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Distribution of Corrosion Attack in Chloride Exposed Concrete – Summary of Field Observations

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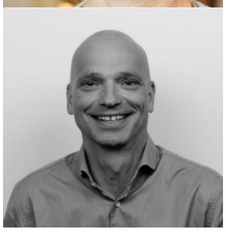

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ABSTRACT

Reinforcement corrosion is the main deterioration mechanism in chloride-exposed reinforced concrete (RC) structures. Depending on the moisture level, corrosion might initiate when aggressive agents like chloride ions reach the reinforcement surface. The propagation of active corrosion depends on both the moisture level and oxygen availability. Corrosion reduces the cross-sectional area and ductility of reinforcement. Depending on the severity of the attack and the corrosion products at the interface, it can lead to cracking and spalling of the concrete, thereby modifying bond-slip behaviour. Knowledge of the distribution of corrosion attack is required for the structural assessment of existing marine-exposed RC structures to extend their service life. This paper summarises observations of corrosion distribution on rebars excavated from RC elements after long-term exposure.

Key words: Concrete, reinforcement corrosion, chloride-induced corrosion, distribution of attack, field observations.

1. INTRODUCTION

Reinforcement corrosion is the primary cause of degradation of reinforced concrete (RC) structures exposed to a chloride-containing environment. The amount of chloride leading to sustained corrosion is, among others, affected by the metallurgy and surface characteristics of the reinforcement [1] and the moisture conditions at the reinforcement [2]. Chloride-induced corrosion is typically localised and results in so-called pits. However, depending on the conditions, it might change to more general corrosion.

Safe and sustainable management of existing RC structures requires knowledge of their structural capacity, including the impact of possible corrosion-induced damages on the performance. Suitable constitutive equations and valid input data are required for such structural analysis of damaged structures. The material behaviour and structural response due to reinforcement corrosion are affected by the spatial distribution of corrosion pits (e.g., distribution of local strain [3]), their geometry [4], and their possible interference [5], leading to changes in the stress-strain behavior of the rebars [6]. At the structural level, these effects can lead to a possible shift in the failure mode, from ductile to brittle, which is undesirable in a robust RC structure [7].

The present work aims to summarise observations of reinforcement corrosion attacked in long-term field-exposed RC elements, focusing on the main longitudinal reinforcement. Section 2 provides definitions used. Section 3 presents the cases and compares some observed features, such as the development of corrosion pattern with time, pitting factor, pit size, and pit proximity. Section 4 briefly discusses possible explanations for the observed corrosion patterns. Section 5 provides the conclusions.

2. DEFINITIONS

The following definitions are used:

Corrosion-induced damage: Cracking and spalling due to the accumulation of voluminous corrosion products at the steel-concrete interface (SCI). Cracks induced by corrosion are also referred to as corrosion-induced cracks.

Corrosion initiation: Formation of a stable anode on the reinforcement surface.

Corrosion pattern: The spatial distribution of corrosion attack; see general, localised, and mixed corrosion.

Defects: Inconsistencies that arise during construction.

Distribution of corrosion attack: Spatial distribution and extent of corrosion.

General corrosion: Corrosion attack on the whole surface.

Initial cracks: Cracks developed in concrete due to loads and other actions before exposure to a corrosive environment.

Localised corrosion: Corrosion attack of limited area (pits) surrounded by non-corroded steel.

Mixed corrosion: Combination of localised and general corrosion (see definitions above).

Pitting factor (P_f): The ratio of the largest corrosion attack to the average corrosion attack. Note that the characteristics of the corrosion attack vary; see Table 1.

Pit proximity: Distance between two adjacent (nearest) corrosion pits on a rebar.

Simulated natural corrosion: Corrosion in an artificial environment that replicates natural conditions. (It neither involves mixing chlorides into the concrete nor employs other electrochemical procedures to accelerate corrosion).

Steel-concrete interface (SCI): The complex, multi-phase, and multi-scale system comprising the reinforcement surface and the nearby part of the embedding concrete.

Top-bar effect: Effect of void formation in a downward direction under horizontal rebars in the upper part of a structure due to settlement, segregation, and bleeding of fresh concrete. The downward direction refers to the downward-facing surface (depends on the casting direction).

Table 1 – Methods used for determination of pitting factor

Parameter	Deepest pit		Average attack		Characterization method	Ref.
	Local	Global	Local	Global		
Diameter	x		x		Image analysis	[8]
Area		x		x	Gravimetric analysis	[9]
Diameter	x			x	Micrometer, microscope & gravimetric analysis	[10]
Diameter	x		x		Sliding calipers & gravimetric analysis	[11]

3. OBSERVATIONS

Observations from the literature on corrosion distribution in marine-exposed field elements are summarised in Table 2. As only three marine cases were identified where the reinforcement was fully excavated, the marine cases were supplemented with data from de-iced fields as well as salt (NaCl) exposed laboratory elements. Except for the 25-year-old marine-exposed beams studied by Geiker *et al.* [12] and the 9-year-old marine-exposed panel by Geiker *et al.* [13], all investigated elements exhibited some level of corrosion-induced damage at the time of the investigation.

3.1 Cases

Geiker *et al.* [12] observed only localised corrosion (no general corrosion) in pre-cracked 25-year-old marine-exposed RC beams (w/b=0.40) with plastic spacers. The beams were held vertically and exposed simultaneously to submerged, tidal, and atmospheric environments (variable tidal heights). Corrosion was primarily observed in a few plastic spacers used to maintain the specified concrete cover. The authors hypothesised that the very local nature of corrosion was due to the cathodic protection of large parts of the rebars due to the early corrosion initiation at plastic spacers, classified as the ‘‘weakest link’’.

Geiker *et al.* [13] examined the reinforcement from a pre-cracked RC panel (*w/b*=0.40, crack width 0.2-0.3 mm) with a large concrete cover (>75 mm) exposed to marine submerged and tidal environments for nine years. Shims were used to maintain the cracks, which were found to facilitate chloride ingress. Although chlorides were detected at the SCI, no significant corrosion was observed on the reinforcement. According to Geiker *et al.* [13], the absence of corrosion was possibly due to the combination of the crack type and location, the large cover, and the binder composition, providing a sustained high hydroxyl ion concentration.

Table 2 – Summary of literature observations of corrosion attack in chloride-exposed RC elements

Ref.	Age (yrs)	Element, size (m)	Rebar diameter (mm)	Load	Cover depth (mm)	Exposure[1]	Initial «defects» (width (mm))	Corrosion induced damage	Corrosion pattern
[12]	25	Beams 3x0.3x0.15	16	x	25	Marine (S+T+A)	Cracks (0.1-0.2) & spacers	-	Localised
[13]	9	Panel 2x1x0.2	12	x (shims)	>75	S+T	Cracks (0.2-0.3)	-	-
[14]	40	Beams 2.4x0.15x0.3	13	-	30	Spl. +T[2]	Cracks & top-bar	Cracking (10yrs)	Mixed
[14]	40	Beams 2.4x0.15x0.3	13	-	30	Spl. +T[2]	Top-bar	Cracking (10yrs)	Mixed
[15]	30	Edge beams	16	Service load	35-85	De-iced	Cracks	Local cracking & spalling	Primarily localised
[16]	35	Edge beams	16	Service load	35-85	De-iced	Cracks	Local cracking & spalling	Primarily localised
[17]	14/19/23	Beams 3x0.28x0.15	12	x	10	W/D[3]	Cracks & top-bar	Cracking (5yrs[5])	Mixed
[7]	26	Beams 3x0.28x0.15	12	x	10	W/D[3]	Cracks (top-bar)	Cracking (5yrs[5])	Mixed
[9]	14/19/23/28	Beams 3x0.28x0.15	12	x	10	W/D[3]	Cracks (top-bar?)	Cracking (5yrs[5])	Mixed
[3]	4-5	Beams 1.1x0.18x0.1	10	-	30	W/D[4]	Cracks (0.1/0.4)	Cracking	Localised (“long pits”)
[3]	4-5	Beams 1.1x0.18x0.1	10	-	30	W/D[4]	-	Cracking	Localised (“long pits”)

1) S – Submerged, Spl. – Splash, T – Tidal, A – Atmospheric, W/D – wetting-drying cycles with a NaCl solution.
2) 0 to 20 years: marine environment at the Sakata Port, 20 to 35 years: sheltered from the rain at the laboratory, and 35 to 40 years: stored at Kyushu University.
3) 0-6 years: continuous spraying, loaded; 6-9 years, loaded @20°C: a wetting-drying cycle of 35 g/l NaCl solution; 9-19 years: the wetting-drying cycle with 35 g/l NaCl solution @outside environment, loaded; 19-26 years: stop spraying, unloaded, outside environment; 26-28 years: the wetting-drying cycle with a NaCl solution, outside environment, unloaded.
4) Wetting-drying cycle with a 16.5% NaCl solution for three years and stored in the laboratory for an additional one or two years.
5) Zhu and François [18].

Dasar *et al.* [14] investigated reinforcement bars in both pre-cracked (with loads removed after cracks formed) and uncracked beams (*w/b*=0.68) after 40 years of mixed exposure. The beams were placed horizontally and exposed to a marine splash and tidal environment for 20 years, subsequently stored sheltered from the rain for the next 15 years, and finally stored at Kyushu University for 5 years (no information on exposure during these last 5 years of storage). According to Dasar *et al.* [14], corrosion-induced cracks were observed after 10 years of exposure to a marine environment. After 40 years, the destructive investigation suggested that the reinforcement experienced both general and localised corrosion (mixed corrosion). Tensile bars in pre-cracked beams showed more severe localised corrosion on the reinforcements' downward-facing surfaces than in uncracked beams. The extent of corrosion on the upward-facing surfaces was similar for both pre-cracked and uncracked beams, noting only minor localised corrosion. In contrast, compressive bars in uncracked beams exhibited localised corrosion on the downward-facing reinforcement surfaces compared to those in pre-cracked beams. Additionally, the reinforcement in the uncracked beams had a larger corroded area on the upward-facing reinforcement surfaces than the pre-cracked beams. Notably, the corrosion was consistently more severe on the downward-facing reinforcement surfaces than on the upward-facing reinforcement surfaces. According to Dasar *et al.* [14], this was due to the top-bar effect.

Lundgren *et al.* [15] reported localised corrosion as a primary form of corrosion on reinforcement bars from the edge beam of a de-iced road bridge in service for 30 years. The edge beam had initial cracks due to inadequate design. The researchers observed varying degrees of corrosion-induced damage, ranging from no signs to extensive cracking and spalling. Even though the corrosion-induced damages were severe, the authors reported localised corrosion as a primary corrosion pattern. According to their observation, localised corrosion typically affected one-half of the bar, sometimes almost eliminating the ribs, while the other half remained almost undamaged.

Continuing the investigations by Lundgren *et al.* [15], Fernandez and Berrocal [16] studied 52 m of reinforcement from edge beams exposed to de-icing salts for a minimum of 30 years, totalling 35 years. The bridge was in service for 30 years, whereas the exposure during the remaining 5 years is unclear. The condition of the rebars ranged from pristine to severely corroded, with the most severe cases exhibiting what the authors referred to as "uniform pitting". The authors highlighted that in specific regions the attack was highly localised with significant loss of cross-sectional area at pit locations in combination with a minimal overall average corrosion level.

Zhang *et al.* [17] examined beams under sustained load exposed to a wetting-drying cycle with a NaCl solution for 14, 19, and 23 years. It was observed that, during the initial stage, the corrosion attack was localised in nature; at later stages, it shifted to general-type corrosion (mixed corrosion). According to Zhang *et al.* [17], during the initial stage of corrosion, macrocell corrosion was pronounced, with the steel at the crack tip acting as an anode. They also noted that the effect of bending cracks is suppressed over time due to crack healing. Further, the reinforcements in the compressive zone were affected by the top-bar effect (see Section 2).

From the same research group, Zhu and François [7] investigated a beam exposed to the wetting-drying cycle with a NaCl solution for 26 years. The corroded beam had reached a stage where they observed both general and localised corrosion (mixed corrosion), with some zones exhibiting significant localised corrosion. The reinforcement exhibited a dominant localised form of corrosion on the downward-facing surface, extending almost the entire length. In contrast, on the upward-facing reinforcement surface, corrosion appeared only at some discrete locations. Compared to the front tensile reinforcement, the back tensile reinforcement experienced less corrosion, both in terms of general and localised corrosion. Further, the corroded regions were observed to coincide with corrosion-induced cracking and spalling of the concrete cover. Similarly, they noted that the compressive reinforcement had more corrosion attacks on the downward-facing surfaces than on the upward-facing surfaces, which they attributed to the top-bar effect.

Continuing the study by Zhang *et al.* [17] and Zhu and François [7], Zhu *et al.* [9] further studied the corrosion propagation and corrosion patterns in beams exposed to the wetting-drying cycle with a NaCl solution after 14, 23, 26, and 28 years. They observed a clear progression of corrosion of the reinforcement with time (see Figure 1 and further description in Section 3.2).

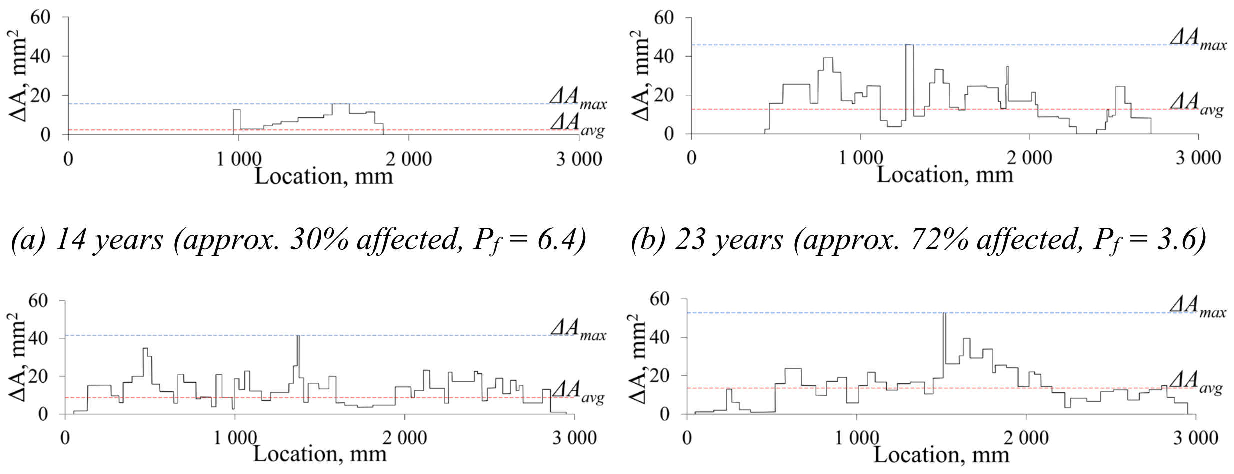
Chen *et al.* [3] carried out a relatively short-term study (4-5 years) on the corrosion of pre-cracked (crack width 0.1 mm or 0.4 mm) and uncracked beams exposed to the wetting-drying cycle with a NaCl solution. The corrosion of the bars in this study was localised in nature. In the case of pre-cracked beams, they observed pits near the initial cracks, while in the case of uncracked beams, they observed numerous tiny pits on the surface of the bars. Most of the observed pits were elliptical-shaped, with some elongating beyond the elliptical cavity. According to Chen *et al.* [3], the long pits observed in the pre-cracked beams are likely a result of corrosion-induced cracks (no details given). However, these cracks were not extensive, possibly due to the relatively short age of the beams.

3.2 Development of corrosion pattern with time

This section reviews observations of the development of corrosion attack/pattern in chloride-exposed RC beams. As described in Section 3.1, observations vary greatly: from localised corrosion in 25-year-old marine-exposed RC beams (*w/b*=0.40) with plastic spacers, to primarily localised corrosion along with corrosion-induced cracking and spalling in 30 to 35-year-old field-exposed de-iced edge beams, to mixed corrosion and corrosion-induced cracking in beams exposed to wetting-drying cycles with a NaCl solution (see Table 2).

The studies by the French group of researchers [9, 17, 18] provide a unique data set of the distribution of corrosion attack in chloride-exposed RC beams, all using similar beams and exposure conditions. Visual observations by Zhu and François [18] and destructive investigations of corroded beams conducted by Zhang *et al.* [17] and Zhu *et al.* [9] illustrate the progression of corrosion with time under sustained loading and controlled wetting-drying cycles with a NaCl solution. Zhu and François [18] reported the appearance of corrosion-induced cracks at the surface after 5 years, predominantly near initial cracks. Figure 1 further illustrates corrosion pattern development with time. The corroded area extended from approximately 30% located at mid-span to cover almost the entire beam after 26-28 years.

Zhang *et al.* [17] suggested that in the later stages of the corrosion propagation phase, during which corrosion-induced cracks propagate longitudinally, interconnect, and widen, the corrosion pattern is primarily influenced by the corrosion-induced cracks: At the initial stage of crack propagation when the cracks are small, localised (macrocell) corrosion remains the dominant type. However, once the cracks exceed a critical width, microcell corrosion becomes predominant, resulting in mixed corrosion. In summary, the beams exposed to the wetting-drying cycles with a NaCl solution exhibited a shift from localised to mixed corrosion. This transition was significantly facilitated by the corrosion-induced cracks. The transition is further demonstrated by a change in the pitting factor from over 6 after 14 years of exposure to around 4 after 28 years. Based on the observations, Zhu *et al.* [9] suggested that the corrosion development of the investigated beams could be divided into three stages: An initiation stage, a development stage where the percentage of the bar affected (corroded area) increases (approx. 5–29 years), and a stable mature stage after the entire bar is affected by corrosion (29 years-).



(a) 14 years (approx. 30% affected, P_f = 6.4) *(b) 23 years (approx. 72% affected, P_f = 3.6)*

(c) 26 years (approx. 92% affected, P_f = 4.7) *(d) 28 years (approx. 92% affected, P_f = 3.9)*

Figure 1 – Development of corrosion pattern over time in beams with corrosion-induced cracks. Cross-sectional loss (ΔA) of tensile reinforcement (diameter 12 mm) in RC beams under service load exposed to the wetting-drying cycle with a NaCl solution. ΔA was determined by gravimetry. Pitting factor, $P_f = \Delta A_{max}/\Delta A_{avg}$, where ΔA_{max} is the maximum cross-section loss and ΔA_{avg} is the average cross-section loss over the length. (Data reported by Zhu et al. [9]).

Dasar *et al.* [14] reported a similar development of corrosion pattern in the beams exposed to wetting-drying cycles. In their study of initially marine-exposed beams (*w/b*=0.68), Dasar *et al.* [14] referenced an earlier study conducted by Hamada *et al.* [19]. They reported that after 10 years, the corroded surface area of steel bars was approx. 45% in pre-cracked beams and approx. 6% in uncracked beams. After 20 years, visual observations revealed a significant increase in the corroded area in both pre-cracked and uncracked beams, with the reinforcement showing severe corrosion and cracking. Further, after 40 years of combined marine and sheltered exposure, the corrosion pattern was of mixed type, and corrosion had spread throughout the reinforcement for both pre-cracked and uncracked beams, affecting both the tensile and the compressive reinforcements [14].

3.3 Pitting factor

Several authors have utilised pitting factors, i.e. the ratio of the largest corrosion attack to the average corrosion attack, to describe the intensity of corrosion attacks in chloride-rich environments. Note that pitting factors reported in the literature may not be directly comparable, as the used characteristics of the corrosion attack vary (see Table 1).

To illustrate the potential use of the pitting factor to describe the development of corrosion with time, the data presented in Figure 1 is used. The maximum and the average cross-section reductions were determined from the graphs. The average cross-section reductions were calculated by considering the entire length of the beams. The pitting factor *($P_f = \Delta A_{max}/\Delta A_{avg}$)* was calculated as 6.4, 3.6, 4.7, and 3.9 for the beams exposed for 14, 23, 26, and 28 years, respectively. As expected, the highest pitting factor is observed after the shortest exposure period, where general corrosion typically will be less developed than localised corrosion. Variation in the development of the corrosion pattern is expected as the data is for four single beams.

3.4 Pit size

Pit size includes the depth, length, and width of pits. Figure 2 illustrates the correlation between pit depth and pit length.

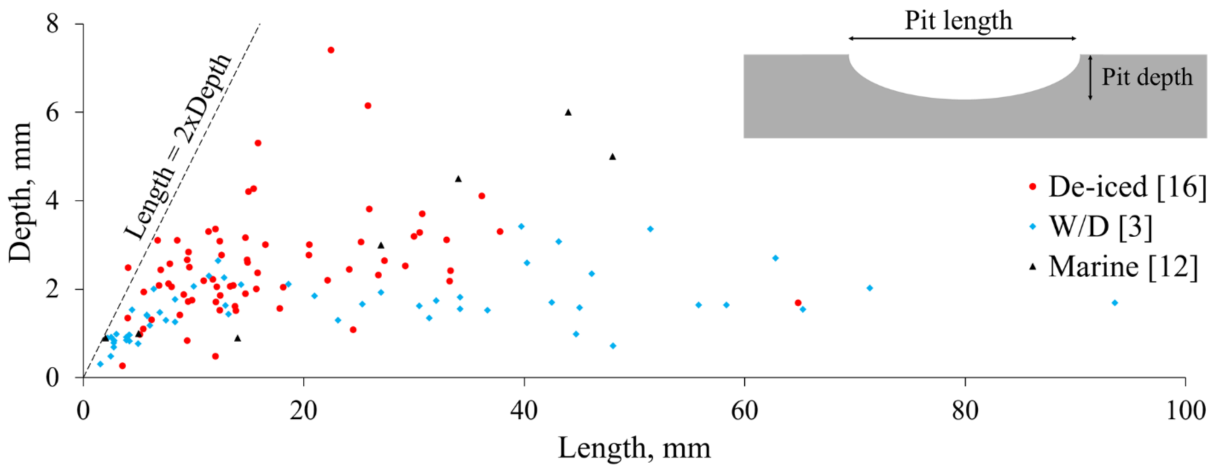


Figure 2 – Pit depth vs pit length of localised corrosion in different exposure conditions (see Table 2 for exposure type and period).

Except for one pit, all pits had a length nearly equal to or greater than twice the pit depth (see line), indicating a half-sphere or more shallow shape of the pits. The general trend suggests that some pits exhibited symmetrical growth in both directions, while the majority of them grew more in the length direction, resulting in a higher aspect ratio (the ratio of pit length to pit depth). The studies by Geiker *et al.* [12] and Fernandez and Berrocal [16], focusing on 25 years of marine-exposed RC beams and 30 years of de-iced RC edge beams, respectively, highlighted substantial variation in pit depth, ranging from a fraction of mm to more than 0.5 cm. Similarly, the variation in pit length was larger, extending from a few mm to several cm. Moreover, the laboratory-exposed beams investigated by Chen *et al.* [3] showed an even larger variation in pit length, with shallower pits after 4-5 years of the wetting-drying cycle with a NaCl solution.

3.5 Pit proximity

In the case of localised corrosion, the information on pit proximity (i.e. distance between nearest pits) could provide a basis for the representation of the spatial distribution of corrosion attack. In the study by Geiker *et al.* [12] on pre-cracked 25-year-old marine-exposed RC beams, where only localised corrosion was observed, it was found that the proximity of corrosion pits depends on the concrete resistivity. For the concrete and exposure conditions investigated, a minimum resistivity of 5000 kΩ-cm² to the nearest major pit was observed.

4. DISCUSSIONS

The summary of observations on corrosion attack and distribution in chloride-exposed RC structures highlights the complexity of reinforcement corrosion in RC.

The initiation of chloride-induced corrosion is affected by the condition of the SCI [2], especially the metallurgy and surface characteristics of the reinforcement [1] and the presence of inhomogeneities and the moisture conditions of the concrete part of the SCI [2]. Moisture also greatly affects the rate of corrosion, among others as reduced electrical resistivity supports larger macro-cells [20].

The initiation and propagation of corrosion appear to be affected by possible design and construction errors causing defects. Examples reported in Table 2 include the use of plastic spacers [12] and the top-bar effect [14, 17] caused by settlement, segregation, and/or bleeding, which is prominent in concrete with a high *w/b* ratio [14].

Robuschi *et al.* [21] recently tested the hypothesis for the impact of transverse cracks on reinforcement corrosion reported based on literature data and found, among others, that corrosion pits are likely to form and grow in the proximity of transverse cracks and that corrosion pits seem to grow slower with time, whereas the number of corrosion pits per area was observed to increase. The impact of initial cracks was also observed by Zhang *et al.* [17], Zhu and François [7], Zhu *et al.* [9], Dasar *et al.* [14], and Chen *et al.* [3]. However, no such effects were reported in Geiker *et al.* [12] and Geiker *et al.* [13].

According to Käthler *et al.* [22], corrosion propagation at cracks highly depends on local moisture conditions and possible inhibition of corrosion. Inhibition could result from repassivation [22], occupation of cracks by rust products, and possible self-healing [17], potentially limiting long-term corrosion propagation. Danner *et al.* [23] found that cracks of widths smaller than 0.2 mm appeared closed after 25 years of marine exposure, which is in line with a recent review paper by Kanavaris *et al.* [24].

Bertolini *et al.* [20] mentioned that longitudinal and transverse cracks significantly affect reinforcement corrosion in different ways. This was also observed by Zhu *et al.* [9], who reported a shift in the corrosion pattern from localised corrosion in transverse cracks to more general (or mixed) corrosion following the formation of longitudinal, corrosion-induced cracks.

According to Bertolini *et al.* [20], contact with chlorides and subsequent drying, as seen in marine splash zones and de-iced structures, is a very aggressive exposure condition. The observations cover different exposure conditions (marine, de-iced, and cyclic wetting-drying cycles with a NaCl solution). This might be supported by the reported observations (marine submerged vs marine splash and wetting-drying cycles with a NaCl solution). However, the present data are limited and do not allow for a clear description of the impact of exposure due to other factors affecting the initiation and propagation of corrosion.

5. CONCLUSIONS

Based on observations from the literature of corrosion distribution in marine-exposed or de-iced field elements and the wetting-drying cycle with a NaCl solution, the following conclusions are made:

- The number of destructive tests on long-term exposed RC elements is limited.
- The observed corrosion patterns significantly vary between cases.
- Most of the published cases show a change in corrosion pattern from localised corrosion to a combination of localised and general corrosion (mixed) in connection with corrosion-induced damage.
- The corrosion initiation and propagation appear to be greatly affected by possible design and construction errors causing defects and heterogeneities at the concrete-steel interface.

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