Impact of cracks on chloride-induced corrosion and durability of reinforced concrete structures – a literature review

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ABSTRACT: Chloride-induced corrosion of steel reinforcement is one of the major hreats to durability of reinforced concrete structures in a marine environment. This leterioration mechanism can shorten the remaining service life of structures signif- cantly. Many research projects have been conducted on sound concrete to im- rove the quantification of residual service life. However, cracks which are inevita- le in practice facilitate the transport of chloride ions, moisture and oxygen initiat- ng the corrosion of steel reinforcement faster than in sound concrete. In this paper he most important factors affecting chloride-induced corrosion in cracked con- rete are discussed. The impact of crack width on chloride-induced corrosion is nalysed in a marine environment, depending on binder type, water-binder ratio, over depth, type of loading, crack frequency, crack geometry and orientation, rack depth, mitigating mechanisms etc. It is recommended to involve variable rack width limits, based on aforementioned factors, in improved structural codes. ome other recommendations for future research are also proposed.

1. Introduction

he durability of concrete structures is one of the most important criteria with re- pect to the design of new structures and to extend service life of existing struc- ures. Therefore, understanding the most dominant deterioration mechanisms hich can occur during the service life of a structure is very important. Several eterioration mechanisms can shorten the remaining service life of reinforced oncrete structures significantly. Chloride-induced corrosion of steel reinforcement one of the major threats to durability of reinforced concrete structures in a ma- ne environment. In a marine environment the splash and tidal zones are consid- red as the area which is subject of the highest corrosion risk of reinforcing steel ue to alternating wetting and drying cycles. Service life is divided into two phas- s, the initiation period and the propagation period (Tutti et al. 1982). During the itiation period chloride ions, water and oxygen penetrate through the concrete over to the steel reinforcement. The initiation period is finished when aggressive ubstances reach the depth of the reinforcing steel in a critical concentration, estroying the passive layer. After activation of corrosion, a propagation phase ccurs where corrosion products induce concrete cracking which facilitates pene-

tration of aggressive substances through cracks. Furthermore, this leads to possible spalling of concrete cover and reduction of structural safety.

Many research projects have been conducted to improve quantification of residual service life but in most of these projects concrete structures have been considered undamaged e.g. Model Code (2006) and Tang (1996). Unfortunately, cracks are inevitable due to thermal effects, loading, restrained shrinkage and the expansive reactions. Cracks facilitate ingress of chloride ions, moisture and oxygen through concrete cover, especially if cracks are interconnected, because then concrete becomes more permeable. Cracks appear during service life of concrete structure mostly due to low tensile strength of concrete. Furthermore, the steel reinforcement is in the cracked zone which is subjected to higher chloride penetration through the concrete cover. The tensile strain capacity of concrete varies with age and with the rate of strain application.

The purpose of this paper is to emphasize the impact of cracks on chloride-induced corrosion and durability of reinforced concrete structures in a simulated marine environment depending on binder type, water-binder ratio, cover depth, type of loading, crack frequency, crack geometry and orientation, crack depth and mitigating mechanisms.

2. Factors affecting chloride penetration and chloride-induced corrosion in cracked concrete

Many factors can have a significant influence on chloride-induced corrosion in concrete. Literature review shows that the quality of concrete is the most important influencing parameter. Concrete quality depends on binder type, water-binder ratio, supplementary cementitious materials, curing, execution, porosity, aggregate size etc. Besides the quality of the concrete, the exposure to environmental conditions is also important to take into consideration. This includes factors such as exposure time, chloride content, temperature and relative humidity. Most of the time reinforced concrete structures are subjected to loads during their service life. According to the type of loading (static, dynamic, compressive, tensile or unload state) different behaviour of chloride-induced corrosion can be expected.

Many studies were conducted to examine the influence of aforementioned factors on chloride penetration and chloride-induced corrosion in sound concrete. Some efforts have been undertaken recently to compare those results with obtained data on cracked concrete specimens exposed to chlorides e.g. Otieno (2010) and Win (2004). Some factors have a more or less similar impact on cracked concrete compared to sound concrete with respect to chloride penetration and chloride-induced corrosion. However, there are some factors which are typically used to investigate their influence on the steel corrosion in cracked specimens. The role of these factors is discussed.

constant cracks under static loading. Crack opening and closing under dynamic load leads to increased chloride ingress, especially towards the crack tip. The increased chloride penetration in dynamic cracks is controlled more by the frequency and rate of load application than by the crack width. Wang (2011) came to similar conclusions, but the influences of temperature and water-binder ratio were combined with dynamic loading which resulted in an increased chloride ingress into concrete. It can be concluded that preferably variable loading conditions have to be simulated during laboratory testing, rather than static or unloaded, as more similar to reality.

3. Influence of cracks

Many inconsistencies are found in structural codes with respect to limitations of surface crack width in order to control corrosion of steel reinforcement. The maximum allowable crack width depends on the exposure class only and differs from country to country. For example, as a value for the most severe environment, British Standard 8110 (1997) and ENV (1991-1-1) prescribe 0.30 mm, but ACI (1994) prescribes 0.15 mm as the maximum allowable surface crack width. However, the Dutch code NEN 6720 prescribed a value of 0.2 mm in reinforced concrete members exposed to aggressive environmental conditions. It was stated by CEB Bulletin 182 (1987) that the quality and the thickness of the concrete cover is by far more important than the maximum width of the cracks, as long as they are below 0.4 mm under the governing loading condition. However, if the concrete cover is larger, the surface crack width will be wider and therefore cannot be accepted by aforementioned rules despite of the fact that a larger concrete cover provides a better protection to chloride-induced steel corrosion. The crack width limitations are not even discussed in the fib report, on service life design (2006), and only uncracked concrete has been taken into consideration.

In recent years, the influence of cracks on chloride penetration and chloride-induced corrosion in concrete has been investigated in a wide range e.g. Mohammed (2001), Adiyastuti (2005), Francois (2006), Audenaert (2009), Pease (2010). Some of these researchers report that limitation of surface crack width is not an appropriate factor to control the effect of cracks on the durability of concrete structures. It was reported by Gowripalan (2000) that surface crack width-concrete cover ratio should be the relevant parameter to be considered in relation to the durability performance of cracked reinforced concrete. The influence of cracks on chloride penetration and chloride-induced corrosion depend on crack width, crack frequency, crack geometry, crack orientation with respect to the steel reinforcement, crack depth and steel-concrete interface.

3.1 Crack width

As far as the influence of cracks on chloride-induced corrosion in cracked concrete is concerned, surface crack width is considered the most important parameter.

While it is generally accepted that appropriate crack width might accelerate corrosion initiation, there is still debate about the effect of cracks on corrosion propagation. On the one hand some authors state that cracks do not influence the propagation period e.g. Francois (1998) and Schießl (1997), while on the other hand it is believed e.g. Otieno (2010) and Otsuki (2000) that cracks affect both initiation and propagation period. In long term corrosion measurements of reinforced concrete by Francois and Arliguie (1999) and Francois (2006), the corrosion process in relation to mechanical cracks and the mechanical behaviour in relation to corrosion intensity were investigated. It was found that the corrosion development had no correlation with the crack width (for widths less than 0.5 mm) or even presence of cracks. It was stated that the load applied to the reinforced concrete beam is more important than the crack width below 0.5 mm with respect to chloride-induced corrosion. In a study by Otsuki (2000) the influence of bending cracks and water-cement ratio on chloride-induced corrosion of reinforcing bars and stirrups was investigated. A significant effect of bending cracks and water-cement ratio on the corrosion rate was obtained. Furthermore, macrocell corrosion occurred and an increased corrosion rate was observed in the vicinity of a bending crack.

The influence of crack widths on the corrosion rate of steel reinforcement was investigated by Mohammed (2001). The relationship between crack width and corrosion rate was obvious in the first two weeks of exposure. In this period a wider crack leads to higher corrosion rate. However, the relation changes after four weeks of exposure. Taking into consideration the service life of a concrete structure, which is determined on the basis of the initiation period, the presence of cracks is more important than their widths with respect to corrosion of steel reinforcement. It should also be mentioned that uncracked specimens were negligibly corroded even after 13 weeks of exposure. In a study by Schießl (1997) a wider crack leads to increased corrosion of steel reinforcement, but on the long term the concrete cover and the concrete composition have a larger influence on corrosion than the crack width due to fact that the crack width decreased during the time of exposure. No significant relationship between crack width and corrosion rate was found. It was concluded that the corrosion rate in the cracked zone is influenced by the conditions between the cracks and the problem of reinforcement corrosion in the cracked zone cannot be solved by crack width limitation between 0.3 mm and 0.5 mm.

In a study by Otieno (2010) the influence of crack width on the corrosion rate of steel reinforcement for different types of binder and water-binder ratios was investigated for 31 weeks and with constant concrete cover. Two times reloading was applied during exposure time, where the crack widths were maintained wider for 24 hours under higher load before relaxing to the previous crack width level. It was noted that for the same water-binder ratio, the influence of crack widths is higher in the case of OPC than slag cement with respect to the corrosion rate. The influence of crack width on corrosion rate is less between 0.4 mm and 0.7 mm crack widths than between the uncracked and incipient cracked samples. It is obvious that adoption of unique threshold crack width can lead to overestimation or underestimation of the corrosion process. Consequently, various threshold crack widths have to be determined for a different concrete cover, binder type and water-binder

2.1 Binder type

Several research projects have been executed to investigate the impact of the binder type on chloride penetration and chloride-induced corrosion in cracked concrete e.g. Konin (1998), Garces Rodriguez (2003), Scott and Alexander (2007). Besides OPC (ordinary Portland cement), blends of Portland cement with fly ash, silica fume, blast furnace slag were tested. At the end of those experiments it is generally concluded that samples including SCM-s (supplementary cementitious materials) have more resistance to chloride penetration than samples with OPC. It occurs due to chemical and physical reasons. SCM-s can bind more chlorides than OPC. Furthermore, pore structure of OPC is more prone to chloride penetration in comparison with pore structure of SCM-s. In a study by Konin (1998) chloride penetration was decreased in the presence of silica fume in cracked concrete specimens and a similar observation was made by Jang (2011) in the presence of fly ash and by Garces Rodriguez (2003) who used blast furnace slag.

In a study by Scott and Alexander (2007) the influence of binder type on corrosion rate was investigated using seven different concrete mixtures comprising OPC and blends of Portland cement with ground granulated blast furnace slag, silica fume and fly ash. It was concluded that the use of any SCM leads to a significant reduction in corrosion rate compared to the use of only OPC due to higher resistivity of SCM-s. For example, average resistivity and corrosion rate values for 20 mm concrete cover and 0.2 mm crack width specimens were around 15 kΩcm , 35 kΩcm, 100 kΩcm and 2.5 µA/cm2, 0.7 µA/cm2, 0.6 µA/cm2 after 85 weeks of chloride exposure for OPC, silica fume and fly ash respectively. It is important to note that samples with Portland cement show a high reduction in corrosion rate when the cover depth of 20 mm is compared to 40 mm. However, negligible corrosion rate reduction was obtained in the case of samples with SCM-s when the cover depth was doubled from 20 mm to 40 mm. It means that the corrosion rate of the samples cast with SCM-s is controlled by resistivity and that a limitation of oxygen availability by increased concrete cover has negligible impact. However, in the case of samples with OPC which have low resistivity, an increased cover depth leads to a significant reduction in corrosion rate due to decreasing the availability of oxygen. On the other hand, all samples with SCM-s showed a lower corrosion risk with a cover depth of 20 mm and a 0.7 mm crack width than OPC with 40 mm cover depth and 0.2 mm crack width. It was concluded that the binder type is much more important with respect to steel corrosion than concrete cover and crack width for a constant water-binder ratio. However, these results were obtained on samples with one single crack and static loading. It is expected that results will be different in the case of many cracks under a variable load, which is more similar to reality. Further research is needed for better understanding the relationship between binder type, concrete cover and cracks (crack width, crack frequency and crack depth).

It can be concluded that concrete including SCM-s is more resistant to chloride-induced corrosion than concrete with OPC. The resistivity of SCM-s leads engi-

neers to utilize this binder in severe environmental conditions due to lower risk of deterioration with respect to durability of reinforced concrete structures.

2.2 Water-binder ratio

The water-binder ratio is an important factor with regard to chloride penetration and chloride-induced corrosion in cracked concrete. It was concluded by the authors Djerbi (2008), Konin (2008) and Win (2004) that the higher is the water-binder ratio, the higher is chloride ingress in concrete. A higher water-binder ratio leads to a more permeable concrete cover and a higher corrosion rate. In a study by Mohammed (2001) the influence of crack width and water-binder ratio on corrosion rate was investigated on 28 days old concrete prisms. It was concluded that the relationship between water-cement ratio and corrosion rate of steel reinforcement in cracked concrete is more relevant than the relationship between crack width and corrosion rate. In study by Otieno (2010) the influence of two types of binder, OPC and 50/50 OPC/GGCS (ground granulated Corex slag) blend, on the corrosion rate in cracked concrete was investigated. It was found that the corrosion rate is decreased when the water-binder ratio is decreased, but OPC specimens are much more sensitive to changes in water-binder ratio than Corex slag specimens.

2.3 Loading

During laboratory research several methods have been developed to induce cracks in concrete specimens after some standard procedure of preparation as described by Šavija and Schlangen (2010). In most investigations cracked samples have been exposed to chloride ingress in the unloaded state. In reality however cracks and steel reinforcement are in the tensile zone of the structure in the loaded state. Consequently, these measurements in the unloaded state might differ from reality. Antoni (2005), Gowripalan (2000) and Lim (2000) took into account this important influencing parameter by measuring chloride penetration in a loaded state. In a study by Gowripalan (2000) a flexural sustained load was applied during chloride exposure which was executed in the form of an immersion test. It was concluded that under flexural loading, at the tensile face higher chloride ingress occurs than at the compressive face.

A sustained compressive load as well as cyclic loading was applied on plain and fibre reinforced concrete samples in a study by Antoni (2005). Under a low level of static loading the results showed a slight reduction of chloride ingress, but under higher stresses an increased ingress has been recorded. Chloride ingress is increased even more at cyclic loading conditions showing different behaviour of fibre reinforced concrete and plain concrete for a different number of cycles and load levels. The influence of cyclic loading on chloride penetration was also studied by Küter (2005) and Wang (2011) who found different effects for static and cyclic loading. It was concluded, in a study by Küter (2005), that cyclic opening and closing of concrete cracks leads to higher chloride ingress than obtained with ratio. The statement that 0.4 mm is the threshold crack width is not valid any more, after that study, due to the fact that incipient cracks, in the case of OPC, lead to a significant effect on the corrosion rate during both phases, initiation and propagation. Corrosion of reinforcing steel was accelerated by reloading due to reactivation of self-healed cracks, damage on the concrete-steel interface, increased stress in the steel, aggregate-paste interfaces etc. The process of self-healing was stopped by reloading, but reloading was applied just twice during exposure. However, in reality loading and unloading occurs every day, which leads to reopening of cracks more often.

It can be concluded that variable loading should be experimentally applied to observe the effect of variable crack width on chloride-induced corrosion for a specific binder type, water-binder ratio and concrete cover. Generally, there is no relationship between crack width and corrosion, but the initiation period is shorter if the crack is wider. However, the influence of crack width on corrosion initiation and propagation is still not sufficiently explored, especially regarding the propagation period, and there is a need for further investigations.

3.2 Crack frequency

Chloride-induced corrosion in cracked concrete does not depend only on the surface crack width. Also the crack frequency (number of cracks per specific length) plays a significant role. In a study by Arya and Ofori-Darko (1996) the effect of crack frequency on the corrosion of reinforcing steel was investigated using reinforced concrete beams with a varying number of parallel sided cracks per meter. However, the crack depth was constant and the sum of total crack width in each series was 2.4 mm. The water-binder ratio and the concrete cover were constant. An increased crack frequency leads to a higher corrosion rate except in the case of 20 cracks where the process of self-healing was active. It was concluded that limiting the crack frequency is more important than limiting the surface crack width in order to control corrosion of steel reinforcement. However, in real structures flexural cracks do not have the same depth along the beam. Although these smooth cracks can be easily controlled by a researcher, disadvantages of this method prevent the use of crack width limitations for practical purposes. For instance, crack roughness, crack tortuosity and crack shape are only a few factors which are the most important with regard to difference between real-induced and artificially induced cracks. Self-healing could occur due to the unloaded state of the beam. On the contrary, under a variable load self-healing and crack blocking by corrosion products might be very small. Consequently, the effect of crack frequency on steel corrosion in function of time would be different for real structures.

3.3 Crack orientation and geometry

As far as crack orientation is concerned two groups can be distinguished: longitudinal (coincident) cracks and transverse (intersecting) cracks. While coincident

cracks are parallel to the reinforcement, intersecting cracks are perpendicular to the reinforcement. Coincident cracks can be extremely dangerous for corrosion of steel reinforcement due to easy access of chlorides, moisture and oxygen to a huge area of the steel reinforcement. The corrosion process will occur even faster in time. Therefore, coincident cracks can significantly shorten the service life of a concrete structure. As far as transverse cracks are concerned, the cathode site is situated between the cracks, where oxygen and moisture have to reach the embedded steel through sound concrete in order to enable the corrosion process. However, it remains an open question, to what extent intersecting cracks affect steel corrosion during the propagation phase.

In a study by Arya (1995) it was concluded that the corrosion rate in the propagation phase depends on crack, concrete and steel properties. In the case of crack properties, the crack propagation state and crack geometry should not be neglected with respect to the effect of cracks on the corrosion of steel reinforcement. While some crack widths do not vary with time (dormant cracks), the other can vary (live cracks). Cracks can be different with respect to their propagation state due to the self-healing process and crack blocking by corrosion products. On the one hand, dormant cracks can be blocked or self-healed. On the other hand, live cracks cannot be blocked due to loading, shrinkage, thermal effects and other expansion reactions. Crack geometry should also be taken into consideration with respect to crack properties. While it is simple to measure the surface crack width, the crack width at the bar surface cannot be observed in practice. Furthermore, the crack width at the bar surface is not related to the surface crack width. It depends on the origin of the crack, the cover depth, steel stresses, the distance between bars, bar diameters and the depth of the tensile zone. It should be emphasized that crack width at the bar surface is more important than surface crack width with respect to corrosion of steel reinforcement.

3.4 Crack depth

The impact of crack depth on chloride penetration in concrete was emphasized in a study by Audenaert and Marsavina (2009 a, b). It was reported that the influence of crack depth is of major importance compared to crack width, and this influence is more emphasized if the duration of exposure is longer. However, the cracks are artificially induced with parallel-wall. It is obvious that such testing conditions deviate from practice where the cracks are V-shaped and crack width and depth are correlated as opposed to experiment, where constant crack width and variable crack depth are created.

An appropriate experimental set-up is required to interconnect the impact of crack width, crack depth, crack frequency and loading on chloride-induced corrosion in a simulated marine environment by future researchers.

4. Conclusion

The uncertainty about the maximum allowable crack width in reinforced concrete structures has large economic consequences. For many existing structures a larger allowable crack width would save huge amounts of money due to the fact that expensive durability repair and maintenance measures can be reduced, delayed or even cancelled. The value of 0.4 mm is generally adopted as threshold crack width based on experimental and field results. It is believed that if the surface crack width is below of 0.4 mm, corrosion of reinforcing steel occurs in a similar way as in uncracked concrete. This simplification by adopting one unique threshold crack width is not very reliable. Other factors such as binder type, water-binder ratio, loading, exposure conditions, crack frequency, crack orientation and geometry, crack depth and mitigating mechanisms influence the effect of crack width on corrosion of reinforcing steel. The threshold crack width in current structural codes based only on exposure class is unsatisfactory. There is a need for an improved approach to this problem. The maximum allowable crack width should not be a unique value due to the complexity of the problem. The threshold crack width depends on the type of concrete structure, the location within the structure, concrete quality, exposure class, loading, cover depth, crack frequency, crack orientation and geometry, crack depth, mitigating mechanisms etc. All these factors should be taken into account, directly or indirectly. It can be concluded that the unique limit value of 0.4 mm is just deterministic solution so far, but it is obvious that appropriate stochastic solution is required to limit crack width. Consequently, variable crack width limits should be accepted depending on aforementioned factors by structural codes.

Although there is no direct relationship between crack width and corrosion rate, cracks have an influence on corrosion initiation and, therefore, it was generally adopted that the initiation period is shorter if the crack is wider. Taking into consideration that service life predictions of concrete structures are still based only on the initiation period, the role of cracks should not be neglected in prediction models. However, interconnected impact of crack width, crack frequency and crack depth on chloride-induced corrosion is not explored a sufficiently with regard to the initiation and propagation phase under simulated environmental conditions in a marine environment.

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