

# Critical Study of Corrosion Damaged Concrete Structures

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**Abstract:** Corrosion of steel reinforcement in concrete is one of the major problems with respect to the durability of reinforced concrete structures. The degradation of the structure strength due to reinforcement corrosion decreases its design life. This paper presents the literature study on the influence of the corrosion on concrete structure starting from the mechanism of the corrosion until the deterioration stage and the structural effects of corrosion on concrete structures.

**Keywords:** Corrosion, reinforced concrete

## 1. Introduction

Over the years, reinforced concrete has been promoted as having a long life during which it requires negligible attention. However, now, a world-wide problem is being experienced due to the deterioration of concrete. The concrete defects and deterioration not only happen on the older concrete structures but are also observed on newly constructed structures. The mechanism of deterioration and its rate are controlled by the environment, the paste microstructure and the fracture strength of the concrete [1]. Corrosion of embedded reinforcement is one of the major problems that contribute to deterioration of structural concrete. The direct effects of the reinforced corrosion are: loss of bar cross section; increase in bar diameter resulting from the volumetric expansion of the corrosion products; a change in the characteristics of the bar/concrete interface upon the formation of corrosion product; and reduction of the concrete section [2]. Loss of bar section may reduce ductility of the steel reinforcing bar. With insignificant ductility, a structure might fail and collapse in a brittle fashion without warning.

## 2. Basic Mechanism of Corrosion of Reinforcement

Research into corrosion of steel reinforcement in reinforced concrete started over 200 years ago when damage was observed at the exposed concrete structures to sea water. According to Biczok [3], the problems of concrete corrosion caused by sea water action was tackled as early 1840 by J. Smeaton and L. J. Vicat, while the report on concrete damage cause by chemical attack and observed on the harbour structure in Algier was published by L. J. Vicat in 1841. The last decade has witnessed a growing concern for problem of corrosion damage in reinforced concrete structures. Because of the importance of understanding the process and influence of various

parameters, it is necessary that an evaluation of corrosion on concrete be carried out.

The mechanism of metal corrosion depends on the involvement of water in the process. Corrosion of steel bar in reinforced concrete is classified as an electrolytic process. Corrosion in the normal sense involves loss of electrons from the metal to the environment (usually water and oxygen) and the formation of corrosion product such as oxides [4,5]. When steel is exposed to normal climatic conditions, it will corrode even when it is not connected electrically to another metal. This process confirms the basic theory where steel is not homogeneous but contains areas of slightly differing composition.

Corrosion of steel in concrete can be modelled as a three-stage process [6]. The first stage, usually called the initiation stage, is the diffusion of CO<sub>2</sub> or chloride through the cover to the steel reinforcement that cause depassivation. The second stage is the activation stage, where more of the rebar network starts to corrode and the rust products are formed. The third stage is deterioration as cracking and spalling occur. Eventually a situation is reached which is defined as the end of the functional life, and rehabilitation must take place by that point.

### 2.1 Initiation stage

Generally concrete provides an alkaline environment to the reinforcing steel where the pH level is between 12.5 and 13.5, resulting in steel being in what is termed a passive state. The dense and relatively impermeable structure of concrete provides the physical protection, while the high alkalinity of the pore solution provides the chemical protection [7]. In practice, depassivation of the film may occur under two specific sets of conditions: (i) reduction of the pH value due to reaction with atmospheric CO<sub>2</sub> (carbonation); and (ii) penetration of chloride ions into the concrete pore solution around the steel [8]. Carbon dioxide (CO<sub>2</sub>) from the external environment penetrates into concrete by the process of

diffusion. In the presence of water, this gas dissolves and reacts with cement to form carbonates. This reaction decreases the pH value to 9.5 resulting in destruction of the passivating layer. Corrosion begins only if the reinforcing steel has significant potential difference along with the presence of sufficient moisture and oxygen [9].

Chlorides penetrate the cover of the reinforced-concrete member by a combination of diffusion and capillary action and they gradually permeate until they reach the steel surface. Steel reinforcement becomes depassivated after a period of time once a threshold of chloride concentration is reached, which depends principally upon the cement composition, concrete quality, and the conditions of environmental exposure, [10].

## 2.2 Activation stage

Once the passive layer breaks down, then areas of rust start appearing on the steel surface [6]. The rate of corrosion may vary from point to point because of variations in alkalinity (pH) and concentration of salt and oxygen in the solution in the concrete close to the bar surface [11].

Iron dissolves away from the anodic region, while the electrons passing to the cathode regions combine with water and oxygen to form hydroxyl ions, [OH]<sup>-</sup>. The hydroxyl ions will combine with the ferrous ions, Fe<sup>++</sup>, released into the electrolyte at the anode, to form ferrous hydroxide (Fe (OH)<sub>2</sub>), a slightly soluble jellylike substance which, in the presence of oxygen, is promptly converted into some other form of iron oxide, e.g.

insoluble or some ferric oxide (Fe<sub>2</sub>O<sub>3</sub>.H<sub>2</sub>O), which is rust (see Fig. 1).

Two kind of electrochemical corrosions have been classified; microcell and macrocell corrosion. Microcell corrosion, consisting of pairs immediately adjacent anodic and cathodic areas which often lead to the uniform ion removal [12]. This type of corrosion is generally caused by carbonation of concrete over a wide area in the vicinity of the steel.

Macrocell corrosion leads to localized attack which can reduce the minimum area of a bar at a relatively rapid attack. Macrocell normally occurs in the case of chloride-induced corrosion which consists of anodically acting areas where the critical chloride content has been reached and large cathodes are next to the anode or sometimes also quite far away from the anode up to a distance of a few metres [13]

When reinforcement rusts, the corrosion products generally occupy considerably more volume than that of the steel destroyed [11]. The magnitude of this increase in volume typically varies in the region of 2 to 3 times the volume of the metal. This leads to the cracking and spalling of the concrete cover observed as the usual consequences of corrosion of steel in concrete and to the red/brown brittle, flaky rust on the bar and the rust stains seen at cracks in the concrete. Some of these corrosion products disperse into the concrete pores surrounding the bar and extend to which they disperse influences the build-up of pressure. Slower rate of corrosion permit corrosion products to disperse. This is significant for the rate of corrosion to be used in the laboratory simulation.

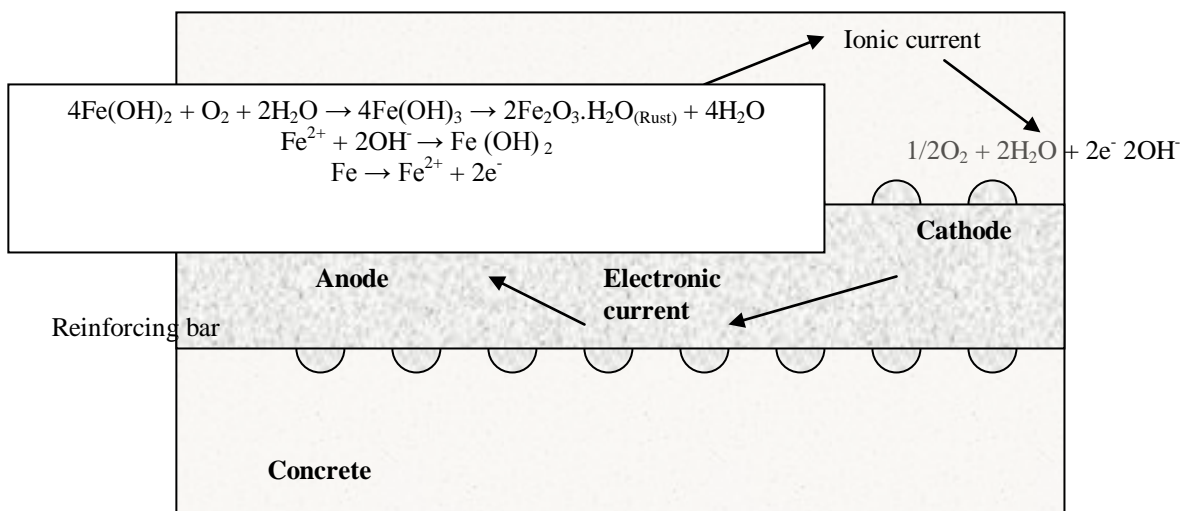
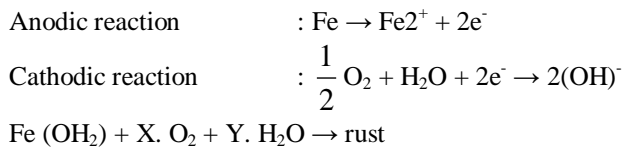


Fig.1 The corrosion reaction on steel.

### 2.3 Deterioration stage

Corrosion will reduce the cross-section of the steel and the concrete, and thereby the load carrying capacity of the structure. Pitting corrosion is more dangerous than uniform corrosion. Without necessarily being evident from the surface of the member, it may progressively reduce the cross sectional area of the rebar to a point where the rebar can no longer withstand the applied load leading to a catastrophic failure of the structure [14].

The basic problem associate with the deterioration of reinforced concrete as a result of corrosion is not only that the reinforcing steel reduces in mechanical strength, but also the products of corrosion exert stress within the concrete that cannot be resisted by the limited plastic deformation capacity of the concrete and the concrete therefore cracks. This leads to the weakening of the bond and anchorage between concrete and reinforcement which directly affects the serviceability and ultimate strength of concrete element within structures [15]. Also, spalling of the concrete cover reduces the cross sectional area of concrete in the member which may also reduce axial, bending and shear capacity.

### 3. Structural Effects of Corrosion

Many experiments have been done in order to investigate the effects of corrosion on the overall performance of an RC member. Castel et al. [16] showed that the stiffness deterioration in the response of a corroded beam depends on the interaction of bar-section reduction and bond deterioration. According to Coronelli and Gambarova [17], the flexural behaviour in a corroded beam is affected not only by the loss of concrete and steel section but also by bond decay. Corrosion affects both the strength and the ductility of the structure at ultimate, because corrosion reduces the steel elongation at maximum load. The effects of corrosion on reinforced concrete member can be divided into three conditions, those on loss of bar cross section, those which affect the surrounding concrete and those which affect interaction (or bond) between bar and concrete [18]. The consequence of each of these aspects and their inter-related effect on the load-carrying capacity of reinforced concrete structures is shown in Fig. 2. Therefore to tackle the problem related with corroded reinforcing bars in concrete, these three main parameters, such as loss of bar section, cover cracking and bond degradation should be considered.

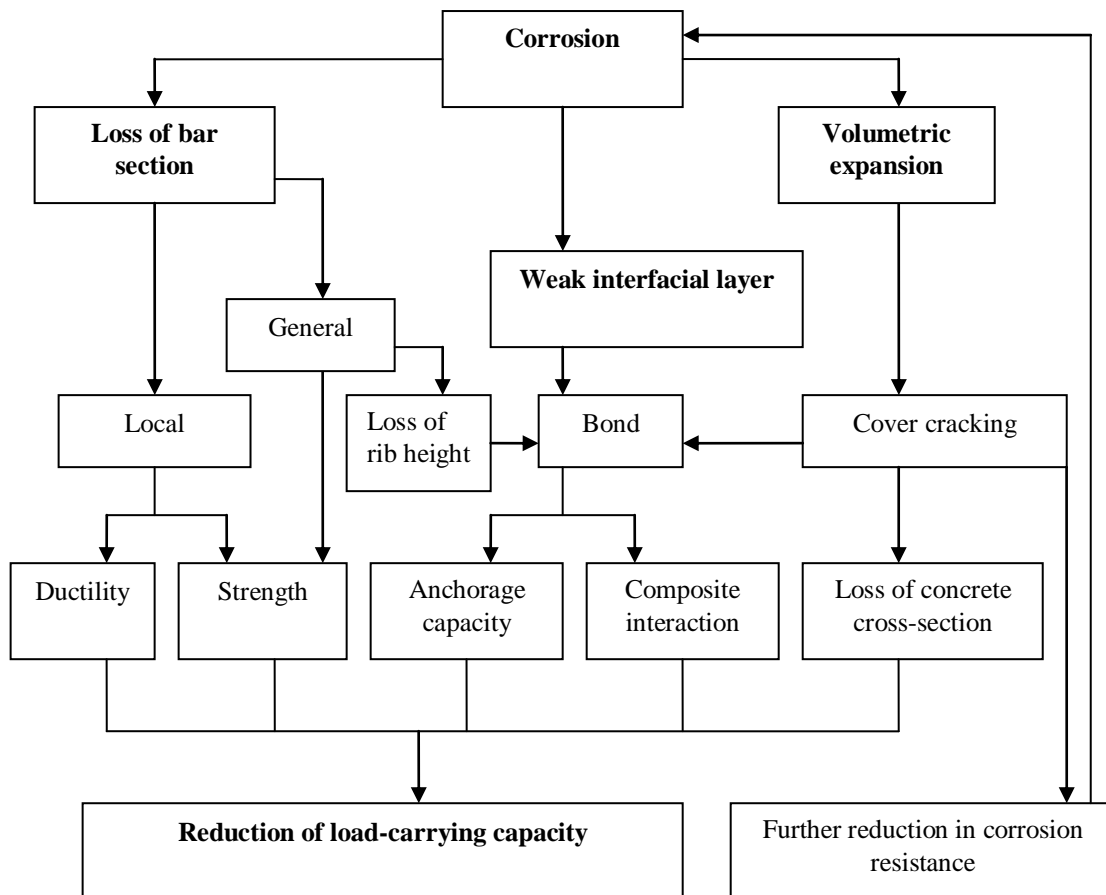


Fig. 2 Effects of reinforcement corrosion on residual structural capacity [18].

### 3.1 On bars

Several experimental studies have investigated the effects of corrosion on the mechanical behavior of steel bars [16,19]. According to Andrade et al. [20], reduction in the bar section between 10 and 25% in the critical zones of the structure will mean the depletion of its residual service life, whereas reduction up to 5% (with cracking and spalling) will indicate an early stage of deterioration.

Experimental work done by Almusallam [7] on the effects of corrosion on mechanical properties of steel reinforcement indicates that, as the degree of corrosion increases, the corresponding elongation of the bar before failure decreases. It also shows that 12.6% or more corrosion increases steel reinforcement brittleness. Conversely, corrosion generated from atmospheric exposure up to 16 months shows no effects on yield and ultimate tensile strength as tested by Maslehuddin et al. [21], but here the amount of section loss was small, and the maximum diameter reduction was only 0.53 percent. Based on a study of ductility of corroded reinforcing bars, Du et al. [22] concluded that the reduction of ductility of corroded reinforcement is primarily a function of the amount of corrosion (% of weight loss), rather than bar type and diameter. Furthermore, strength ratio, hardening strain and elastic modulus are not significantly affected for up to 25% corrosion.

### 3.2 Bond

There are two mechanisms by which corrosion may affect the bond between reinforcing bars and concrete [10]. First, most of the corrosion products that accumulate on the bar surface occupy a larger volume than that of the original un-corroded metal, thereby causing cracking or spalling of the concrete cover. Loss of cover inevitably implies loss of confinement and reduction in bond strength at the interface zone between the two materials. In addition, the surface of the bar becomes covered with corrosion products. This interferes with the development of bond mechanisms that rely on adhesion on the bar surface.

Degradation of anchorage bond of reinforced bar due to corrosion has been investigated by many researchers. Several experiment tests have been conducted in order to understand the degradation behaviour and identify the distress parameters that contribute directly to the degradation. In plain bars, two different mechanisms might thus be responsible for loss of bond as a result of corrosion [18]: (i) a mechanical weak layer of corrosion product at the steel/concrete interface, and (ii) a reduction in the confinement as cover cracks develop along the bar owing to volumetric expansion of the product of corrosion.

A test conducted by Morinaga [23] shows that the influence of corrosion on bond strength was different between plain round and deformed bars. On plain round bars, bond strength was determined mainly by the adhesive force between concrete and bar surface, while on deformed bars the key action of the ribs on the surface

of the bar was not affected by the corrosion. He assumed that there is no distinctly negative influence of corrosion on bond strength until the degree of corrosion reaches the very heavy grade. However, Cairns et al. [24] conducted friction tests to measure the change in coefficient of friction between steel plates and concrete as a result of corrosion. They concluded there was no evidence to support the influence those corrosion products produce a mechanically weak layer at the bar-concrete interface.

General trend of changes of bond strength after corrosion has been initiated is presented in Fig. 3 [25], although there are exceptions in certain circumstances, described later. Initially, bond strength is increased by a small amount of corrosion but starts to decrease with further increases in corrosion level.

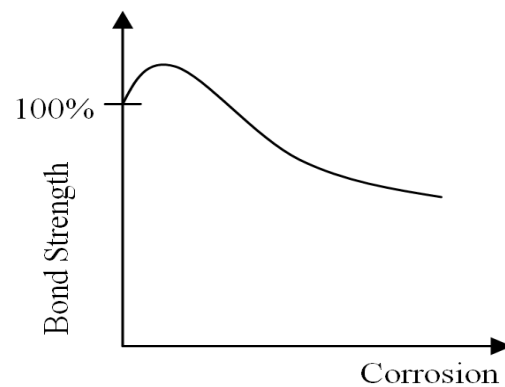


Fig. 3 Bond strength versus corrosion

This trend was observed by Cabrera and Ghoddoussi [25] and Al-Sulaimani et al. [27]. They used the same size of pull-out specimens (150 mm x 150 mm) reinforced with different bar diameters. Both results show that bond strength increased when the corrosion level increased up to 1% section loss and decreased with further corrosion. Bond strength increment was inversely related to bar diameter, as in the work of Al-Sulaimani; 3 different bar diameters which implies on different of cover to diameter ratios were used where 10 mm bar shows the highest increment of 56% (0.87% section loss) followed by 14 mm and 20 mm bar diameter (32% and 27% respectively, corresponds to 0.9% and 0.65% section loss).

In the Cabrera and Ghoddoussi test, only a 12 mm bar diameter was used and gave around 14% increment on bond strength (0.71% section loss). This increment was lower than in the Al-Sulaimani test even the level of corrosion was almost similar, which results from the influence of surface crack width which reduced the confinement of the test bars. During their test, specimens were in the precracking stage with no surface crack observed, while in the Cabrera test, 0.2 mm width surface crack appeared when the bond strength starts to decrease.

The same result was observed by Auyeung et al. [28]. They used axial tension pullout test specimens to study the bond behaviour of a corroded reinforcement bar. After 1% of corrosion, bond strength decreased

rapidly. Cantilever test specimen was used by Almusallam et al. [29] where open stirrups were provided to avoid shear failure during the bond test. They found up to 4% of weight loss, 16% increment of bond strength which then decreased as the amount of corrosion increased. By 8% of corrosion (post cracking stage), bond strength was almost 30% lower than that of uncorroded specimens.

Pull-out tests conducted by Fang et al. [30] on pullout specimens confined with two 6 mm diameter stirrups at 40 mm spacing show no obvious degradation in bond strength. When the degree of corrosion was 6%, the bond strength decreased by only 12%, which was far lower than in the unconfined specimens reported previously. Other tests were conducted on 24 specimens reinforced with 20 mm hot-rolled deformed steel bars and having 80 mm embedment length (Fang et al. [31]). These confined and unconfined specimens were corroded with varying corrosion degrees from 0% (non corrosion) to 6% mass loss. The experiment results have been compared with analytical results from nonlinear finite element analysis. They found that confinement supplied an effective way to counteract bond loss for corroded steel bars of the medium corrosion level (around 4% to 6% mass loss). Both experiment and analysis showed that the bond strength of unconfined steel bars was 30 – 65% lower than that of confined steel bars for a similar corrosion level.

Williamson and Clark [32] considered five variables: level of corrosion, pre-load, cover depth, bar type (plain and deformed) and specimen age in studying the effects of corrosion on bond strength. They found that pre-loading the specimens during the corrosion process affected only deformed bar specimens with the greatest cover thickness. At 20% corrosion with cover to diameter ratio of 2, the appearances of extensive cracks has slight effects on bond strength when compared with uncorroded specimens.

#### 4. Corrosion Induced Surface Crack

The appearance of surface cracks on the corroded structures results from the volumetric expansion of active corrosion of the reinforcing bars. This volume depends on the type of oxide, degree on hydration and on the dispersion of corrosion products into the surrounding pore structure [33]. When corrosion initiates, it progresses by causing an expansion of the rust produced in the vicinity of the rebar. Longitudinal corrosion cracks form along the corroded reinforcing bars when the tensile stress in the concrete surrounding the rebar exceeds the tensile strength of the concrete [8]. These cracks cause loss of concrete integrity which reduces the concrete contribution to the load-bearing capacity and affects the external appearance of the structure [34].

Experimental works were conducted by Andrade et al. [35] to identify the influence of bar location, impressed current intensity and cover thickness on surface crack as a function of rebar corrosion. They found that 20  $\mu\text{m}$  of bar radius loss to corrosion was needed to

induce surface crack, but no influence of cover/ diameter ratio on the cracking initiation time. The influence of corrosion on crack initiation was discussed previously in *fib* Bulletin 10 [25] and tabulated in Table 1. Different section loss was produced to induce surface crack from 0.3% to the maximum 4% of section loss. In general, high amounts of corrosion induced by high impressed current are required to initiate cracks on a thick concrete cover.

On crack propagation, Rodriguez et al. [34] mentioned that crack evolution depends mainly on the position of the bar in concrete element (top or bottom cast position) and on the corrosion rate  $i_{corr}$ , although this influence was negligible for usual corrosion rate values ranging between 0.1 – 2  $\mu\text{m}/\text{cm}^2$ . They developed an empirical expression from their experimental results on different casting positions, where crack width as a function of attack penetration was derived as:

$$w = 0.05 + \beta[x - x_o] \quad (w \leq 1.0 \text{ mm}) \quad (1)$$

where  $w$  is the crack width in mm,  $x$  is attack penetration in micron,  $x_o$  is the attack penetration corresponding to crack initiation and  $\beta$  is a coefficient which depends on the bar position ( $\beta = 0.01$  for top cast bar, 0.0125 for bottom cast bar).

Alonso et al. [33] found a linear relationship between crack width growth and radius loss during the propagation period of the crack. In conclusion, they summarized the evolution of crack width as in Table 2.

Vidal et al. [39], based on their work on two beams naturally corroded over periods of 14 and 17 years found that attack penetration calculated from pit penetration and diameter decrease to quantify reinforcement corrosion only gives a good prediction of crack initiation, but not of crack propagation. It was due to the fact that the attack penetration used was derived from the pitting condition which was calculated from several experimental data, which to some extent were limited to certain problems and the corrosion environment only, while section loss was determined from actual mass loss after the corrosion process, which gives more accurate results. In this work, they concluded that longitudinal crack initiation depends on the cover/ diameter ratio and the bar diameter, but the quality of the steel concrete interface may have some effects. However, on crack propagation, cover/ diameter ratio and the bar diameter seem to have no effects on the crack width evolution as a function of steel cross-section loss.

Several studies have been conducted to investigate the influence of surface crack on bond strength reduction. On plain bars, longitudinal cracking reduced the confining pressure on the bar interface which reduced the bond strength, which was shown by Cairns et al. [18] for specimens without links. This condition was not observed in specimens with links because confining pressure was maintained by the links. The relationship between bond strength and crack width from different casting position is depicted in the following equations, refer equation (2) and equation (3).

$$f_{bres} = \frac{f_{bu}}{(1 + 0.8w_{cr})} \tag{2}$$

$$f_{bres} \leq \frac{f_{bu}}{(0.5 + 1.6w_{cr})} \text{ for top cast bar} \tag{3}$$

where:

- $f_{bres}$  – residual bond strength for assessment
- $f_{bu}$  – design bond strength
- $w_{cr}$  – maximum width of longitudinal cover crack

On deformed bars, Almusallam et al. [29] reported that at the initial stage of crack formation ( $\approx 0.2$  mm width), ultimate bond load was decreased to around 60%. After a certain degree of corrosion, the effects of crack width on bond strength was insignificant because of

sufficiently wide cracks; the reinforcement bars had already lost much of their confinement, and a further increase in crack width does not cause any further reduction in the confining force.

### 5. Conclusion

- i. Three mechanisms, namely cover cracking, bar section loss and bond strength deterioration were identified as having influence on reduction on residual capacity in corroded structure.
- ii. Section loss (%) and attack penetration (mm) are the two main parameters used by previous researchers in quantifying amount of corrosion.
- iii. In general, some enhancement of bond strength on the early stage of corrosion due to some changes in steel/concrete interface.
- iv. Surface crack was formed due to volumetric expansion of corrosion products around the steel bar.

Table 1: Amount of corrosion to initiate crack of concrete cover [24].

Researchers	Bar $\phi$ (mm)	$c/\phi$ ratio	Impressed Current (mA/cm <sup>2</sup> )	Crack Width (mm)	Section Loss (%)	Corrosion Penetration (mm)
Al-Sulaimani et al. [27]	10	7.5	2	-	5	0.13
	14	5.36	2		3	0.11
	20	3.75	2		2	0.10
Cabrera and Ghoddoussi [26]	12	5.75	3 Volts	0.2	1-2	0.03-0.06
Clark and Saifullah [36]	8	0.5	0.5		0.4	0.008
	8	1.0	0.5		0.6	0.012
	8	2.0	0.5		1.3	0.026
Andrade et al. [35]	16	1.25-1.88	0.1	0.05	0.015-0.018	0.4-0.48
		1.25	0.01	< 0.05	0.017	0.43
Saifullah and Clark [37]	8	1.0	0.04	-	1.1	0.022
	8	1.0	0.25		0.78	0.016
	8	1.0	2		0.3	0.006
Rodriguez et al. [38]	16	2.0-4.0	0.003-0.10	-	0.4- 1.0	0.015- 0.04
Almusallam et al. [29]	12	5.0	10	-	4.0	0.12

Table 2: Influence of several parameters on the initiation and propagation of crack width [32].

Variable	Time of evolution of the crack for the same attack penetration	
	Initiation	Propagation
Increases $I_{corr}$	Indifferent	Longer
Increase $c/\phi$	Longer	Low to high influence
Increase porosity	Longer	High influence
Stirrup (isolated)	Indifferent	Indifferent

## References

- [1] Basheer, P.A.M., Chidiact, S.E., and Long, A.E. Predictive model for deterioration of concrete structures. *Construction and Building Materials*, Volume 10(1), (1995), pp. 27-37.
- [2] Cairns, J., Du, Y., and Law, D. Residual bond strength of corroded plain round bars. *Magazine of Concrete Research*, Volume 58(4), (2006), pp. 221- 231.
- [3] Biczok, I. Concrete corrosion concrete protection. 8th Edition. *Akademiai Kiado*, Budapest, Hungary (1964).
- [4] Pludek, V.R. Design and corrosion control. *The Gresham Press*, Surrey, UK, (1977).
- [5] Pantazopoulou, S.J., and Papoulia, K.D. Modeling cover-cracking due to reinforcement corrosion in reinforced structures. *Journal of Engineering Mechanics*, Volume 127( 4), (2001), pp. 342- 351.
- [6] Broomfield, J.P. Corrosion of steel in concrete, understanding, investigation and repair. *E&FN Spon*, London, UK, (1997).
- [7] Almusallam, A.A. Effects of degree of corrosion on the properties of reinforcing steel bars. *Construction and Building Materials*, Volume 15, (2001), pp. 361-368.
- [8] Bentur, S., Diamond, S., and Berke, N.S. Steel corrosion in concrete: fundamental and civil engineering practice. *E&FN Spon*, London, UK, (1997).
- [9] Marquest, P.F., and Costa, A. Service life of rc structures: carbonation induced corrosion. prescriptive vs. performance-based methodologies. *Construction and Building Materials*, Volume 24, (2010), pp. 258- 265.
- [10] Stanish, K., Hooton, R.D., and Pantazopoulou S.J. Corrosion effects on bond strength in reinforced concrete. *ACI Structural Journal*, Volume 96(6), (1999), pp. 915- 921.
- [11] Beeby, A.W. Cracking, cover and corrosion of reinforcement. *Concrete International Design and Construction*, Volume 5(2), (1983), pp. 35- 40.
- [12] Cao, C., Cheung, M.M.S., and Chan, B.Y.B. Modeling of interaction between corrosion-induced concrete cover crack and steel corrosion rate. *Corrosion Science*, Volume 69, (2013), pp. 97-109.
- [13] Raupach, M. Chloride-induced macrocell corrosion of steel in concrete-theoretical background and practical consequences. *Construction and Building Materials*, Volume 10(5), (1996), pp. 329-338.
- [14] Ahmad, S. Reinforcement corrosion in concrete structures, its monitoring and service life prediction-a review. *Cement and Concrete Composite*, Volume 25, (2003), pp. 459-471.
- [15] Azad, A.K., Ahmad, S., and Azher, S.A. Residual strength of corrosion-damaged reinforced concrete beams. *ACI Materials Journals*, Volume 104(1), (2007), pp. 40- 47.
- [16] Castel, A., Francois, R., and Arliguie, G. Mechanical behavior of corroded reinforced concrete beams: bond and notch effects. *Material Structure*, Volume 33, (2000), pp. 545-551.
- [17] Coronelli, D., and Gambarova, P. Structural assessment of corroded reinforced concrete beams: modeling guideline. *Journal of Structural Engineering*, Volume 130(8), (2004), pp. 1214-1224.
- [18] Cairns, J., Du, Y., and Law, D. Residual bond strength of corroded plain round bars. *Magazine of Concrete Research*, Volume 58 (4), (2006), pp. 221-231
- [19] Palsson, R., and Mirza, M.S. Mechanical response of corroded steel reinforcement of abandoned concrete bridge. *ACI Structural Journal*, Volume 99(2), (2002), pp. 157-162.
- [20] Andrade, C., Alonso, C., Garcia, D., and Rodriguez, J. Remaining service lifetime of reinforced concrete structures: effect of corrosion in the mechanical properties of the steel. *Proc. of the Symposium on Life Prediction of Corrodible Structures*, Cambridge, UK, (1991).
- [21] Maslehuddin, M., Allam, I.A., Al-Sulaimani, J., Al-Mana, A.I., and Abduljauwad, S.N. Effect of rusting of reinforcing steel on its mechanical properties and bond with concrete. *ACI Materials Journal*, Volume 87(5), (1990), pp. 496-502.
- [22] Du, Y.G., Clark, L.A., and Chan, A.H.C. Effect of corrosion on ductility of reinforcing bars. *Magazine of Concrete Research*, Volume 57(7), (2005), pp. 407-419.
- [23] Morinaga, S. Prediction of service lives of reinforced concrete buildings based on rate of corrosion of reinforcing steel. *Special Report No 23*, Institute of Technology Shimizu Corporation, Japan, (1998).
- [24] Cairns, J., Du, Y., and Law, D. Influence of corrosion on the friction characteristic of the steel/concrete interface. *Construction and Building Materials*, Volume 21, (2007), 190-197.
- [25] The International Federation for Structural Concrete. Bond of reinforcement in concrete. *fib Bulletin 10*, Lausanne, Switzerland, (2000).
- [26] Cabrera, J.G., and Ghoddoussi, P. The effects of reinforcement corrosion on the strength of the steel/concrete "bond". *Proc. International Conference on Bond in Concrete: From Research to Practice*, Riga, Latvia, (1992).
- [27] Al-Sulaimani, G. J., Kaleemullah, M., Basunbul, I. A., and Rasheeduzzafar. Influence of corrosion and cracking on bond behaviour and strength of reinforced concrete members. *ACI Structural Journal*, Volume 87,(2), (1990), pp. 220-231.
- [28] Auyeung, Y., Balaguru, P., and Chung, L. Bond behaviour of corroded reinforcement bars. *ACI Materials Journal*, Volume 97(2), (2000), pp. 214- 220.
- [29] Almusallam, A.A., Al-Gathani, A.S., Aziz, A.R., and Rasheeduzzafar. Effects of reinforcement corrosion

- on bond strength. *Construction and Building Materials*, Volume 10(2), (1996), pp. 123 – 129.
- [30] Fang, C., Lundgren, K., Chen, L., and Zhu, C. Corrosion influence on bond in reinforced concrete. *Cement and Concrete Research*, Volume 34, (2004), pp. 2159-2167.
- [31] Fang, C., Lundgren, K., Plos, M., and Gylltoft, K. Bond behaviour of corroded reinforcing steel bars in concrete. *Cement and Concrete Research*, Volume 36, (2006), pp. 1931-1938.
- [32] Williamson, S.J., and Clark, L.A. Effects of corrosion and load on reinforcement bond strength. *Journal of the International Association for Bridge and Structural Engineering*, Volume 12( 2), (2002), pp. 117-122.
- [33] Alonso, C., Andrade, C., Rodriguez, J., and Diez, J.M. Factors controlling cracking of concrete affected by reinforcement corrosion. *Materials and Structures*, Volume 31, (1998), pp. 435-441.
- [34] Rodriguez, J., Ortega, L.M., Casal, J., and Diez, J.M. Corrosion of reinforcement and service life of concrete structures. *Durability of Building Materials and Components*, Volume 7(1), (1996), pp. 117- 126.
- [35] Andrade, C., Alonso, C., and Molina, F.J. Cover cracking as a function of bar corrosion: part 1- Experimental test. *Materials and Structure*, Volume 26, (1993), pp. 453-464.
- [36] Clark, L.A., and Saifullah, M. Effect of corrosion on reinforcement bond strength. *Proceeding Conference on Structural Faults and Repair*, Edinburgh, UK, (1993).
- [37] Saifullah, M., and Clark, L.A. Effect of corrosion rate on the bond strength of corroded reinforcement. *Sheffield Academic Press*, Sheffield, UK (1994).
- [38] Rodriguez, J., Ortega, L.M., and Casal, J. Corrosion of reinforcing bars and service life of reinforced concrete structures: corrosion and bond deterioration. *Proc. of the International Conference on Concrete across Borders*, Odense Denmark, (1994).
- [39] Vidal, T., Castel, A., and Francois, R. Analyzing crack width to predict corrosion in reinforced concrete. *Cement and Concrete Research*, Volume 34, (2004), pp. 165-174.