DYNAMICALLY LOADED BEAM FAILURE UNDER CORRODED CONDITIONS

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Abstract: De-icing salts, used on roads in heavy winters, may enter reinforced concrete (RC) structures via its capillary pore system or via cracks, initiating reinforcement corrosion and reducing its remaining service-life. Vehicles passing real bridges exert a dynamic impact action that might activate a fatigue failure mechanism. In order to generate more knowledge on the interaction between corrosion and fatigue, a four-point-bending test setup is developed where two lab-scale RC beams are loaded simultaneously. In this setup, RC beams are loaded dynamically, while for one of the beams, corrosion is accelerated by means of a chloride-solution bath mounted on top of it. The second beam, which is the control, is only exposed to tap water. Many test repetitions are foreseen, but so far, three tests are conducted using two different loading levels. It turned out that the reinforcement bar, which corroded due to chloride exposure, failed first in all cases. This paper reports results of the failure mechanism whereby forensic engineering was used to examine the interaction between corrosion and fatigue, and that this might result in a harmful undesirable failure mechanism. The results, therefore, should also be considered for service-life design predictions of infrastructure.

Keywords: Corrosion, cracks, forensic engineering, failure mechanism, fatigue, reinforced concrete

1. INTRODUCTION

To reduce the effect of freezing on roads during heavy winters, de-icing salts are frequently used in the Netherlands for already more than five decades. Unfortunately, de-icing salts dissolve in water, may penetrate into cracked reinforced concrete (RC) structures, and potentially corrode the reinforcing steel [1]. Corroded steel as such has a lower bearing capacity than unaffected steel [2] and might reduce the remaining service-life of RC structures. Steel corrosion in RC structures shows three typical impacts: 1) expansion of the steel volume [3]; 2) reduction of the bond strength [4]; and 3) reduction of the steel sectional area [5]. These impacts could influence other failure mechanisms as well, e.g. the volume expansion might cause cracking and induce concrete spalling. Reduction of the steel cross-sectional area will result in a higher steel stress level, and could reduce the static failure capacity. Moreover, a higher stress level, caused by corrosion, might influence the fatigue failure capacity as well. To investigate the impact of (local) rebar corrosion on the fatigue capacity of RC structures, a dynamically loaded four-point-bending test has been developed

[6]. This test setup consists of two RC beams, where in one beams corrosion is accelerated by means of a water-chloride solution while the other was exposed to water only. Up till now, three tests are performed and the first two showed the same failure mechanism, i.e. tensile strength failure of the reinforcement bar (rebar). This happened consistently for each beam that was exposed to a water-chloride-solution, and whereby some (pitting) corrosion was observed in the rebars. However, the chloride-affected beam of the third (last) test failed in shear at a lower number of cycles (see section 4). After this unexpected failure, it was decided not to start up a new test, but instead, to continue testing the second water exposed beam, but to change its exposure solution from tap water to a water-chloride-solution. After further testing, this beam failed similar as the first two tests. In the Figures, this third test is divided into test 3A (before shear failure) and 3B (after shear failure). Forensic engineering was done on those spots where corrosion was observed. This paper reports the results on the considered failure mechanism and provides the observations achieved from forensic engineering.

2. EXPERIMENTAL SETUP

In the considered four-point-bending test, two reinforced concrete beams are situated above each other and loaded by the same hydraulic cylinder that also contained a pressure cell which measures the actually applied load. To achieve similar material properties, both beams are cast in one go. To mimic a real bridge situation with a negative bending moment above the supports of an ongoing beam, the test beams were installed up-side-down, whereby the steel rebar (and also the cracks) will be located in the upper parts as well (Figure 1). A small bath, made of PVC, is mounted on top of each beam. Rebar corrosion is generated, by filling one bath with a 10% chloride-water solution for two days per week, i.e. mimicking a drying-wetting cycle which is known as the most unfavourable environmental condition [7]. The second beam acts as a control and its bath is filled with tap water during the same exposure time. An extended description of the experimental testing programme is discussed in an earlier publication [6].

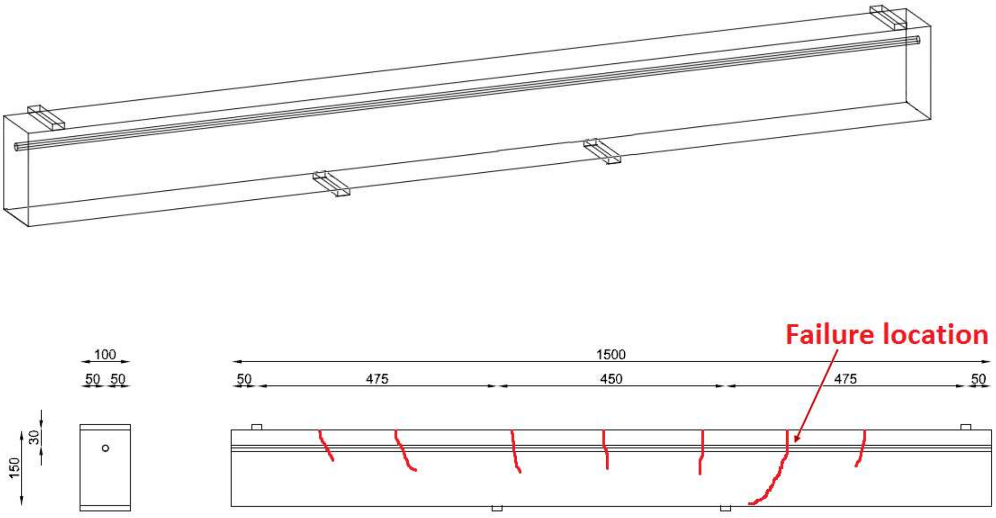

Figure 1 – Illustration of the beam layout and indicated the crack pattern and the location where failure occurred. Note: number of cracks and its location is not the same in all beams.

Up to now, the test was performed three times with two different stress levels. The lower and upper bound of the dynamic load during the first test were 1.7 and 17 kN (steel stress: 35 and 345 MPa). During the second and third tests, these values were 2.0 and 12.0 kN (steel stress: 40 and 290 MPa). The loading frequency for all three tests was 0.5 Hz (Table 1). For each test, two beams are casted using the same mix procedure [8] and stored in a climate controlled fog room (T=20°C, RH=100%). All beams were loaded at nearly the same age resulting in comparable material and mechanical properties. However, small differences in aggregates humidity, local mixture compositions, and also hydration effects resulted in strength scatter (Table 2). Except for the tensile splitting test of test 2, the compressive and tensile splitting strength was both measured from 3 cubes (150x150x150 mm^3), which were casted together with the beams.

Table 1 – Loading properties

	Min. Force	Max. Force	Amplitude	Frequency
Test 1	1.7 kN	17.0 kN	15.3 kN	0.50 Hz
Test 2	2.0 kN	12.0 kN	10.0 kN	0.50 Hz
Test 3	2.0 kN	12.0 kN	10.0 kN	0.50 Hz

Table 2 – Concrete strength

	Age	Compressive strength		Tensile splitting strength	
Test 1	28 days	μ = 35.5 MPa	σ = 0.21 MPa	μ = 2.92 MPa	σ = 0.17 MPa
Test 2	28 days	μ = 34.8 MPa	σ = 0.73 MPa	μ = 2.72 MPa	One cube only
Test 3	49 days	μ = 38.2 MPa	σ = 0.80 MPa	μ = 3.23 MPa	σ = 0.26 MPa

3. NON-DESTRUCTIVE CORROSION MEASUREMENT

During testing, the deflection, width of three cracks [9], Half-Cell Potential (HCP), and Linear Polarization Resistance (LPR) [10] were continuously measured on both beams. HCP and LPR provide information about corrosion activity, where HCP is a method that relates to the probability of corrosion development, and LPR to the corrosion rate. Although these methods are most commonly used [11], they are very sensitive for structural and environmental conditions [12]. Because of this, HCP and LPR data from different structures are hard to compare. However, since the beam dimensions, beam mixture, and environmental conditions are similar for the different tests, deviations within the HCP and LPR measurements on the different tests should be limited. Figure 2 shows the results of the HCP measurements, in which Figure 2A presents the chloride affected beam and Figure 2B the tap water exposed beam. The fluctuations which are observed in the electrical potential in the RC beams may have two reasons. Firstly, in order to be able to measure the electrical resistance (LPR), an additional potential was added to and neglected from the rebar. This potential fluctuation could be measured by HCP. Secondly, potentials are sensitive to humidity, so exposing the concrete beams to a liquid impacts the potential as well.

From Figure 2 can be observed that the beam which is affected by chlorides shows a more negative potential than the beam that is exposed to tap water only. A beam with a potential below -350 mV, has a corrosion probability of over 90% [11]. Based on this it is most likely that all chloride affected beams are corroding. On the contrary, the potentials of the tap water exposed beams are less negative which lowers the corrosion probability of these beams significantly. However, although the probability is smaller, corrosion of these water exposed beams cannot be excluded.

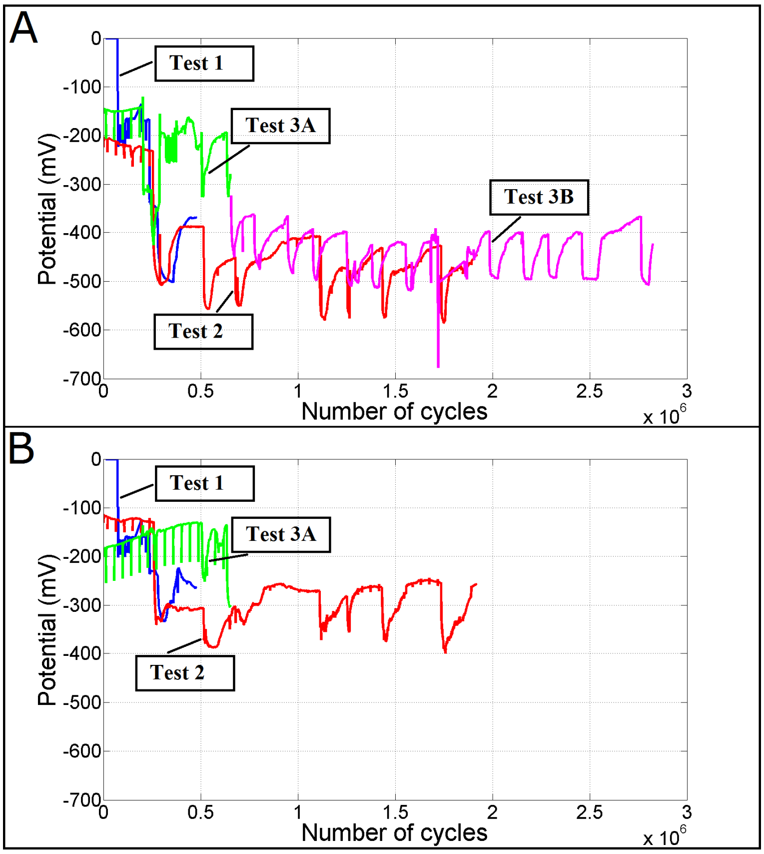

Figure 2 – Results of the HCP measurements. Figure 2A contains the results of the chloride affected beam and Figure 2B the beam which is exposed to tab water

The deflection difference between the loading points at midspan and the supports at the ends of the beams, was measured with LVDTs. Figure 3 shows these deflections versus the number of loading cycles for every tests separately. In more detail, Figure 3A shows the response of the chloride affected beam and Figure 3B the tap water exposed beam. The curves in these figures show small fluctuations, which can be attributed to temperature effects. Differences in humidity (exposure) caused larger impacts on the stiffness/deflection of concrete structures [13], and turned out to be responsible for the larger fluctuations. Since the curves of Figures 3A and 3B show the same shape, it is very likely that the maximum deflection is hardly influenced by chloride-induced corrosion. Figure 4 shows the last 1500 cycles (50 minutes) of testing for all three beams which failed in bending. The graph shows that the deflection of all three beams increases significantly during the last period of loading. This change in behaviour, which represents a reduction in structural stiffness, and which is probably caused by a weakening of the rebar due to local damage like pitting corrosion most likely in combination with fatigue. It is conceivable that the rebars showed local yielding just before failure, without almost any visible crack indication (warning) of the beam.

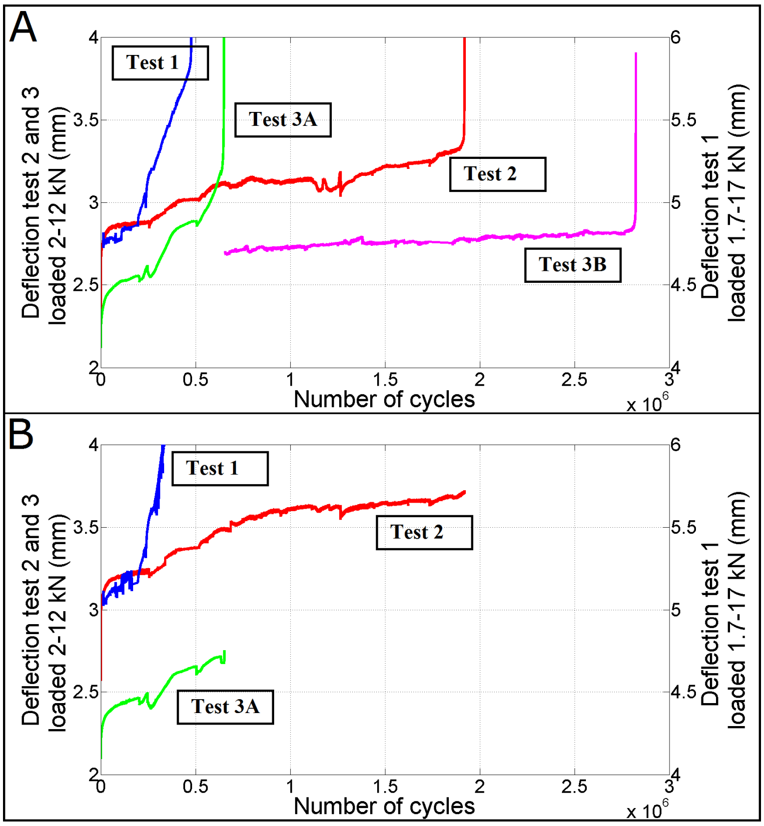

Figure 3 – Measured beam deformations versus number of loading cycles. Figure 3A shows results of the chloride affected beam and Figure 3B of the water exposed beam .

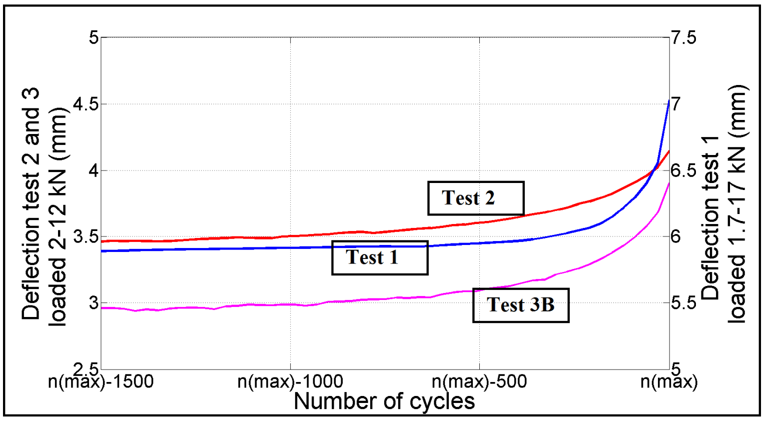

Figure 4 – Measured beam deformations during the last 1500 cycles before failure.

4. FORENSIC ENGINEERING

Considering the tests done so far, it was found that in all cases, the chloride affected beams failed while the beams with tap water exposure remained intact, and keeping its bearing capacity. Except for one accidental shear failure mechanism, all tests showed the similar failure mechanism, i.e. a bending crack, close to the midsupport and along the bending-shear area, causing failure of the rebar in the beam. The locations where the cracks appeared is indicatively shown in Figure 1.

All beams with the chloride solution bath mounted on top showed corrosion and were the once that failed during testing. This makes it very likely that corrosion a kind of impact on the failure mechanism. As also clear traces of corrosion were observed at the failure surface of the rebar, more detailed forensic engineering was executed to better understand this observed phenomenon.

The first test ran for 18 days and had only one wetting cycle (12 days dry, 3 days wet, and 3 days dry). Although this period is relatively short, a limited amount of corrosion activity was measured by automatic degradation detection (LPR) (see Figure 2) [10]. To investigate this development of corrosion activity over the length of the rebar, parts of the beam were removed and the rebar inspected visually. After removing the concrete sections, corrosion was observed at several locations, which were exactly those locations where the cracks occurred, i.e. chloride, water, and oxygen can penetrate easily through the cracks and accelerate local corrosion activity [14]. A similar investigation is executed for the second beam where it turned out that the amount of corrosion was much less than the amount of corrosion observed in the first beam. Besides this, the cracked section of the rebar was observed using an ESEM microscope. Both microcracks and corrosion activity could be identified on the microscale image (Figure 5).

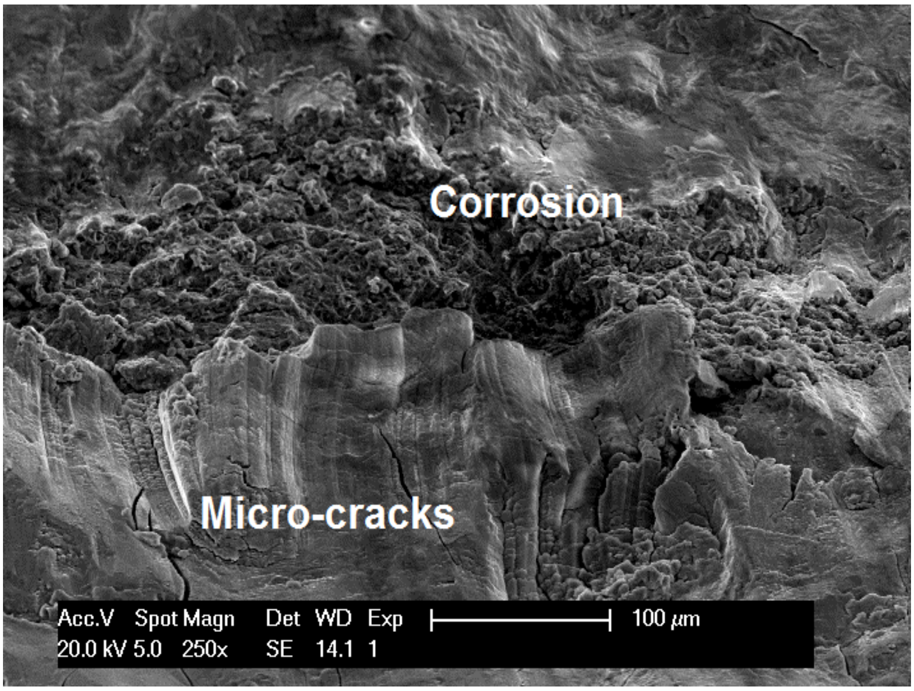

Figure 5 – Microscale ESEM image of the failed rebar cross-section.

Removing the rebar from the tested beam for analysis was done by 25 cm wide sectioning and then splitting these sections over vertically, exposing the rebar (Figure 6). This rebar analysis was done for the corroded beam of the second test, that failed after nearly 2 million cycles (52 days of loading). Significant corrosion was observed at the failure cross-section and along the rebar for several centimetres. Figure 6 gives an impression of the corroded cross-section inside the beam after sectioning and splitting. The tap water exposed beam, which did not fail during the dynamic test, was tested statically to measure the actual beam capacity and/or possible reduction of the bearing capacity due to the dynamic action. The results showed hardly any reduction after nearly 2 million load cycles and nearly two months of water exposure. Water exposure seemed not to having affected the static bearing capacity of the beam.

Figure 6 – Picture of the corroded cross-section after splitting (a part of) the beam

One mm thick PVC plates were attached to the side surfaces of the beams acting as a part of the bath, and also to prevent leakage. In the first and second test, these PVC plates were installed in the formwork mould before casting such that a seamless interface with the hardening concrete would develop. However, this connection failed partially due to the dynamic impact, and leakage could not prevented. To avoid this problem in the third test, the PVC plates were fully glued on the concrete beams after hardening, which limited leakage to a manageable volume. A side-effect of this approach was that the PVC plates turned out to carry part of the load and affected the internal stress distribution of the concrete beam. Due to this, cracks could not develop freely and the failure mechanism in the concrete beam shifted from bending to shear. Because of this, the chloride affected beam of test 3 failed after just 655,000 cycles. It turned out that the capacity of the concrete beam was limited significantly due to shear failure. After this unexpected situation, it was decided to proceed with the test by loading only the second beam and change the exposure condition from tap water to chloride solution, which finally resulted in bending failure after 2.82 m cycles (69 days). It was also the reason that the curves of test 3 in Figures 2 and 3 were split into 3A (the first 655,000 cycles) and 3B, the remaining 2.2 m cycles.

The beam used for the third test, and that also failed in bending was cut in sections followed by vertical splitting as well. Visual observation showed that the failed section had the highest corrosion activity. It was also observed that corrosion was less pronounced in comparison with the second test, which was also concluded from the HCP and LPR results (Figure 2).

5. FAILURE HYPOTHESIS

As discussed in section 2, the three tests are executed three times at two different loading levels and applying the same frequency. The loading impact was highest for the first test, which resulted in the lowest number of cycles during before failure, i.e. 478,000 cycles (18 days). In the second test, the beam failed after 1.92 m cycles (52 days) and the third test ended after 2.82 m of loading cycles (69 days). The failure loads and the loading levels of all three tests are provided in Table 3.

Except for one shear failure, for which the reason was discussed before (section 4), all beams which were affected by a chloride solution failed in tension of the rebar, as result of the bending moment. An increased deformation was observed during the last half hour of the cyclic loading (service-life) for all tests (section 3). This strong increase in deformation indicates an enhanced steel strain, which might be caused by a higher steel stress caused by a local reduction of the rebar's cross-sectional area. Reason for this could be that local (pitting corrosion) damage might cause fatigue induced micro-cracking [15] and may harm the integrity of the steel's cross-sectional area. A local reduction of the rebar's cross-sectional area might result in higher steel stresses, which in combination with the alternating loading level, might lead to local crack propagation. If the damage is large enough to increase the actual stress level up to the yielding level, deformations might increase dramatically. Since the damage is localized in a crack, the total increase in deformation is limited (Figure 3 and Figure 4). Furthermore, the corrosion damage, which is observed in the cracked cross-section of all tests (section 4) agree with this hypothesis. A nonlinear finite element model will be developed to study the fundamental evidence for this mechanism as well. The results of this model will be discussed in future publications.

Table 3 – Failure properties

	Failure load		Failure mechanism
Test 1	478,000 cycles	18 days	Bending
Test 2	1.92 m cycles	52 days	Bending
Test 3A	655,000 cycles	19 days	Shear*
Test 3B	2.88 m cycles	69 days	Bending
* Shear failure as discussed in section 4.			

6. CONCLUSION

An experimental setup for a dynamic four-point-bending-test with two reinforced concrete (RC) beams is developed to understand the relation between corrosion and fatigue under cyclic loading. To activate corrosion in one of the beams, a bath with a chloride-solution is mounted on top of it. A second bath filled with tap water is installed on top of the other beam, which acts as a control. So far, the test is performed three times with two different loading levels. In every test, the beam which was affected by the chloride solution failed in bending, in which the ultimate tensile strength of the reinforcing bar (rebar) was reached. Increased deformation is observed in the last half hour of loading, for all tests, just before failure. However, environmental and exposure conditions resulted in a scatter of the measured deformations within the same range, which made it hard to identify this “warning”.

Forensic investigations showed that corrosion developed in every crack location of those tested beams that were exposed to the chloride-solution. Furthermore, it is observed that the corrosion activity at the cracked location was heavily developed. From these observations it is reasonable to conclude that corrosion has an influence on the fatigue failure load.

Although it is not yet proven by a nonlinear finite element model, corrosion activation leads to a local damage in the steel sectional area (pitting), which increases the local steel strains and steel stresses in the crack area. Micro-cracks, caused by fatigue, might accelerate this corrosion and damage process. When the local stress level has reached the yielding stress, deformations increase, and failure will occur, leading to a reduced remaining service-life.

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