order to implement the time dependence in the probabilistic design model, extensive laboratory tests on about 120 macro cell corrosion specimens are being carried out. During a time span of two years, electrochemical measurements and visual inspections are conducted on the test specimens to investigate especially the time-dependent behaviour of the anodically acting parts. The determination of the characteristic corrosion patterns and metal removal of the anodic areas are achieved with a unique 3-D optical technique using high-resolution digital cameras.

1 INTRODUCTION

The objective of this work is to investigate the influence of geometric effects as well as the time dependent behaviour of chloride induced macro cell corrosion processes of steel in concrete. The corrosion process – especially in the case of macro cell formation – is influenced by a variety of factors which have to be considered to develop a design model for the remaining lifetime after depassivation. When modelling macro cell corrosion a major problem is posed by different geometrical arrangements of diverse structural members like beams or slabs. Furthermore a structure can be affected by chloride attack in different manners, e.g. as a result of local damage to surface coatings or a local exposure to splash water, leading to different arrangements of active and passive areas on the reinforcement bars.
As it is almost impossible to cover this wide range of geometrical varieties by a laboratory test programme a different approach was chosen described in the following:

Recent research results show (/2/, /4/) that macro element formation in concrete members can be successfully investigated by applying numerical methods. One advantage of this approach is the possibility of substituting laboratory experiments with computer simulations to study the effects of diversified boundary conditions.

A numerical simulation allows the study of galvanic systems under constant steady-state conditions. Additionally the time dependence of the corrosion process needs to be considered for a damage model. In particular the anodic polarisation behaviour is time-dependent because corrosion pits at the surface of depassivated steel bars can change their quantity and size. New pits can occur and existing pits can repassivate. In terms of a time-dependent damage model these issues will be investigated in a comprehensive experimental test programme.

2 SIMULATION OF POTENTIAL DISTRIBUTIONS AND CORROSION CURRENTS

2.1 General

In the first phase of this project a variety of laboratory test specimens consisting of simple beam-like structures, slab-like specimens and girder structures with complex reinforcement arrangements were produced. Subsequently numerical simulations were carried out with a boundary element programme called BEASY CP, which is capable of solving the Laplace-equation and Ohms law inside an electrolyte and applying the following boundary conditions to describe the polarisation behaviour of the metal electrodes /3/.

- constant potential
- constant current density
- linear or non-linear relation between current density and potential (polarisation curves)

2.2 Assumptions

Two basic input parameters are necessary. First of all the concrete resistivity was taken from sensor readings. Secondly appropriate polarisation curves for both electrodes, anodes and cathodes, must be considered. For the cathodically acting reinforcement the polarisation curve was assumed to obey the Butler-Volmer equation.

The anodically acting reinforcement was considered by using an integral polarisation resistance $R_a$. This linearization is a simplifying assumption and it has to be checked whether it leads to reasonable results.

The necessary parameters (Tafel-slope, anodic polarisation resistance, etc.) were calculated by regression analyses from Instant Off measurements.

2.3 Results

2.3.1 Potential distributions

As one result the potential distribution can be visualised for all geometrical arrangements. The symmetry of the specimens was considered in the simulations. A detailed description of the conducted tests can be found in /5/.
2.3.2 Macro cell current

For an estimation of corrosion rates and the remaining lifetime the macro cell current is of main concern.

In order to validate the results of the simulations they were compared to values obtained from laboratory test specimens with known boundary conditions. The difference between simulated and measured macro cell currents is in most cases less than +/- 10 %, indicating that the galvanic systems were simulated correctly by use of the selected assumptions. Detailed information about these simulations can be found in /5/.

3 PARAMETER STUDY

Based on these results appears to be possible to study macro cells under different boundary conditions to derive necessary parameters for the engineering model of the research group, see /1/. In the following a brief example for the slab-like geometries is presented.

To develop models the boundary conditions have to be varied within a practical range. In order to investigate the influence of important parameters like driving voltage, resistivity or cathode to anode surface area ratio a parameter study with the values given in Table 1 was carried out.

Resistivities between 100 and 500 Ωm represent wet concrete structures, e.g. in marine environments, values above 10,000 Ωm usually occur in dry concrete members. The given cathode to anode surface area ratios were calculated by taking typical reinforcement amounts into account which occur under practical conditions.

Table 1: Parameter variations

<table>
<thead>
<tr>
<th>Geometry</th>
<th>SP</th>
<th>SL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity [Ωm]</td>
<td>100, 500, 1000, 10000</td>
<td></td>
</tr>
<tr>
<td>Driving voltage [V]</td>
<td>0.3, 0.4, 0.5</td>
<td></td>
</tr>
<tr>
<td>Cathode/anode surface area ratios</td>
<td>53:1, 96:1, 192:1, 18:1, 36:1, 54:1</td>
<td></td>
</tr>
<tr>
<td>Anodic polarisation resistance [Ωm²]</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

The cathodic polarisation curve for all calculations was assumed to obey the Butler-Volmer-equation. The constant anodic polarisation resistance of $R_a = 2$ Ωm² corresponds to the measured mean value of all OPC specimens.
3.1 Results

During the parameter study the effects of the various parameters on corrosion currents, anode to cathode ratios and cell factors of the corrosion system were investigated.

3.1.1 Influence of the concrete resistivity

For the case of the slab-like geometries the macro cell current as a function of the concrete resistivity (log scale) for different driving voltages is shown in Figure 3.

![Figure 3: Current vs. concrete resistivity](image)

As expected the results show a strong influence of the concrete resistivity on the macro cell current, because beyond a resistivity of 1000 $\Omega$ m the current decreases significantly. This corresponds to common knowledge. However, it has to be noted that no other limiting factors (e.g. limiting oxygen diffusion) were considered. Further results of these studies can be found in /5/.

4 TIME DEPENDENCE

4.1 General

As mentioned above it is possible to investigate macro cell formation in concrete members by laboratory experiments and coupled with numerical analyses for steady-state conditions, but in terms of a lifetime assessment the time-dependent changes of a galvanic system must be considered. On the basis of models for the time dependent corrosion current $i_{\text{corr}}(t)$ and depth of the corrosion damage $x_{\text{corr}}(t)$ the primary objective of this test series consists of the investigation of the time-dependent system parameters of the working hypothesis shown below under selected boundary conditions:

$$i_{\text{corr}}(t) = \frac{U(t)}{r_a(t) + \frac{r_c(t)}{A_a(t)} + k_a \rho_x(t)} + i_{\text{self}}(t)$$  \hspace{1cm} (1)

and

$$x_{\text{corr}}(t) = \alpha(t) \frac{11.6}{A_a(t)} i_{\text{corr}}(t)$$ \hspace{1cm} (2)
Where: $i_{\text{corr}}$ = corrosion current, $U(t)$ = driving voltage, $r_x(t)$ = anodic and cathodic polarization resistances with respect to the electrode surface, $A_x(t)$ = electrode area anodes and cathodes, $k_e$ = cell constant, $\rho_e(t)$ = electrolytic resistivity, $x_{\text{corr}}(t)$ = uniform loss of cross section due to corrosion, $\alpha(t)$ = pitting factor relating localized damages to $x_{\text{corr}}$.

In order to achieve this goal an extensive laboratory test series was initiated in 2008 where the influence of selected parameters such as temperature, cement type, water application and chloride content on the above mentioned parameters will be investigated.

Due to the probabilistic approach of the design models of the research group the number of test specimens was chosen to allow for statistical analyses of the respective model parameter. In this way the dependency of these parameters on the various boundary conditions will be quantified and subsequently integrated into the design model.

4.2 Working programme

The work programme reads as follows:

- continuous and periodical survey of relevant corrosion parameters by means of electrochemical investigation methods
- destructive investigation of test specimens after selected time intervals with subsequent analysis of corrosion damage in the anodic areas of the corrosion cells as well as supplementary determination of relevant parameters such as the total chloride content

4.3 Test specimens and test series

All in all 8 different laboratory test series will be conducted, which will allow for a detailed investigation of the time dependent macro cell action under selected boundary conditions. For each series, up to 18 macro cell test specimens were prepared resulting in a total number of about 120 specimens, see Figure 4. The parameters for the working hypothesis shall hereby be quantified statistically which is crucial for the establishment of a full probabilistic corrosion model.
In order to create immediate macro cell corrosion activity the concrete surrounding the anode
contains 3% chlorides with respect to the cement mass. The high chloride content was chosen
to ensure depassivation in order to investigate the time-dependent development of the macro
cell corrosion process within the given project schedule (i.e. 2 years). All electrochemical
tests will be conducted using a MnO\textsubscript{2}-reference electrode which is embedded in each test
specimen. For the set-up a minimum ratio between cathodic (K) and “anodic” surface (A)
areas of 45:1 is provided by the arrangement shown in Figure 4, left. Due to the fact that
chloride induced corrosion is a rather local phenomenon, the ratio between the cathodic
surface area and the actively corroding anodic surface areas will be far higher, which should
be demonstrated by means of a post-test surface analyses of the anodic bar. In order to avoid
any edge effects, the lateral surfaces of the test specimens are coated with an epoxy resin.

In defined time intervals (i.e. 12, 18 and 24 month) between 3 and 6 test specimens of each
series will be investigated in a destructive manner and the results will be analysed taking into
account the typical scatter of corrosion test results of steel in concrete.

4.4 Methodology
To gather all necessary information in order to describe the time dependent behaviour of the
respective parameters of the working hypothesis the following methodology will be used, see
Figure 5.

As described above the laboratory investigations can be divided in two main parts:
electrochemical measurements and destructive investigations which will be explained briefly
in the following.

4.4.1 Electrochemical measurements
The time dependent electrochemical characteristics of the macro cell corrosion system are
being analyzed by constantly recording the corrosion currents and closed circuit - potentials of
anodically and cathodically acting members of the corrosion cell, see Figure 6, left.
By integrating the measured currents the steel removal $\Delta m_a$ of each anode will be determined by means of Faraday’s Law. In this way a statistical quantification of this parameter will be possible at any given stage during the test phase.

Furthermore so called “instant-off” measurements with a subsequent quantification of the rest potentials of anode and cathode will be conducted on each specimen, see column 4, Figure 5. Through this important information about the driving voltages $\Delta E(t)$ and a so called specific “integral” polarization resistance of anodes ($r_a(t)$) and cathodes ($r_c(t)$) can be quantified. A detailed description of the techniques used will be published soon.

On selected specimens the polarization resistances will be quantified in both the “on” and “off” phase of the test in order to find out about the relationship between these parameters. As described up to 6 test specimens will be analysed destructively by dismounting the anodes carefully. After a first optical characterization of the corrosion damage the gravimetric mass loss of each anode will be determined and compared to the calculated mass loss based on the macro cell current measurements. In this way the mass loss due to micro cell corrosion will be quantified in order to find out about the proportion of this corrosion type on the total mass loss of the respective corrosion system.

4.4.2 3D surface analyses

A detailed surface analysis of the dismounted anode bars will be achieved by means of a high resolution 3-D camera technology. The images of the scanned anode surface will then be analysed using suitable software packages with respect to pit distribution and pit depths, see Figure 7. By using this technique the actually corroding surface areas will be detected and hence corrosion damage categories will be established. Comparative studies between the analysed damage types and electrochemical characteristics such as the specific polarization resistance will be conducted in order to establish possible correlations.
Figure 7: 3D optical scan of a steel surface damaged due to pitting corrosion (left), software based analysis of pit distribution and depths (middle and right)

5 CONCLUSIONS

To investigate macro cell formation in concrete members, laboratory tests and numerical simulations were carried out. The results show a strong impact of the concrete resistivity and thereby of the moisture content on the resulting macro cell current. Further more the geometrical arrangement of anodes and cathodes including the cathode/anode-ratio are also decisive parameters. The numerical model will serve as a validation for the results of the probabilistic corrosion model of the research group.

Further investigations into the macro cell action of steel in concrete with respect to different boundary conditions will be conducted by means of electrochemical and destructive testing methods. The time dependent data will be used to develop engineering models for the active corrosion stage of steel in concrete. A unique 3-D surface scanning method will be to examine actively corroding areas and characteristic corrosion damage types resulting from the chosen experimental conditions. By evaluating the data sets the time dependent behaviour of anodic regions in the case of the chloride induced macro cell corrosion of steel in concrete will be described.

6 REFERENCES

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