EFFECT OF CORROSION ON THE FATIGUE SERVICE-LIFE ON
STEEL AND REINFORCED CONCRETE BEAMS

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Abstract

Chloride-induced corrosion is a point of big concern in reinforced concrete (RC) structures. To monitor the actual health and to predict the remaining service-life of structures, it is important to understand the structural behaviour and the failure mechanism of structures exposed to chlorides under fatigue loading conditions. A beam test, whereby two RC beam are loaded dynamically, was developed to investigate the behaviour of a RC structure between first loading and structural failure. A parallel rebar test, whereby a plain rebar is loaded dynamically, was performed to focus on the behaviour of a plain rebar in a chloride environment. The results of both tests show that corrosion reduces the maximum number of iterations until failure. Deflections of the beams and elongations of the rebars show a significant increase close to failure. A finite element model is developed to simulate the impact of corrosion on the structural performance of a plain rebar. Preliminary calculation results show high local stresses close to the damaged interfaces. These high stresses result in local fatigue damage, which can initiate global failure of the structure.

Keywords: Chemical reaction, concrete beam, corrosion, dynamic tests, fatigue service-life, reinforcement steel bars

1 Introduction

Structural damage of reinforced concrete (RC) structures is increasing over the past decades. One of the key-elements of structural damage is corrosion of the reinforcing bar (rebar), which is often initiated by carbonation or chloride ingress. While carbonation is a global attack and cause overall corrosion of the steel reinforcement, chlorides can penetrate easily through the cracks and can cause localized corrosion of the rebar (Apostolopoulos, Demis & Papadakis 2013). This local damage could weaken the structure significantly and might cause structural failure.

Real structures in non-aggressive environment conditions are barely exposed to chlorides in the summer period. However, due to deposition of de-icing salts in winter times, these structures are also exposed to a chloride-environment. These different exposure conditions should be taken into account when analysing the condition of a structure. The upper reinforcement at the supports of multiple span bridges is decisive for the flexural bearing capacity. Since the upper reinforcement suffers most from chloride penetration, this research is focused on this reinforcement.

Over the past fifty years, traffic has increased significantly in both weight and intensity. This increase results in higher stress amplitudes and more loading cycles, which reduces the expected service-life. Localized corrosion combined with repeating load cycles might result in a dangerous situation. However, the knowledge about the failure mechanism of localized corrosion and its structural behaviour under dynamic load is limited.

For better understanding the impact of chloride-induced corrosion in loaded RC structures, a test-setup was developed whereby two lab-scale beams were loaded dynamically. The beams were exposed to different environments. One beam was exposed to a chloride-water solution to accelerate corrosion, while the second beam was exposed to tap water and acts as a reference (Veerman 2014). In addition to the beam-tests, dynamically loaded tensile tests were performed on plain rebars. Furthermore, a finite element model (FEM) is developed to analyse the stress-distribution of plain rebars under different exposure conditions.
2 Reinforced concrete beam test

To generate hogging moments during the tests, the beams were loaded up-side-down, whereby bending cracks develop in the top-side of the beam (Fig. 1). The beams were reinforced with one rebar (diameter 12 mm) to investigate the impact of corrosion of the performance of a single rebar on a RC beam.

![Fig. 1 Setup of the beam-test. Fig 1A is an illustration of the setup, Fig 1B shows the real test.](image)

### 2.1 Loading and exposure

The performed four-point-bending-tests consist of two beams (100x150x1500 mm$^3$). Both beams were casted at the same time, were made of the same mixture, and were hardened under the same environmental conditions. The concrete compressive strength (35 MPa) was measured on three cubes (150x150x150 mm$^3$). The steel yielding strength (550 MPa) was determined in a direct tension test. These values were used to calculate the static load bearing capacity of the RC beam according to Eurocode 1992-1-1 (European_Committee_for_Standardization 2005). The results of these calculations are given in Table 1. The results show that the flexural bearing capacity of the beam is about the same as the shear bearing capacity. The average values of the concrete compression tests were used to calculate the load bearing capacity. Within the calculations, reduction factors for the load and material properties are not taken into account ($\gamma=1.0$). Without these reduction factors, the calculated bearing capacity might overestimate the actual load bearing capacity. (Table 1).

<table>
<thead>
<tr>
<th>Beam bearing capacity</th>
<th>Bending capacity (calculated)</th>
<th>Shear capacity (calculated)</th>
<th>Test result (shear)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M_{Rd} = 6.5$ kNm</td>
<td>$V_{Rd} = 12.4$ kN</td>
<td>$F_{max} = 24.3$ kN</td>
</tr>
<tr>
<td></td>
<td>$F_{max} = 27.4$ kN</td>
<td>$F_{max} = 26.8$ kN</td>
<td></td>
</tr>
</tbody>
</table>

It is hardly possible to perform high cycle fatigue tests with a maximum impact close to the static load bearing capacity. Crack control calculations in the Serviceability Limit State (SLS) allow stresses up to 70% of the failure calculation in the Ultimate Limit State (ULS). Two tests were performed with a load amplitude between 1.7 and 17.0 kN (70% of ultimate capacity). Three other tests were loaded between 2.0 and 12.0 kN (50% of ultimate capacity) (Table 2). Since the concrete beam is not prestressed, the steel stress can be calculated using Equation 1.

$$\sigma_S (SLS) = \frac{\sigma_S (ULS)}{F_{ULS}} = 550 \frac{F_{SLS}}{27.4}$$

### 2 Table 2

Loading properties of the beam-tests

<table>
<thead>
<tr>
<th>Test type</th>
<th>Min. Load</th>
<th>Max. Load</th>
<th>Stress average</th>
<th>Stress amplitude</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>1.7 kN</td>
<td>17.0 kN</td>
<td>188 MPa</td>
<td>307 MPa</td>
<td>0.50 Hz</td>
</tr>
<tr>
<td>Test 2</td>
<td>2.0 kN</td>
<td>12.0 kN</td>
<td>141 MPa</td>
<td>201 MPa</td>
<td>0.50 Hz</td>
</tr>
</tbody>
</table>
For wetting the beams, a bath was mounted on top of each beam. For two tests, the baths were made of PVC. For three other tests, the baths were made of rubber. Each test contained two beams, whereby corrosion was accelerated in one beam by filling its bath with a 10% chloride-solution. The bath of the second beam, which acted as a reference, was filled with tap water during the same period. To avoid leakage, vertical sides and the bottom side of the beams were covered with the same material as its bath. Different environmental conditions were created by wetting the beams for a period of two days, followed by five days of drying. Since corrosion is a slow process, a long testing period is necessary to generate a significant reduction of the load bearing capacity. Since materials are weakened by a repetition of loads and fails after a certain number of repetitions, the test period can be extended by applying a lower frequency. A loading frequency of 0.50 Hz (1 cycle per 2 seconds) was applied during all tests.

2.2 Failure

Up to now, five tests have been performed: two tests with a maximum load of 17 kN (70% of ultimate capacity), and three tests with a maximum load of 12 kN (50% of ultimate capacity). Since the beams were made without shear reinforcement, steel corrosion has only impact on the flexural strength of the beam. However, the shear capacity of a RC beam is more sensitive to variation of the concrete properties than the flexural capacity of a RC beam. Since these variations are not taken into account in the calculations, it is possible that the calculation overestimates the actual load bearing capacity. Both shear and bending failure mechanisms occurred during testing (Table 3). In addition, Table 3 contains the maximum number of cycles until failure of the beams. Fig. 2 shows the results of the tested beams.

Although the failure mechanism was not the same in all tests, it was always the chloride-exposed beam which failed first. After failure of the first beam, the second beam was tested loaded statically to measure the remaining load bearing capacity. It is clear that chloride-induced corrosion affects the failure mechanism. However, a quantitative assessment of the impact was not yet found.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Min. Load</th>
<th>Max. Load</th>
<th>Number of cycles</th>
<th>Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A chloride</td>
<td>1.7 kN</td>
<td>17.0 kN</td>
<td>478,000</td>
<td>Bending</td>
</tr>
<tr>
<td>1A tap water</td>
<td>1.7 kN</td>
<td>17.0 kN</td>
<td>478,000 *</td>
<td>-</td>
</tr>
<tr>
<td>1B chloride</td>
<td>1.7 kN</td>
<td>17.0 kN</td>
<td>6,300</td>
<td>Shear</td>
</tr>
<tr>
<td>1B tap water</td>
<td>1.7 kN</td>
<td>17.0 kN</td>
<td>6,300 *</td>
<td>Static</td>
</tr>
<tr>
<td>2A chloride</td>
<td>2.0 kN</td>
<td>12.0 kN</td>
<td>1,920,000</td>
<td>Bending</td>
</tr>
<tr>
<td>2A tap water</td>
<td>2.0 kN</td>
<td>12.0 kN</td>
<td>1,920,000 *</td>
<td>Static</td>
</tr>
<tr>
<td>2B chloride</td>
<td>2.0 kN</td>
<td>12.0 kN</td>
<td>655,000</td>
<td>Shear</td>
</tr>
<tr>
<td>2B both**</td>
<td>2.0 kN</td>
<td>12.0 kN</td>
<td>655,000 + 2,169,000</td>
<td>Bending</td>
</tr>
<tr>
<td>2C chloride</td>
<td>2.0 kN</td>
<td>12.0 kN</td>
<td>1,942,000</td>
<td>Bending</td>
</tr>
<tr>
<td>2C tap water</td>
<td>2.0 kN</td>
<td>12.0 kN</td>
<td>1,942,000 *</td>
<td>Shear</td>
</tr>
</tbody>
</table>

* Beam did not fail after this number of cycles.
** Due to shear failure of the chloride-affected beam, the exposure conditions of the remaining beam shifted from tap water into chloride-solution till the beam failed.
2.3 Deflection and crack width

Due to the test configuration, both tested beams bend upwards at mid-span and bend downwards at the beam ends. For all beams, the summation between upwards bending and the downwards bending was monitored during the test. Due to small imperfections in the test configuration, the beams might show differences in bending along the width of the beam. Therefore, the deflections were monitored at both sides of the beam and the average values of these measurements are used in this paper.

The deflections of test 2C under the maximum load (12 kN) are presented in Fig. 3, whereby the blue (upper) curve represents the deflections of the chloride-exposed beam and the red (lower) curve the deflections of the beam exposed to tap water. Both curves show fluctuations, which could be identified as effect of variation in the room temperature and ambient humidity, or to the wetting/drying cycles. The curve of the chloride-exposed beam shows a rapid increase of the deflection during the last 1,000 cycles before failure. Prior to this period, both curves show several periods wherein the deflection increases. However, during the last 250,000 cycles (1.69m – 1.94m) the deformation of the chloride-affected beam increases while the deflection of the beam exposed to tap water remains constant. This difference might be caused by corrosion of the rebar. However, it is also possible that the environmental conditions of the beams were different. Due to the fluctuation of the curves, it is hard to identify the increase during this last 250,000 cycles.

Beside the deflection, the width of several cracks were monitored. Fig. 4 shows the evaluation of crack widths with time. The curves in this figure represents the width of three cracks of the failed beam, whereby the blue (upper) curve is related to the crack at the location were the rebar broke. This curve shows a slight increase during almost the whole test period and a significant increase close to failure. The other curves, representing the width of two other cracks, show a more stable behaviour and do barely change with time.

Fig. 2 Relation between the stress and the maximum number of cycles until failure. All these results comes from the failed beams were exposed to chloride-water solution.

Fig. 3 Monitored deformation of the beams of test 2C against the number of cycles. The blue (upper) curve represents the chloride-affected beam (which failed). The red (lower) curve represents the tap water exposed beam.
3 Single rebar tension test

The beam tests provide a good impression of the structural behaviour of a RC beam. Although the mixture and the environmental conditions were similar for the different beams, the concrete material properties are not the same for each beam. To become familiar with the fluctuations in the material properties, multiple tests are necessary. Unfortunately, one single test requires one month of preparation and two months of loading. Therefore, the number of tests that can be performed in a reasonable time is limited. To investigate the behaviour of a plain rebar during the development of localized corrosion, a rebar test was developed and executed. The impact of different stress-amplitudes, different load frequencies, and different chloride-concentrations were investigated by repeating the test several times.

It was proposed that the corrosion development of the plain rebar in the rebar test was about the same to the corrosion development of the rebar in the beam test. Therefore, the total length of the chloride-exposed area of the rebar should be similar in both tests. The summed widths of all cracks of a single beam in the beam test was used as estimation for this length, which is approximately 2 mm. To avoid overall corrosion, the plain rebar was covered with a neoprene rubber coating. An uncoated section of 2 mm at the mid-section of the rebar (Fig. 5) was exposed to a chloride-water solution with a variable chloride-content (Section 3.1). Since the exposed areas are similar, the failure mechanisms of the bar should correspond to the flexural failure mechanism of the beam tests.
3.1 Testing properties

Eleven rebar-tests were executed. These tests contain different stress-amplitudes, different load frequencies, and different exposure conditions. Some of the amplitude-frequency-exposure combinations were repeated to enhance the reliability of the results. The load and exposure conditions are given in Table 4.

<table>
<thead>
<tr>
<th>Test</th>
<th>Stress average</th>
<th>Stress amplitude</th>
<th>Frequency</th>
<th>Exposure</th>
<th>Number of cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_40_2-5_0</td>
<td>125 MPa</td>
<td>20 MPa</td>
<td>2.5 Hz</td>
<td>Normal environment conditions</td>
<td>3,564,000 *</td>
</tr>
<tr>
<td>T_50_2-5_0</td>
<td>150 MPa</td>
<td>250 MPa</td>
<td>2.5 Hz</td>
<td>Normal environment conditions</td>
<td>1,694,000 *</td>
</tr>
<tr>
<td>T_50_2-5_05</td>
<td>150 MPa</td>
<td>250 MPa</td>
<td>2.5 Hz</td>
<td>5% NaCl</td>
<td>550,000</td>
</tr>
<tr>
<td>T_50_2-5_10</td>
<td>150 MPa</td>
<td>250 MPa</td>
<td>2.5 Hz</td>
<td>5% NaCl</td>
<td>559,000</td>
</tr>
<tr>
<td>T_50_2-5_10 B</td>
<td>150 MPa</td>
<td>250 MPa</td>
<td>10 Hz</td>
<td>10% NaCl</td>
<td>617,000</td>
</tr>
<tr>
<td>T_50_2-5_10 C</td>
<td>150 MPa</td>
<td>250 MPa</td>
<td>2.5 Hz</td>
<td>10% NaCl</td>
<td>741,000</td>
</tr>
<tr>
<td>T_60_2-5_10</td>
<td>175 MPa</td>
<td>300 MPa</td>
<td>2.5 Hz</td>
<td>10% NaCl</td>
<td>418,000</td>
</tr>
<tr>
<td>T_60_2-5_10 B</td>
<td>175 MPa</td>
<td>300 MPa</td>
<td>2.5 Hz</td>
<td>10% NaCl</td>
<td>318,000</td>
</tr>
</tbody>
</table>

* No failure

3.2 Failure

Since the rebars were not pre-damaged, rebar failure must have been initiated by loading and exposure during the test. The disadvantage of a tension test is that it is very difficult to grip the bars without introducing high local stresses which may cause premature failure (Tilly 1979). It is most likely that failure of a rebar occurs at the locations of these high local stresses, which occurred at some preliminary tests. However, in all tests where these additional stresses were limited, the bar failed at
the chloride-exposed section (Fig. 6). Therefore, it can be concluded that chloride-induced corrosion had a significant impact on the failure mode of the bar. In addition, the bars which are not exposed to a chloride-solution but to a non-aggressive environment (T_40_2-5_0; T_50_2-5_0) showed hardly any corrosion and could resist much more cycles than the locally corroded specimens (Fig. 7). It can be concluded from the performance of the bars under different exposure conditions that the number of load cycles until failure of the bars exposed to 5% chloride-water solution were similar to the bars exposed to 10% chloride-water solution.

![Fig. 7](image7.png)

Fig. 7 Relation between the stress and the maximum number of cycles until failure. All exposed rebars failed at the exposed location in the middle of the rebar.

### 3.3 Deformations

During the rebar test, the distance between both supports were monitored using LVDTs. By analysing the data, it should be taken into account that the data is related to the total length of the bar (420mm), but also to the transition length between the bar and the support and the stiffness of the setup.

Fig. 8 shows the additional elongation of the rebar with time over the total duration of test T_60_2-5_10 (stress amplitude: 300 MPa, load frequency: 2.5 Hz, chloride-exposure: 10%, see Table 4). The additional elongation is the difference between the measured elongation with time and the elongation of the first cycle. The presented elongations are related to the maximum applied stress (325 MPA). It can be observed that there is hardly any additional elongation of the rebar over the first 310,000 cycles. During the beam test, the deflection of the beam increased rapidly during the last 1,000 cycles until the rebar broke (Fig. 3). The axial length of the rebar shows a significant increase during the last 1,000 cycles of the rebar test (Fig. 9). Therefore, it can be concluded that the rebar in the beam test shows a similar behaviour as the bar in the rebar test.

![Fig. 8](image8.png)

Fig. 8 Additional elongation of the rebar during the rebar-test over the total loading period.
4 Finite element calculation

A finite element (FE) model is developed to understand the behaviour of a steel bar under applied test conditions. The numerical calculations were made by the Finite Element program DIANA, Displacement Analyser (tnodiana 2014), developed by TNO in the Netherlands (tnodiana 2014).

4.1 Calculation model

The tested rebars had a length of 420 mm and a diameter of 12 mm. This length was necessary to grip the bars, to observe the deformations and to manage the chloride-exposure. Since this length was not necessary for introducing and redistribution of the applied stresses, the length of the rebar in the FE model could be reduced. The FE model consists of tetrahedron (TE12L) volume elements (tnodiana 2014) with different dimensions (0.1-1.0 mm). To reduce the calculation time, only a small part i.e. 21 mm, of the rebar is modelled. Furthermore, it is assumed that the load and the damage is symmetrical around the rebar. With these assumptions, it is possible to model only a quarter (π/2 rad) of the rebar without influencing the calculation results.

The numerical model of the bar contains elements of approximately 1.0 mm. Localized corrosion damage was modelled by removing failed elements from the calculations (Fig. 10-C and 10-D). Preliminary linear calculations showed that 1.0 mm reduction of the bar radius would result in failure of the bar. Since the stresses in this area are highly important for calculating the local fatigue behaviour, the element size in this area was reduced to 0.1 mm. The potential damage section was divided in ten layers of 0.1 mm, which could be removed individually during the calculation procedure (Fig. 10-A).

The stress-strain relation of the rebar is modelled as bi-linear, with a Young’s modulus of 205,000 MPa and a yield stress of 500 MPa. Strength hardening and strain softening were not modelled in this preliminary calculation. Test measurements will be used to update the modelled material properties to the actual situation, which will result in more accurate calculation results.

It is difficult to avoid high local stresses by gripping the bar during testing. However, due to the length of the sample, these additional stresses do barely effect the stresses at mid-section. This results in mainly tensile stresses at the chloride-exposed section of the rebar. The model presented in this paper contains a single load case with tensile stresses of 325 MPa, corresponding to the maximum stress of test T_60_2-5_10 (Table 4, Fig. 8 and 9).
4.2 Calculation results

The results, presented in this paper, show the stresses in the rebar as a function of damage at the corroded section of the rebar. Fig. 11-A shows the Von Mises stresses (Mises 1913) in the undamaged rebar section. It can be concluded that the stresses are equally distributed over the cross-section of the rebar and are similar to the applied stress of 325 MPa. A damaged section of 0.3 mm (Fig. 11-B) increases local Von Mises stresses (Mises 1913) till the modelled yield stress (500 MPa) over a short distance. Heavier damage profiles (Fig. 11-C (0.6 mm) and 11-D (0.9 mm)) show larger strains and larger areas where yielding occurs. Due to the stress variation over the radius of the rebar, it is difficult to derive a single S-N curve.

Chloride-induced corrosion causes local damage. Once damage starts, the local stresses will be redistributed around the damaged section and cause high concentrated stresses (Fig. 11). These stresses result in additional local fatigue damage what can easily lead to failure without showing large deformations. This mechanism can be dangerous and is undesired.

Since the stresses of the damaged bar are unequally distributed along the radius of the bar, the corrosion-fatigue failure mechanism can only be calculated by analysing the stresses along the radius of the rebar separately. These stresses change when the corrosion depth increases. The total fatigue damage can be calculated using the formula of Minor (Ellyin 1997) (Equation 2) for every section separately, taking the different stress levels into account. When the corrosion degradation is limited, the stresses are equally distributed and fatigue degradation is limited. However, when corrosion degradation increases, peak stresses develop and fatigue degradation accelerates. In other words: if the corrosion damage increases, the fatigue degradation increases as well, and the total degradation increases significantly. This explains the rapid increase of the deflection of the beam (Fig. 3 and 4) and the increase of the axial length of the rebar during the last 1,000 cycles (Fig. 8 and 9).

\[
\sum \frac{n_i}{N_{f_i}} = 1
\]  

(2)
5 Conclusions

In this paper, the effect of corrosion damage in a RC beam was tested to gain more knowledge about the effect of chloride-induced corrosion on the failure mode of the beam. Up to now, five tests have been performed with two different load amplitudes. Each test contained one beam which was exposed to a chloride solution and a second beam which was exposed to tap water. In all cases, the chloride-affected beam failed first. During testing, the deflections of the beams were monitored. However, the deflection curves of the chloride-affected beams are similar to the deflection curves of the beams which were exposed to tap water. The main difference between the generated data is the rapid increase of deformation during the last 1,000 cycles of the chloride-affected beam.

A second set of experiments was developed to investigate the effect of corrosion on a plain rebar. Eleven tests were performed, in which the stress amplitude and the chloride-content were applied as variable. It can be concluded from all performed tests that chloride-exposure has a major impact on the service-life. However, it could also be concluded from the tests that the maximum number of load cycles until failure do not change for an exposure to a 5% chloride-water solution and an exposure to a 10% chloride-water solution. A rapid increase of the elongation of the bar was monitored at the last 1,000 cycles until failure.

A 3D FE calculation model is developed to calculate the stresses in the rebar as function of the degree of damage. Preliminary calculation results show high concentrated stresses close to the ‘damaged’ section. Due to these stress concentrations, the maximum number of cycles until failure reduces. This was confirmed by the experiments.

References

C. A. Apostolopoulos, S. Demis and V. G. Papadakis (2013), Chloride-induced corrosion of steel reinforcement – Mechanical performance and pit depth analysis, Construction and Building Materials
European_Committee_for_Standardization (2005), NEN-EN 1992-1-1,
R. v. Mises (1913), Mechanik der festen Körper im plastisch-deformablen Zustand, Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse


tnodiana (2014), DIANA - Training Course Manual & Tutorials


tnodiana (2014), TNO DIANA - A TNO Company (http://tnodiana.com/)

R. P. Veerman (2014), Measuring deflections of a corroded concrete beam loaded dynamically by a four-point-bending test, The 10th fib international PhD Symposium in civil engineering, 21-23 July 2014, Quebéc, Canada