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SIGNIFICANCE OF CRACKS IN DURABILITY DESIGN AND ASSESSMENT OF HYDRAULIC CONCRETE STRUCTURES DUE TO REINFORCEMENT CORROSION

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Abstract: Cracking is an indispensable phenomenon in reinforced concrete. The reinforcement carries appreciable loads only after cracks have formed. However, cracks may significantly impair the function of structures. The verification for various states of structural elements in the ultimate and serviceability limit states is carried out taking account of various crack characteristics (crack width, crack type, etc.). For the protection of reinforcement against corrosion, in particular, cracks are important as they destroy the passivity of the reinforcement ensured by the enveloping concrete.
This paper considers various reinforcement corrosion mechanisms in cracked areas of structural elements and corresponding special features attributed to hydraulic structures. Case studies with a description of the problem are presented alongside existing technical rules for the protection of reinforcement against corrosion.

Keywords: reinforced concrete, corrosion, crack, depassivation.

1 Introduction

Hydraulic engineering structures such as locks, weirs and quays are very solid reinforced concrete structures. Owing to the large dimensions of the structural elements, such structures are subject to high levels of thermal effects due to the heat of hydration which give rise to internal stresses and restraint forces. Hydraulic engineering structures are thus particularly susceptible to cracking. The environmental actions are, in particular, permanent or temporary exposure to the action of water, approaching ships, hydroabrasion, frost and the penetration of chlorides from seawater or de-icing salt. Hydraulic engineering structures are generally designed for a working life of at least 100 years.

This paper considers the following two issues relating to the corrosion of reinforcing steel in the cracked sections of structural elements in hydraulic engineering structures:

1.1 Corrosion of reinforcing steel at cracks in sections exposed to the action of chlorides

Reason: Structures in coastal areas are constructed with finely distributed cracks so that consideration always needs to be given to whether additional protection against chloride-induced corrosion of the reinforcing steel is required. The German annex to EC2 [DIN EN 1992-1-1/NA:2015] specifies that particular measures must be taken in the case of trafficked areas (such as parking decks) that are exposed to the action of chlorides (exposure class XD3), for example application of a crack-bridging coating, sealing the surface or using a method of construction that prevents cracking. In other words, adequate durability is not ensured in such cases by the concrete composition and the concrete cover to reinforcement, solely.

1.2 Corrosion of reinforcing steel in cracks in underwater structural elements on inland waterways (fresh water)

Reason: In recent years, corrosion processes have been detected in the underwater sections of cracked reinforced concrete structural elements that are exposed to fresh water. Such processes had previously been considered unlikely to occur on account of the boundary conditions (lack of oxygen). Corrosion is caused by depassivation of the reinforcing steel following leaching from the concrete (calcium hydroxide) owing to the significant leakage of water through the cracks and the subsequent development of the cathodic subprocess in remote, well-ventilated sections of the structure (above water level).

2 Cracking of structural elements

Cracking is an indispensable phenomenon in reinforced concrete. The reinforcement carries appreciable loads only after cracked have formed. However, cracking may also significantly impair the function of structural elements unless it is adjusted to suit the type, function and environment of the structure concerned. Design principles for dealing with cracking are therefore set out in various codes [DAfStb 2017, DBV 2016, DBV 2018]. Generally speaking, there are three basic design principles [DBV 2016]: crack avoidance, crack distribution and cracking with subsequent treatment. In the majority of cases, the principle of crack distribution is the most cost-effective and practical option. It is based on compliance with a design crack width which is achieved by appropriate design of the reinforcement. The minimum reinforcement required for crack control ensures that cracking is spread over several very fine cracks.

Cracking must always be expected in solid hydraulic engineering structures on account of the early restraint forces caused by the tensile stresses due to the heat of hydration. Figures 1 and 2 show cracking that occurred in a quay on the North Sea coast shortly after placement of the concrete. Cracks with widths ranging from ≤ 0.1 mm to around 0.3 mm with a spacing of between approximately 25 to 120 cm (on average around 60 cm) were detected along the inspected section of the structure which was around 500 m in length (total length of the quay: 950 m). The detected crack widths were mostly less than 0.2 mm, with isolated crack widths of up to 0.3 mm. The cracks detected on the top surface of the quay also continued on the waterside face and can thus be characterised as separation cracks. Vertical coring revealed that the cracks extended down to a depth of 400 mm. Tapering of the cracks was only detected in a few cases. The quay has a length of 950 m and was constructed without joints. Figure 2, right, shows the standard cross-section of the quay. To ensure durability, the quay was designed with a design crack width of 0.25 mm in accordance with [DIN 19702:2013]. Wider cracks are generally grouted. The cracking pattern described above was observed while the quay was drying out (a few hours after it had rained). The cracks were not visible when the quay was dry and only barely visible when the quay was wet.

Self-healing of separation cracks is unlikely to occur as such cracks are not subject to long-term exposure to water (see Section iv). In addition, the formation of calcium carbonate crystals is inhibited by soft rain water penetrating the cracks.

Figure 1: Transverse cracks running across the entire width of the top surface of a newly constructed quay; general view (left); typical crack spacing between 30 and 60 cm (right)

Figure 2: Cracking pattern on the face of the quay (left); cross-section of the quay superstructure (right)

Subsequent cracking in hydraulic engineering structures is mostly due to tensile stresses caused by thermal actions (later on by restraint forces). Compared with other types of civil engineering structure, such as road bridges and parking decks, solid hydraulic engineering structures are subject to relatively low levels of tensile stresses due to mechanical loads. Further cracking may be caused by frost exposure, corrosion of the reinforcing steel, hydroabrasion, and so on.

3 Fundamentals of the corrosion of reinforcing steel

Steel in concrete with a sound microstructure is protected from corroding by a passive layer. The layer is composed of a thin film of iron oxide/iron hydroxide [Leek 1991] as a result of iron ions migrating from the surface of the steel into the highly alkaline pore solution (pH $\geq$ 11) where they react with the dissolved oxygen, thus preventing further oxidation of the steel. The passive layer can be destroyed by the two mechanisms described below, after which the reinforcing steel can begin to corrode:

- Decrease in the pH at the surface of the reinforcing steel. Iron oxide/iron hydroxide is soluble in low pH environments so that further iron ions migrate to the pore solution where they oxidise. Depassivation of the surface of the reinforcing steel due to a decrease in the pH can be caused by the following two mechanisms:
    - Carbonation of the concrete, i.e. reaction of the alkalis in the concrete with carbon dioxide from the atmosphere; "carbonation-induced corrosion of reinforcing steel".

However, owing to the prevailing wet conditions, the risk of damage to hydraulic engineering structures by carbonation-induced corrosion of the reinforcing steel is low and no further consideration is given to it here.

  - Leaching from the concrete – Leaching of portlandite from uncracked concrete with a sound microstructure is very slow so that there can be no significant decrease in the pH. Leaching of portlandite is only relevant for separation cracks with leakage of water and can lead to depassivation of the surface of the reinforcing steel in such cases (see below).

- Penetration of chlorides to the surface of the reinforcing steel and development of a critical chloride content at which corrosion is induced. The chloride ions destroy the iron oxide/iron hydroxide film (chloride-induced corrosion of reinforcing steel).

Once the protective passive layer has been lost, anodic dissolution of the reinforcing steel can take place. Apart from the anodic dissolution of iron in reinforcing steel, other conditions also have to be present before oxygen corrosion of reinforcing steel is initiated. These are as follows:

- The reinforcing steel must be electrically conductive – uncoated steel always conducts electricity,
- the concrete must be electrolytically conductive – this is always the case in hydraulic engineering structures owing to the prevailing moisture conditions,
- the formation of anodic and cathodic regions in the structure – this is caused by the differences in potential, e.g. due to local depassivation of the reinforcing steel, and
- oxygen supply to the cathodic region. The initiation of corrosion may be inhibited in underwater structures due to a lack of oxygen even if depassivation of the surface of the reinforcing steel has taken place. However, the cathodic subprocess of corrosion may occur in low oxygen environments as the passive steel surface (cathode) is frequently extensive. In addition, a large proportion of the cathodic region of underwater structures often lies in the wet concrete above water level which is exposed to the oxygen in the atmosphere.

The initiation of corrosion in reinforcing steel does not lead to any visible damage to the structure. The subsequent corrosion of the reinforcing steel has consequences for the serviceability and loadbearing strength of the structure (damage phase). Cracking, spalling of the concrete cover, loss of the bond between the concrete and the steel, a reduction in the cross-section of the steel or even failure of the structural element may occur. While the initiation phase (for intact and uncracked concrete) can be determined with sufficient accuracy by mathematical models (see e.g. [Rahimi 2017]) there are currently no tried-and-tested models permitting assessment of the corrosion damage phase, i.e. from depassivation of the reinforcing steel up to the point at which cracking, spalling of the concrete cover or even failure of the structure occur.

4 Effect of cracking on the corrosion of reinforcing steel

Cracking in the structural element affects both the initiation of corrosion of the reinforcing steel, i.e. depassivation of the surface of the reinforcement, and the subsequent corrosion rate.

While the initiation phase leading to depassivation of the reinforcement in uncracked structural elements is relatively long and is defined as the working life of the structural element for durability design purposes, it can generally be assumed that rapid depassivation of the reinforcement will occur in cracks. The protective passive layer around the reinforcement in the cracked section can be destroyed by a decrease in the pH of the concrete at the surface of the reinforcement due to leaching from the concrete ($Ca(OH)_2$), in addition to carbonation and the penetration of chlorides (see Section iii).

Anodic dissolution of iron takes place in the depassivated reinforcing steel in the cracked sections during the active corrosion phase while the cathodic partial reaction (oxygen reduction) occurs in the reinforcing steel outside the cracked section. In this case, it is the rate of corrosion that is relevant for estimating the working life of the structural element.

The factors affecting depassivation and corrosion of the reinforcing steel in cracked hydraulic engineering structures can be summarised as follows.

Type of crack: A distinction is made between separation cracks, which run through the entire cross-section, and bending cracks, which only run through the tensile zone. When water leaks through the separation cracks, rapid depassivation of any reinforcement crossing the crack will occur on exposure to chlorides. If the water exchange rate is high, the pH will decrease, even without the action of chlorides, due to leaching from the concrete and depassivation of the reinforcing steel will occur. High rates of corrosion can also be expected in separation cracks with high water exchange rates due to the progressive depassivation of the reinforcing steel (chloride accumulation, leaching) and leaching of the dissolved products of corrosion, preventing closure of the cracks. By contrast, depassivation of the reinforcing steel due to the action of chlorides will take longer in the case of bending cracks and lower corrosion rates can be expected. Leaching through bending cracks in the concrete is negligible as there is no exchange of water in this case.

Crack width: Crack width, as a geometrical feature of cracks, is only of minor importance, both for depassivation and for the rate of corrosion, provided it is less than around 0.5 mm (see e.g. [Schießl 1986, Keller 1991]). However, it is a major factor influencing whether cracks have the ability to self-heal or not.

Self-healing of cracks: “Self-healing” is a term used to describe the closing of cracks owing to the formation of calcium carbonate in the cross-section of the crack. For self-healing to take place, the crack width must be small (generally ≤ 0.2 mm), the crack must be constantly exposed to the action of water, the pressure gradient must be low (ratio of the water storage level to the thickness of the structural element), the water must have certain properties (pH > 5.5, aggressive carbon dioxide < 40 mg/l) and there must be very little or no crack movement (less than 10% of the crack width) (e.g. due to temperature changes or changes in the water storage level) [Edvardsen 1996, DAfStb 2017].

Quality and thickness of the concrete cover to reinforcement: The quality and thickness of the concrete cover is an important factor affecting the initiation and rate of corrosion, irrespective of whether the structural element is cracked or uncracked. A thick concrete cover increases the length of the time that elapses prior to depassivation of the reinforcement in the crack. A thick and dense concrete cover increases the electrolytic resistance of the concrete and slows down the cathodic partial reaction and thus the corrosion rate.

Exposure: The frequency of water exposure and the moisture gradient in the structural element both affect the penetration of chlorides into the cracks and the structural element itself. Capillary suction in the zone of fluctuating water levels and the spray zone may lead to a (rapid) increase in the concentration of chlorides in the cracks. Accelerated penetration of chlorides owing to capillary suction may also occur if the structural element dries out on the side facing away from the water. Chloride transport in cracks that are permanently filled with water is controlled by diffusion and is thus a gradual process. For structural elements exposed to fresh water, depassivation of the reinforcement due to leaching from the concrete can only occur if there is a high rate of water exchange through the cracks.

Mechanical loading: Mechanical loads may shorten the corrosion initiation phase by causing microcracks in the concrete and destroying the contact zone between the concrete and the reinforcing steel. Transcrystalline cracks may develop within the cross-section of rebars weakened by pitting if the corroding reinforcement is subjected to tensile stresses [Nürnberger 1998]. Depending on the level and frequency of the tensile stresses and the intensity of the erosive corrosion, fracturing of the reinforcement may occur. In reinforced concrete structures subject to non-static loads, this damage mechanism is known as corrosion fatigue or vibration-induced corrosion cracking. Vibration-induced stresses can be caused by frequent fluctuations in the water level at hydraulic engineering structures, for example.

5 Investigations of structures exhibiting chloride-induced corrosion of the reinforcing steel

An approximately 40-year-old quay on the North Sea coast (similar to the structure shown in the diagram in Figure 2) was examined in order to address the first issue described in Section i. Five drilled cores were taken from the top surface of the capping of the quay (Ø/L=100/~350 mm) (cores no. 1 to 5). There was at least one pronounced crack (width 0.1 to > 0.5 mm) in each of the selected sections; the cracks extended into the face of the capping and can thus be considered as separation cracks. Calcium carbonate deposits could be seen on the sides of all five cracks in the face of the capping, indicating water exchange through the cracks. The drilled cores were taken perpendicular to the cracks. After the cores had been split it could be seen that each crack had extended across at least one rebar. The rebar fragments in the cores were all exposed and a pickling solution was subsequently used to remove the hardened cement paste and rust products, thus enabling the surface of the rebars to be visually examined for erosive corrosion. Partial or extensive erosive corrosion had occurred on each fragment of the rebars that had crossed a crack, resulting in a reduction in the cross-section of the steel. The greatest reduction in the cross-section was detected on the rebar fragments in cracked sections nos. 4 and 5 in which cracking of the structure appeared to be particularly pronounced (wide cracks, no tapering over long stretches of the cracks), see Figures 3 to 5. The few rebar fragments next to the cracks in the drilled cores did not exhibit any reduction in cross-section due to erosive corrosion, Figure 5, right.

Figure 3: Continuous crack on the face of the quay with calcium carbonate deposits near to where drilled core no. 4 was taken on the top surface (left); drilled core no. 4, 1st layer of rebars, concrete cover approx. 60 mm (right)

Figure 4: Drilled core no. 4, 1st and 2nd layer of rebars (left); drilled core no. 4, split, 1st and 2nd layer of rebars (right)

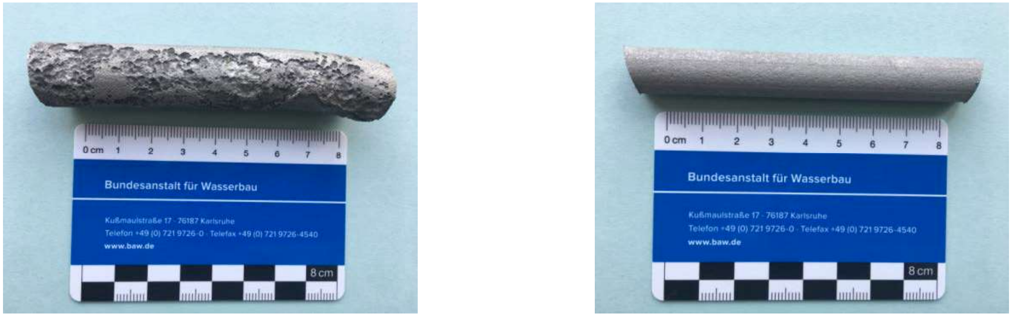

Figure 5: Drilled core no 4, rebar in 1st layer after application of the pickling solution, extensive erosion (left); rebar in 2nd layer after application of the pickling solution, no reduction in the cross-section (right)

Figure 6: Drilled core no. 1, after sampling, 1st layer of rebars, width of crack at surface approx. 0.25 mm, concrete cover approx. 60 mm (left); drilled core no. 1, rebar in first layer after application of the pickling solution, minor reduction in the cross-section at the right-hand edge (right)

In addition to the drilled cores, samples of borehole cuttings were taken from the top surface to determine the chloride content. The samples of borehole cuttings were taken from areas close to the crack as well as from uncracked sections. Borehole cuttings were taken from all five of the selected cracks around 1 cm to the left and right of the edges of each crack, at depth intervals of 20 mm down to a depth of around 80 mm. To analyse the chloride content, the two samples of borehole cuttings taken at each depth were mixed and harmonised. The samples of uncracked concrete comprised two drill cores taken at intervals of 10 mm at a distance of around 1 m from each of cracks no. 3 and 5 (down to a depth of 60 mm). The resulting chloride profiles are shown in Figure 7. The chloride profiles in the cracked sections (apart from crack no. 3) exhibit higher chloride contents in the deeper layers of the structural element (from around 30 mm) than in the uncracked sections. For cracks no. 4 and 5, the chloride content at the depth of the concrete cover (60 mm) corresponds to the critical chloride content of 0.5 % by mass of the binder content [DAfStb 2001] which is the chloride content at which corrosion is initiated. The actual chloride contents at the edges of the cracks may be assumed to be higher than the values determined by testing as it is technically not possible to take samples only from the edges of the cracks and the measured values have been smeared with the chloride content of the uncracked section.

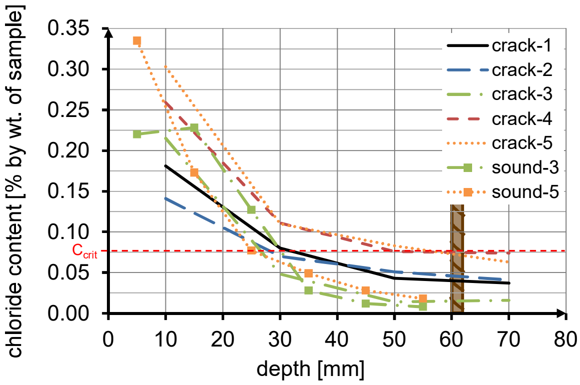

Figure 7: Profiles of the measured chloride contents (in % by mass of sample) in close proximity to the cracks (crack-1 to crack-5) and in approx. 1 m distance to the cracks no. 3 and 5 (sound-3 and sound-5)

The face of the quay capping is exposed to the action of chlorides from seawater, mainly in the form of spray water and spray mist. The top surface is also exposed to chlorides from de-icing salt in winter. All in all, the action of chloride can be assumed to be far more pronounced than for parking decks. Corrosion of the latter is caused by the action of water that is contaminated with de-icing salt and carried into parking decks by vehicles in winter.

The investigations revealed that, even for very wide and pronounced separation cracks, there was relatively little reduction in the cross-section of the reinforcement over the 40 year working life. The erosive corrosion has hitherto affected neither the serviceability (e.g. spalling of the concrete cover) nor the loadbearing strength of the structure (reduction in load transmission owing to the reduction in the cross-section of the reinforcement). It is not possible to forecast how the damage will progress as the appropriate technical instruments are not available. A possible reason for the very slow advance of corrosion may be the good quality of the relatively thick concrete cover (blast furnace cement concrete). The concrete thus has a relatively high electrolytic resistance.

6 Investigations into the corrosion of reinforcing steel occurring in cracks in underwater structural elements on inland waterways (fresh water)

Pronounced cracking with calcium carbonate deposits and some corrosion was detected in several locks when they were drained to enable scheduled inspections to be conducted.

Figure 8 shows a chamber wall of one of the locks (around 40 years old). Extensive rust streaks can be seen in the construction joint above the bottom of the lock. The outer layers of reinforcement in a small section of the chamber wall were therefore exposed with a high-pressure water jet to permit inspection. It was discovered that six parallel vertical rebars (Ø 25 mm) in the exposed section had fractured at the level of the construction joint. The likely cause is a marked reduction in the cross-section of the rebars owing to corrosion in conjunction with high cyclic tensile stresses due to lockage operations. Water leaks through the open construction joint owing to the difference between the water level in the chamber and the groundwater level (behind the chamber wall). Depassivation of the reinforcing steel therefore occurs as a result of leaching from the concrete (portlandite). The affected section of the wall is relatively thin and only has a little secondary reinforcement. There was no reduction in the cross-section of the neighbouring rebars outside the construction joint.

Figure 8: Lock chamber wall with the exposed section directly above the bottom of the lock (left); fractured rebars in the construction joint (right)

Tests on another lock are shown in Figures 9 to 12. Rebars close to the surface of the structure near pronounced cracks and construction joints were exposed in two different sections of the lock. In one case, the reinforcement (Figure 9, right, and Figure 10) was exposed in a horizontal construction joint in the wall separating two side ponds (Figure 9, left). Extensive corrosion with development of red rust and loss of material was detected at this point. The construction joint is located in the zone of fluctuating water levels and water leaks through it. There is an almost constant water pressure gradient in the construction joint owing to the different water levels in the two locks.

Figure 9: View of the side ponds of the lock (left); exposed rebars in the leaking horizontal construction joint of the wall between the two side ponds (right)

Figure 10: Corroded rebars in the construction joint

In the second case, rebars were exposed near a horizontal construction joint and a vertical crack in the drainage zone of the bottom gate of the lock (Figures 11 and 12). The construction joint and the vertical crack are both leaking as calcium carbonate deposits have developed in the crack and in the construction joint. The lock-side concrete surfaces in this section of the lock are constantly under water and the groundwater level behind the wall is several metres above the water level in the drainage zone of the lock, resulting in a water pressure gradient. Rebars crossing the vertical crack exhibited superficial corrosion without any apparent reduction in their cross-section. The exposed rebars next to the crack did not exhibit any corrosion. Compared with the two previous examples, there appears to be cathodic inhibition of the corrosion at this point owing to the lack of oxygen as the structural element (drainage area) is almost constantly submerged. In addition, the structural element is not exposed to high levels of tensile stress.

Figure 11: View of the lock, bottom gate, drainage area (left); horizontal construction joint and vertical crack prior to exposure of rebars (right)

Figure 12: Calcium carbonate deposits at the leaking vertical crack (left); rebars exposed near the vertical crack (right)

7 Summary and outlook

The risk of corrosion of the reinforcing steel in cracked structural elements depends on numerous factors. There are currently no technical specifications and instruments permitting a reliable assessment.

The rebars exposed at the pronounced cracks in the quay under investigation exhibited only minor reductions in their cross-section as a result of chloride-induced corrosion. Amongst other things, this is due to the reinforcement being subjected to low levels of mechanical loading (compared with parking decks and other slender trafficked areas).

Some local erosive corrosion and even fracturing of the rebars were detected in structural elements exhibiting cracks with leakage of fresh water which cannot self-heal. The critical locations were either in the zone of fluctuating water levels or in the underwater sections of slender structural elements that are subject to cyclical loading due to changes in the water level (lock chamber wall).

Investigations of other existing structures on inland waterways and in coastal areas are currently being conducted to establish whether cracking and/or self-healing of cracks has occurred and to determine the condition of the reinforcement and which actions the structures are exposed to.

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