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Review

# The Role of Cracks in Chloride-Induced Corrosion of Carbon Steel in Concrete—Review

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**Abstract:** The majority of works in the field of chloride-indued corrosion of steel in concrete are focused on the cracks formed by the corrosion products. However, the number of studies on the influence of cracks (pre-cracked concrete) on corrosion is limited. Cracks create preferential/free paths for the penetration of chlorides, water, and oxygen into concrete; thus, the presence of cracks in concrete can intensify chloride-induced corrosion of steel reinforcement. This paper presents a review of the effects of cracking on the corrosion of steel in concrete. It was widely reported in the reviewed papers that cracks have a negative impact on concrete durability. They influence the chloride penetration and the chloride-induced corrosion of reinforcement in terms of the initiation and propagation stages. This influence is a complex function of many factors, including mix design, exposure conditions, crack frequency, crack orientation, crack width, and cover depth. Although there is a general agreement on the effects of cracks on the initiation of corrosion, the role of cracks and their widths on the propagation of corrosion in the long term is still under debate.

**Keywords:** corrosion; concrete; crack; chlorides; permeability

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## 1. Introduction

Generally, reinforced concrete uses carbon steel to provide the tensile properties needed in structural concrete. Steel-reinforced concrete represents a very successful combination of materials from a mechanical point of view and a chemical perspective. Sound (uncracked) concrete provides the steel with excellent protection against corrosion due to the highly alkaline (pH 12.5–13.8) pore solution contained in the cement paste component of the concrete. A passive film forms on the steel at a high pH level, protecting it from corrosion [1]. However, the corrosion of reinforcing steel bars in concrete structures is often the primary deterioration mechanism in those structures. Chloride ions can break the passive film on the surface of steel and initiate corrosion. Chloride ions can be present in the concrete due to the use of chloride-contaminated components or $CaCl_2$ as an accelerator when mixing the concrete or by penetration into the concrete from the outside environment, e.g., deicing salts. A localized breakdown of the passive film occurs when a sufficient concentration of chlorides reaches the reinforcing bars and the corrosion process is then initiated [1]. Chlorides in concrete can be either dissolved in the pore solution (free chlorides) or chemically and/or physically bound to the cement hydrates and their surfaces (bound chlorides).

Corrosion is an electrochemical reaction consisting of anodic and cathodic half-cell reactions [2]. Micro-cell corrosion refers to the situation where active dissolution and the corresponding cathodic half-cell reaction occur in adjacent parts of the same metal. For a steel reinforcing bar in concrete, the surface of the corroding steel can act as a mixed electrode containing both anode and cathode regions connected by the bar itself. Macro-cell corrosion can also form on a single bar exposed to different environments within the concrete or where part of the bar extends outside the concrete [3]. In both cases, the concrete pore solution functions as an electrolyte. When the reinforcement corrodes, the formation of the corrosion products may lead to a loss of bond between the steel and the concrete. They are also expansive and cause delamination and spalling. Corrosion also decreases the cross-section and, as a result, the load-bearing capacity of the steel. Additionally, expensive corrosion products lead to cracking and spalling [4].

As schematically illustrated in Figure 1, in the presence of cracks in concrete, the aggressive nature of chloride-induced corrosion and the related rate of deterioration of a steel-reinforced concrete structure are intensified [5]. The presence of cracks creates preferential paths for the penetration of corrosion-inducing species, i.e., $Cl^-$, water, and oxygen, leading to the easier and faster initiation and propagation of the corrosion of steel in concrete. The effects of cracks on corrosion are a function of their width, depth, frequency, tortuosity (surface roughness), and orientation (relative to the steel reinforcement) [6–11].

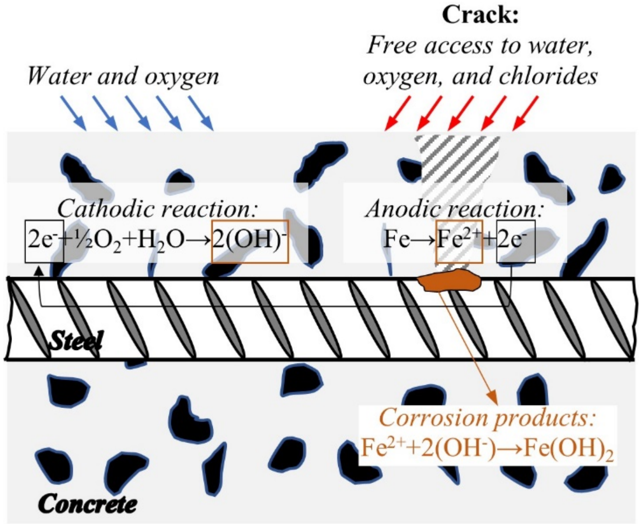

**Figure 1.** Schematic illustration of the chloride-induced corrosion of steel in cracked concrete.

Due to the importance of this subject, the number of research programs conducted on this topic has rapidly increased in recent years. There is a need in the body of knowledge to encapsulate the relevant findings in the form of a state-of-the-art review. This paper reviews the influence of cracks on the corrosion of the steel reinforcing bars in concrete structures.

There are many related topics beyond the targeted scope of the current review that warrant their own review papers. A comprehensive review of these topics is left for other papers; however, a few brief comments should be made to explain the complex nature of steel corrosion and concrete cracking. The corrosion of steel reinforcement can be both the result and the cause of cracking. This paper focuses on how cracks influence corrosion; however, the opposite effect can also occur. The products of the electrochemical corrosion process have a greater volume than uncorroded steel. Thus, when steel embedded in concrete corrodes, the expanded products lead to bursting stresses in the concrete, which in turn lead to cracking and spalling to make room for the new products. The additional cracks and spalling can accelerate corrosion, which can accelerate concrete damage, and so on. The mutually influential processes of cracking and corrosion can thus lead to the rapid deterioration of structural concrete with steel reinforcing bars.

## 2. Different Types of Cracks

Cracking in reinforced concrete structures occurs due to diverse and complex processes such as physical loads, creep and shrinkage, and thermal stress. Cracks form when the summation of tensile stresses exceeds the concrete tensile strength. According to ACI committee 224, cracking can be classified into two main categories based on the time of the crack occurrence, i.e., cracks occurring before concrete hardening (plastic stage) or after concrete hardening, as shown in Figure 2 [12]. The cracking phenomena can be further subdivided. For example, cracking due to applied loads can be characterized as flexural, shear, or torsional cracks. Cracking can also be characterized by size, location, and severity. Internal microcracking, or non-structural cracks, result from the intrinsic properties of concrete and its ingredients [13].

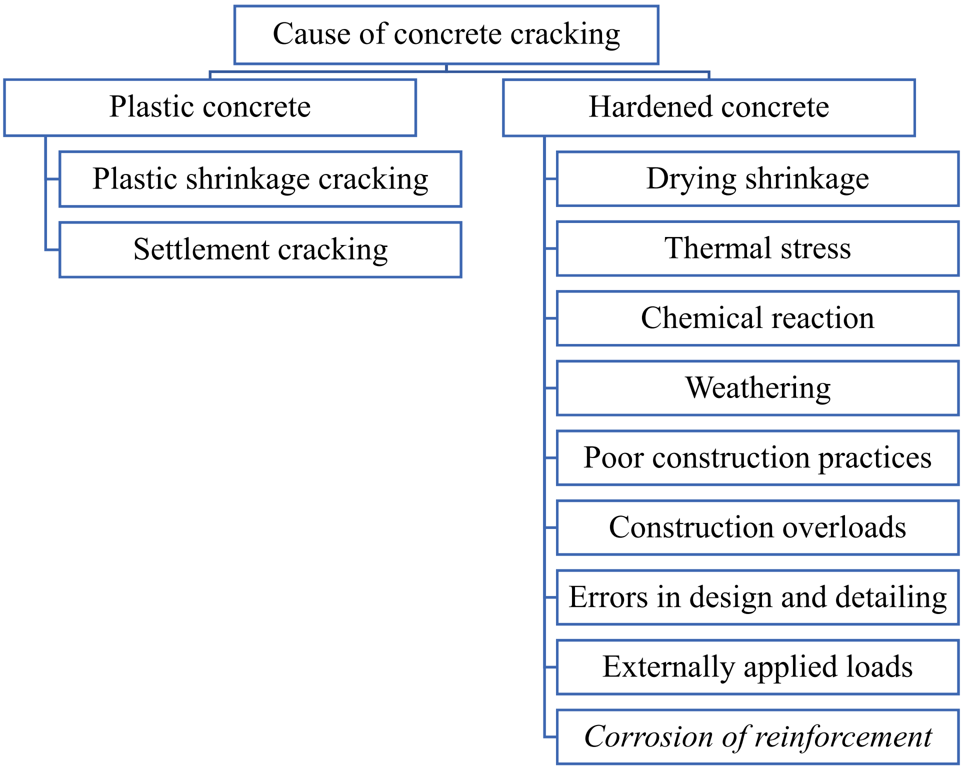

**Figure 2.** Causes of concrete cracking.

## 3. Crack Size

The term "allowable crack width" denotes the range of maximum crack widths acceptable in reinforced concrete members, which should not impair durability or serviceability. "Crack control" includes actions taken during design to limit the quantity and size of cracking and to keep cracks within allowable limits. Even though proper mix design, placement, and curing can prevent or minimize the occurrence of many types of cracks listed previously, concrete cracking is still inevitable during the life span of reinforced concrete structures. Therefore, many building and construction codes include a range of crack limits based on the severity of the exposure conditions and the type of the structure. Table 1 summarizes these tolerable crack width values from different codes [12,14–17]. The crack widths are defined at the surface of the concrete structure under the quasi-permanent load combination. It should be noted that these values are for reinforced concrete, not for pre-stressed concrete.

These guidelines can be used to select reinforcement details to control cracks during the design stage. The guidelines can also be used as thresholds for evaluating concrete cracking in existing structures. There is no consensus regarding the maximum crack widths, as shown in Table 1. For example, the maximum allowable crack width in reinforced concrete members exposed to deicing chemicals is 0.18 mm by ACI Committee 224 and 0.3 mm by Eurocode 2. Two additional points are important regarding allowable crack widths. First, crack widths can change over time, and second, these crack width values are not always a reliable indication of the occurrence of corrosion and deterioration [12]. Thus, these limitations are helpful guidelines and starting points but are not hard and fast rules.

**Table 1.** Allowable crack widths from different codes. Note ACI and AASHTO values are converted from inches to mm.

| Reference | Exposure Condition | Crack Width (mm) |
|---|---|---|
| ACI committee 224 | Dry air or protective membrane | 0.41 |
| | Humidity, moist air, soil | 0.30 |
| | Deicing chemicals | 0.18 |
| | Seawater and seawater spray, wetting and drying | 0.15 |
| | Water-retaining structures | 0.10 |
| AASHTO LRFD | Corrosion is not concern | 0.43 |
| | Corrosion is a concern | 0.32 |
| Eurocode 2 | All classes except for X0 and XC1 | 0.3 |
| Eurocode 2 | Class X0 (No risk of corrosion)<br>Class XC1 (Carbonation induced corrosion-Dry of permanent wet) | 0.4 |
| fib-model code | Classes X0 (No risk of corrosion) and XC (Corrosion induced by carbonation) | 0.3 |
| fib-model cod | XD (Corrosion induced by chlorides other than from seawater), XS (Corrosion induced by chlorides from seawater), and CF (Freezing and thawing attach) | 0.2 |
| BS-8110 | No risk of corrosion or attack/Dry or permanently wet | 0.4 |
| | All other conditions | 0.3 |

## 4. Concrete Cracking Effects

As a result of the low permeability of the concrete, the rate of transport of deleterious materials is low. This is critical to durability, particularly for reinforced concrete members in aggressive environments. However, concrete is a frequently cracked material due to numerous physio-chemical mechanisms, as described previously. Many of these cracks could be considered acceptable in terms of the allowable limits outlined in the design codes. However, these limits may not be sufficient to prevent the ingress of deleterious materials. For example, the maximum acceptable surface crack widths for reinforced concrete members exposed to deicing salts is 0.18 mm according to the ACI committee 224 [12]. However, Krauss and Rogalla found that chloride and water can penetrate the concrete surface with cracks as narrow as 0.05 mm and thereby accelerate the corrosion of reinforcing steel at the crack location [18]. This width is less than one-third of the ACI 224 allowable limit. In addition to enabling the corrosion of reinforcement, cracks may impair structure appearance (aesthetic impact), durability (beyond reinforcement corrosion), and serviceability (ability to perform the intended function). Increased displacement is one example of a serviceability concern. As the concrete cracks, member stiffness is reduced and displacements increase.

### *4.1. Effects of Cracks on Chloride Ingress*

Chloride penetration, among the various factors that may influence the durability of concrete, is highlighted as the primary cause of embedded steel corrosion. Cracks enhance the penetration of chloride ions by providing easy access, leading to corrosion initiation and localized debonding at the crack location.

Many researchers have examined the effects of cracks on concrete permeability and chloride penetration into the concrete. Examples of these studies are summarized in (Table 2).

It can be seen that a wide variety of results have been achieved regarding the effects of cracks on chloride penetration. One trend in the referenced studies is that chloride penetration is a function of the crack width unless the cracks are very small (no access to chloride through cracks), very large (free access of chlorides through cracks), or in between; increased accessibility develops with increasing crack width. This was observed in 14 of the 22 studies summarized in the table. Still, 8 of 22 studies reported no influence between crack width and chloride penetration. Because of these sometimes conflicting results, there is no clear consensus on the impact of crack width.

**Table 2.** Summary of some studies on chloride penetration in cracked concrete.

| Paper | Crack Size (mm) | Material | Conclusion |
|---|---|---|---|
| [19] | 0.07 and 1.08 | Steel fiber reinforced concrete | Chloride concentrations increase with larger crack widths. Cracks ≤0.2 mm wide have a marginal influence on chloride concentration. |
| [20] | 0.05 to 0.4 | Normal strength concrete and high-strength concrete | Crack width influences water permeability more than chloride permeability. Chloride conductivity was sensitive to cracking only for high-strength concrete with low water to cement ratio. |
| [21] | 0.20, 0.30, 0.50 | Mortar | The crack width and crack depth are influential factors. |
| [22] | 0.05 to 0.50 | Steel reinforced concrete | Chloride penetration is significantly impacted by applied loads, more so than crack width or even the presence of cracks themselves. |
| [23] | up to 0.30 | Steel reinforced concrete | The value of the chloride diffusion coefficient in the tension zone was found to be relatively higher than in the compression zone due to the damage at the aggregate paste interface in the tension zone. |
| [24] | 0.06 to 0.74 | Concrete | Crack width and the crack wall roughness have no effect on chloride diffusion in concrete. |
| [25] | Multi cracks 0.10 and 0.20<br>Single crack 0.10, 0.20, 0.30, 0.50 | Steel reinforced concrete | Concentration distribution of chloride was similar in all specimens, except the specimen with a crack width of 0.50 mm, which had higher penetration. |
| [26] | 0.20 and 0.70 | Steel reinforced concrete | The presence of cracks enabled a rapid ingress of chlorides. Generally, the chloride concentration increased with crack width. |
| [27] | 0.03 and 0.40 | Steel reinforced mortar | The effective diffusion coefficient increased as crack width was increased. The effect was marginal for widths <135 µm. |
| [28] | 0.03 to 0.25 | Ordinary portland cement concrete, high performance concretes, and high performance concretes with silica fume | The chloride diffusion coefficient increased with the increase of crack width. |
| [29] | 0.06 to 0.32 | Mortar | Chloride penetrations tend to increase as crack widths increase, except in the case of crack width <0.06 mm, penetration decreased with time due to self-healing. No chloride penetration was observed for widths <0.03 mm regardless of age. |
| [30] | Up to 0.20 | Concrete, Steel reinforced concrete | Chloride penetrations increased as crack width increased for widths 0 to 0.1 mm. Crack widths between 0.10 and 0.20 mm had a similar influence. |
| [31] | 0.20, 0.30 or 0.50 | Concrete | No clear relationship between chloride ingress and crack width was reported. |
| [32] | 0.06, 0.08, 0.11, 0.15 and 0.20 | Concrete | A threshold crack width of 55–80 µm was reported; widths below this threshold did not affect chloride diffusion coefficients. Chloride diffusion increased as a function of crack width above the threshold. |
| [33] | 0.05, 0.10, 0.15, and 0.20 | Concrete | Increasing crack width leads to a higher chloride concentration at the crack surface. |

**Table 2.** *Cont.*

| Paper | Crack Size (mm) | Material | Conclusion |
|---|---|---|---|
| [34] | Target cracks are 0.02, 0.04, 0.05, 0.10, 0.15 and 0.20 | Concrete | Two critical crack width values were reported: 0.013 mm and 0.04 mm for short- and long-term experiments, respectively. Width had no significant influence below the critical value on the chloride penetration, whereas chloride penetration proceeded faster above the critical widths. |
| [35] | 0.40 and 0.70 | Steel reinforced concrete | The corrosion in both initiation and propagation phases was significantly affected by the presence of cracks; moreover, corrosion rate was proportional to crack width. |
| [8] | 0.20, 0.30, 0.40, and 0.50 | Steel reinforced concrete | The corrosion rates for cracked specimens increased relative to chloride concentration and crack width. |
| [36] | 0.10, 0.30, and 0.40 | Concrete | Regardless of crack opening size, corrosion activity was greatest at the location of the crack. The degree and extent of corrosion were proportional to the crack opening size. |
| [37] | 0.10 and 0.40 | Concrete | There was no correlation between the maximum flexural crack width and the maximum local corrosion level. |
| [38] | 0.10 to 0.20 | Concrete | Increased chloride ingress was detected in cracked areas, but very little corrosion was observed where cracks reached the reinforcement. |
| [39] | 0.1 and 0.2 | Concrete | Cracks are favored regions for corrosion initiation in cyclic wetting/drying exposure. Once corrosion has initiated and propagated, the environmental exposure RH strongly influences the macro-cell current between the wetting events. |

### *4.2. Influence of Concrete Cracking on Reinforcement Corrosion*

The influence of concrete cracking on reinforcement corrosion could be a function of the frequency of cracks (number of cracks per a specific length), crack direction compared to the reinforcement, crack width, and crack length.

#### 4.2.1. Effects of Crack Frequency

Arya and Ofori-Darko conducted a study on 28 135 mm × 100 mm × 1360 mm steel-reinforced concrete beams containing 0, 1, 4, 8, 12, 16, and 20 parallel cracks per meter, with a water-to-cement ratio and concrete cover of 0.65 and 42 mm, respectively [40]. The total sum of the crack widths of each cracked beam was 2.4 mm, i.e., some beam specimens had fewer but wider cracks and others had more but narrower cracks. Beams were sprayed with a 3% NaCl solution for 24 months. The results of all cracked beams, except the one with 20 cracks, showed an increase in the weight loss of the embedded reinforcement with the increase in crack frequency. In the case of the beam with 20 cracks, it was suggested that the cracks were undergoing a self-healing process. The authors hypothesized that the corrosion of the reinforcing steel might be effectively controlled by limiting the number of cracks rather than limiting the surface crack widths.

On the contrary, in the study by Schiessl and Raupach, the opposite behavior was observed where the corrosion rate decreased as the spacing between the cracks decreased (i.e., frequency of cracks increased) [41]. They also reported that the corrosion rate doubled as the crack frequency decreased by half. They suggest that increasing crack quantity resulted in more anodic points and fewer cathodic areas between cracks.

In another study by Blagojević, the corrosion of the embedded steel in cracked concrete beams with different concrete covers of 20, 30, and 40 mm was investigated [42]. The beams with 20 mm, 30 mm, and 40 mm of concrete cover had 9, 8, and 6 active cracks, respectively, with a mean crack width of 0.15 mm for each beam. The results showed that the corrosion of the reinforcement tended to decrease when the crack frequency decreased and the concrete cover increased. It was concluded that the frequency of cracks was a function of concrete cover; therefore, the crack frequency was considered a secondary parameter in steel corrosion.

As can be seen, there is no clear answer regarding the relationship between the crack frequency and the corrosion rate. It appears that corrosion is affected by many interacting variables, including crack frequency and concrete cover.

#### 4.2.2. Effects of Crack Orientation

Concrete cracks can be classified according to their orientation with respect to the reinforcement, i.e., longitudinal (or coincident) cracks that are parallel to the reinforcement and transverse (or intersecting) cracks that are perpendicular to the reinforcement [43,44]. Typically, longitudinal cracks develop as the result of plastic shrinkage, bond failure, and plastic settlement [44,45]. Longitudinal cracks are problematic because they expose a large portion of the embedded reinforcement to the aggressive species, e.g., chlorides, leading to the initiation of corrosion in multiple locations [44–46]. Poursaee and Hansson studied the corrosion in concrete beams with longitudinal and transverse cracks and they observed that the corrosion current density was higher in the case of concrete with longitudinal cracks than that with transverse cracks of the same width of 0.1 mm [11]. However, in the reinforced concrete structures with transverse cracks, steel often carries significant tensile stresses, impacting the corrosion rate, as observed by [22,47]. Two possible scenarios of longitudinal cracks are suggested. In the first one, a single bar running parallel to the crack of a corrosion cell (anodic and cathodic reactions) occurs within the crack zone. In the second one, the anodic reaction occurs at the intersecting point of the longitudinal and transverse reinforcement, where they are connected electronically, whereas the cathodic reaction takes place in the reinforcement in the uncracked parts of the concrete. More corrosion activity is expected in the second scenario due to the combined large cathode area in sound concrete and the small anode area at the crack.

#### 4.2.3. Effects of Crack Width

Crack width is an important criterion influencing the corrosion of embedded reinforcement steel in concrete. Hence, the influence of crack widths on steel corrosion in concrete has been extensively studied in recent decades. However, the role of cracks and their widths on long-term corrosion (propagation stage) is still debatable.

Uncracked and cracked steel-reinforced concrete specimens with different crack widths of incipient cracks, 0.4 mm and 0.7 mm, and different binder and $w/b$ (water-to-binder) ratios were included in an experimental study by Otieno et al. [6,35]. The specimens were subjected to a pond test with saltwater with 5% NaCl with three days of wetting and four days of drying each week. During exposure, cracks were reopened two times (between weeks 9–10 and 18–19). The entire test program lasted for 31 weeks. It was found that the corrosion in both the initiation and propagation phases was significantly affected by the presence of cracks. Moreover, the corrosion rate was proportional to the increase in the crack width for a given binder type and $w/b$ ratio. For a given $w/b$ ratio, the corrosion rate was higher in the case of ordinary portland cement concrete than it was for slag cement. An acceleration in the steel reinforcement corrosion due to reloading was also observed. The authors suggested that the concrete quality, $w/b$, and/or cover depth should be taken into account when adopting a crack-width threshold in which the corrosion activity in cracked concrete could be considered the same as in sound concrete.

Sahmaran and Yaman [48] conducted two different tests on pre-cracked mortar. Chloride penetration and the initiation of corrosion were evaluated using a salt ponding test. An accelerated corrosion test was performed by immersing pre-cracked specimens in a 5% NaCl solution and applying a constant voltage of 12 V to determine the effects of cracks on corrosion propagation. Crack widths were generated by flexural loads with a range of cracks from 0.029 to 0.390 mm. The results showed that crack width influenced corrosion initiation and propagation. The chloride diffusivity coefficient was observed to increase with crack widths. In addition, it was noted that a crack width larger than 135 μm had the most significant impact on the initiation and propagation stages. A laboratory study by Schiessl and Raupach [41] showed a considerable influence of crack widths on the chloride-induced corrosion of steel in the short term for widths of 0.3–0.5 mm. In long-term observations, no notable influence of crack widths on the corrosion rate was reported, and the corrosion rate appeared to be controlled by the conditions between the cracks (e.g., concrete cover and composition). Under laboratory conditions, crack healing may play a role, whereas under real conditions this effect may be considerably less (in real structures the cracks open and close due to traffic loads, temperature deviations, shrinkage, etc.). They concluded that crack widths cannot fully address reinforcement corrosion. Jaffer and Hansson studied the corrosion of cracked concrete under load [49]. They found that corrosion formed at the intersection of cracks and rebar only. Their experiments included 36 steel-reinforced concrete beams with two concrete mixes, including ordinary portland cement concrete and high-performance concrete with slag and fly ash. Furthermore, they considered three loading types: dynamic, static, and unloading. Specimens were cracked under three-point bending and then partially immersed vertically in a 3% NaCl solution. Their experiments included wet and dry cycles over 18 months. They concluded that the influence of cracks on the corrosion process is an important criterion in the health monitoring of reinforced concrete structures.

Mohammed et al. [50] carried out a study to investigate how crack width and bar-type influence the corrosion rate. This study used single-crack steel-reinforced mortar specimens and multicrack reinforced concrete beams. The single-crack specimens had crack widths of 0.1 mm, 0.3 mm, and 0.7 mm. The mortar specimens were made with water-to-cement ratios of 0.3, 0.5, and 0.7. Uncracked specimens were also considered in this study. The specimens were periodically sprayed with a 3.5% NaCl solution and the experiment lasted for 13 weeks. A higher corrosion rate was observed in specimens with larger crack widths in the first two weeks of the experiment; however, after four weeks of exposure, the relationship between crack width and the corrosion rate was not distinct. A negligible current density was reported for the uncracked specimens after 13 weeks. It was concluded that cracks are more consequential for the corrosion of steel reinforcement than crack widths.

François et al. conducted long-term studies to investigate the influence of concrete cracking on reinforcement corrosion [22,47] and the mechanical behavior of reinforced concrete structures in aggressive environments [51]. The program was conducted on 3 m long reinforced concrete beams. The specimens were kept in a confined salt fog of 35 g/L of NaCl in a loaded state. The first two studies were carried out after 12 years and the third after 17 years of exposure. The authors concluded that cracks have no effect on steel reinforcement corrosion development for crack widths less than 0.5 mm. The results showed that the applied load plays a major role in the corrosion and mechanical behavior of reinforced concrete members exposed to aggressive conditions. The authors suggested that service loads lead to microcracking, which allows the ingress of harmful substances. These substances then affect the service life of the structure by initiating corrosion.

Another study by François et al. [52] showed that the crack existence, regardless of width, greatly influenced the corrosion initiation time for steel-reinforced concrete specimens in the NaCl solution. However, there was no notable influence of crack width on long-term corrosion due to the formation of additional cracks due to corrosion. The additional cracks began to dominate the corrosion activity and the process was controlled by mechanical stress intensity.

Dang et al. [53] investigated ring-shaped mortar samples with cracks from 0 to 100 μm. A process of wet and dry cycles with 35 g/L NaCl salt solution was carried out to accelerate reinforcement corrosion. The samples were broken after 1.5 and 2.5 years and visually investigated. The results also showed the importance of cracks in corrosion with no relationship between crack width and corrosion.

The influence of cover cracking on chloride-induced corrosion was experimentally investigated by Li et al. [8] through a 654-day laboratory test on cracked reinforced concrete specimens exposed to a chloride solution. The concrete specimens were made with different crack widths of uncracked, 0.2, 0.3, 0.4, and 0.5 mm, and immersed in a NaCl solution. The results showed that the corrosion rates for the cracked specimens increased with the increasing percentage concentration of chloride and the increasing crack width.

Chen and colleagues [37] studied the corrosion pattern and characteristics of rebars in un- and pre-cracked reinforced concrete beams subjected to natural corrosion for more than three years. They found no correlation between the maximum flexural crack width (nominally 0.1 and 0.4 mm) and the maximum local corrosion level.

Abo Alarab et al. [36] studied the influence of transverse crack opening size on the chloride-induced corrosion of steel bars in cracked concrete with three different crack opening sizes, 0.1, 0.3, and 0.7 mm. The results in the cracked and uncracked specimens showed that, regardless of the crack opening size, corrosion activity was most significant at the location of the crack. However, the corrosion process in specimens with a 0.1 mm crack opening slowed throughout the experiment. It is hypothesized that this is due to the build-up of corrosion products in the cracks. Since chloride ions were already in the vicinity of the steel, filling the crack would lead to a lack of oxygen, slowing the corrosion process. Compared with the specimens with a 0.1 mm crack opening, the corrosion activities in specimens with 0.3 and 0.7 mm crack openings remained relatively steady within the test period. The degree and extent of corrosion were proportional to the crack opening size, with the 0.7 mm crack opening being the highest and the 0.1 mm crack opening being the lowest.

## 5. Summary of Findings

The studies described above demonstrate the complicated relationship between concrete crack width, chloride diffusion, and reinforcement corrosion. At least the following factors confound this relationship:

- Initiation time versus propagation time
- Type of concrete and reinforcement
- The stress level in the reinforcement
- Duration of the experiment
- Formation of additional cracks due to corrosion itself
- Cover distance

Sixty-four percent of the referenced studies indicated that chloride penetration was a function of crack width. Still, 36 percent of the studies reported no influence between crack width and chloride penetration. Because of these sometimes conflicting results, there is no clear consensus on the impact of crack width. It appears that when all variables are constant, increased crack width tends to increase the corrosion of the reinforcement. The relationship between crack width and corrosion tends to be most significant for crack widths larger than approximately 0.20 mm. When cracks are narrow, the corrosion process is slowed down, possibly due to self-healing and corrosion products filling the cracks and thus limiting access to oxygen and chlorides. When cracks are large enough, their widths do not impact the ability of corrosive materials to enter the cracks and initiate and propagate corrosion.

This article reviewed different aspects related to the influence of cracks in concrete on the corrosion of the reinforcing carbon steel bars. It can be concluded that:

1. Cracks have a negative impact on concrete durability. Many codes and jurisdiction-specific guidelines include limits for crack width to mitigate this impact.
2. Cracks influence the chloride penetration and the chloride-induced corrosion of reinforcement in terms of the initiation and propagation stages. This influence is a

complex function of many factors, including mix design, exposure conditions, crack frequency, crack orientation, crack width, and cover depth.

3. There is a general agreement about the effects of cracks on corrosion initiation; however, the role of cracks and their widths on the propagation of corrosion in the long term is still under debate due to the complexity of factors described previously.

Because the impact of cracking on corrosion is a complex physical phenomenon, it is not easy to include all of the confounding factors in a single study. Based on the results of this review, a few recommendations are made to assist future researchers in selecting variables and designing experiments. First, give specific attention to the propagation of corrosion as this is a topic that is still under debate. Second, studies with multiple specimen types and/or crack causes should be considered. For example, some of the specimens could be beam specimens with flexural cracks, and others could be restrained bar specimens with shrinkage cracks. Understandably, previous works have relied on a single specimen type. Parallel tests with multiple specimen/crack types will demonstrate if the influence of cracking on corrosion is a function of the specimen and/or the causes of crack formation. Third, field studies are recommended. Coastal bridges with repetitive elements could be fruitful to study. Crack sizes in the elements—such as end region cracks in precast/pretensioned concrete girders—could be compared with the results of the electrochemical tests of corrosion.

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