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Corrosion Effect on Bond Loss between Steel and Concrete

Charis Apostolopoulos and Konstantinos Koulouris

Abstract

This chapter is devoted to the effects of steel corrosion on bond relationship between steel and concrete. One of the basic assumptions in design of reinforced concrete members is the perfect steel - concrete bond mechanism, so that strain of reinforcing bar is the same as that of the surrounding concrete and these two different materials act as one. However, corrosion of steel reinforcement consists one of the main durability problems in reinforced concrete members, downgrade the bond behavior and therefore their structural integrity. Corrosion degrades the reinforcement itself, reducing the initial cross-section of the steel bar and its mechanical properties. Furthermore, tensile stresses in surrounding concrete caused due to oxides on the corroded reinforcement, lead to the gradual development of tensile field to the surrounding concrete, with spalling of the cover concrete and loss of bond mechanism as a consequence. In this chapter, an overview of damage of reinforced concrete due to steel corrosion is given, focused on the bond mechanism; factors that play key role in the degree of bonding and, also, proposed models of bond strength loss in correlation with the surface concrete cracking due to corrosion are indicated. To conclude, the ongoing research in this area of interest is presented, based on recent scientific studies.

Keywords: steel corrosion, bond loss, surface cracking, bond strength, predictive model, corrosion damage

1. Introduction

Reinforced concrete consists the most widely used construction material of the existing building stock, providing high bearing capacity in conjunction with low production cost. Due to weakness of plain concrete to withstand tensile forces, steel reinforcing bars are introduced into concrete to enhance its overall mechanical performance. The key consideration so as to ensure that steel and concrete cooperate is the bond mechanism between them. However, corrosion of steel reinforcement constitutes a major degradation factor, which leads to premature aging of RC structures. Recent reports have indicated huge economic impacts due to corrosion damage, since a significant part of the annual budget in many countries is spent on maintenance, repair, and rehabilitation of RC structures [1, 2]. For instance, results of a study conducted by NACE [1] refers that the cost of corrosion is globally estimated to be US\$2.5 trillion, approximately 3.4 percent of the global GDP.

It is a common knowledge that corrosion process has initially slow rate in nature, since it takes a long period of more than about 10 or 15 years until the aggressive environmental agents diffuse into concrete and reach the steel reinforcement so

as to create the electrochemical cell of corrosion. Concrete cover thickness and a thin passive layer on steel surface, due to high alkalinity of concrete (pH at about 12.5) protect the reinforcement, delaying the penetration and diffusion of corrosive factors. Nevertheless, when aggressive environmental factors, as chloride ions, reach a critical concentration rate, accompanied by reduction of pH below 9, steel reinforcement depassivates and corrosion initiates [3]. Several scientific studies have been conducted, investigating the rate of chlorides' diffusion through the porous concrete, aimed at the establishment of a critical value (threshold) of chloride content in order to predict the onset of corrosion [4–6]. The majority of researchers model chloride transport in concrete using the Fick's second law of diffusion, neglecting the chloride interaction with the solid phase [7]. However, there are many uncertainties since many factors influence the rate of chloride penetration into concrete, such as porosity and cracks of concrete, temperature, moisture and salinity of corrosive environment. Hence, due to misinterpretations and various results in literature to date, there is no broadly accepted by the scientific community method of estimating and modeling the onset of corrosion by means of the critical chloride content. Due to the abovementioned, modern international regulations on the design of concrete structures, as BSI EN 206–1 [8], based on long term service life of reinforced concrete, proposed minimum values of cover thickness and concrete classes, depending on the environmental exposure conditions, in order to ensure high protection level of reinforcement against corrosion.

As aggressive agents penetrate and act in limited exposed to corrosion areas rather than the entire length of the reinforcing bars, the corrosion effect is mainly characterized by non-uniformity along the steel bars and is detected by pits on their surface. During corrosion process, steel tends to return to its initial ore form resulting in mass loss and its conversion to iron oxides (rust) on steel surface. Consequences of corrosion damage on steel reinforcement are the reduction of the initial cross-section, resulting in increase of applied mechanical stresses and stress concentration due to pit development, as well as the degradation of its mechanical properties. During the last decades, an effort has been made so as to estimate and quantify the corrosion effect on steel reinforcing bars. The non-uniform distribution of corrosion damage on the steel cross section agreed to be one of the primary cause of mechanical properties' degradation, which has been studied by many researchers [9–13]. Sun [12] and Andisheh et al. [13] tested bare reinforcing bars under monotonic loads, depicting the significant material degradation. Extending the research upon steel corrosion in concrete, experimental studies on embedded reinforcing bars [14–16] indicated more severe corrosion damage, accompanied by narrow pits, which leads to further reduction of mechanical response. Nonetheless, experimental results of both bare and embedded corroded steel reinforcement mainly showed ductility drop rather than reduction of effective stress. To this effect, several studies targeted on the relationship between the degree of corrosion of steel reinforcement and the bearing capacity of corresponding reinforced concrete structures [17–19]. Recently, Kashani et al. [20] presented a state of the art review up to date concerning the current knowledge upon residual capacity of corroded RC elements.

The iron oxides developed due to corrosion phenomenon on steel bars' surface occupy 4 to 6 times greater volume of the mass lost, generating tensile stresses in surrounding concrete with subsequent concrete cracking and spalling of the cover concrete. Hence, corrosion impairs the interface between steel and concrete and therefore affects the bond between them [21]. Bond is the imperative mechanism to denote the transfer of forces between reinforcement and surrounding concrete [22], which is mainly influenced by chemical adhesion, friction and mechanical interlock due to the presence of ribs.

Besides corrosion phenomenon, the aspects of steel – concrete adhesion depend to a high extent on numerous parameters related to both steel and concrete, namely steel bar geometry, concrete strength and confinement due to transverse reinforcement and concrete cover thickness [23]. The influence of compressive concrete strength on bond behavior of RC specimens has been studied by Abosrra et al. [24] and Zandi and Coronelli [25]. Yalciner et al. [26] conducted an experimental study on bond strength loss due to corrosion taken into account both the compressive strength of concrete f_c and the ratio of concrete cover thickness to nominal steel diameter c/D . Testing RC specimens without stirrups, Maslehuddin et al. [27] indicated that although a slight improvement of bond strength is demonstrated in low corrosion levels, sharp degradation of bond strength is recorded as corrosion increases. Recently, experimental studies by Zandi et al. [28], Lin et al. [29] and Apostolopoulos and Koulouris [30] investigated both the significant role of stirrups spacing and corrosion carrying out eccentric pull out tests on RC elements with usual design values of concrete cover.

2. Corrosion of steel reinforcement

Steel reinforcement is the determinant factor of bearing capacity of reinforced concrete elements. However, in case of structures located in coastal regions (or marine environment), where high chloride contents are indicated, steel reinforcement degrades due to chloride-induced corrosion and subsequently leads to durability problems of the entire RC structures.

It is a common knowledge that steel reinforcement is initially protected by concrete cover and a passive layer on its surface. In particular, concrete cover thickness acts as a physical barrier between steel and corrosive environment, delaying the penetration and diffusion of corrosive factors through pores of concrete. At the same time, high alkalinity of concrete due to cement ($\text{pH} \sim 12.5$) results in protection of steel, forming a thin passive layer of ferric oxides on its surface. Chlorides reach the surface of concrete, enter the pore system either by diffusion (in stationary pore water), or by capillary suction of the surface water in which they are dissolved (or by combination of both transport mechanisms) [31]. It is assumed that there is an initiation period, until chloride ions reach the reinforcement, during which substances as water, chloride ions diffuse into concrete and reach the certain concentration necessary to trigger corrosion of the steel reinforcement [32]. This process has slow rate in nature, since it takes a long period of more than about 10 or 15 years, until the aggressive environmental agents reach the steel reinforcement, accompanied by reduction of concrete pH below 9, depassivate it and then corrosion initiates, **Figure 1**. When the passive protection breaks down then onset of steel corrosion (oxidation) takes place and gradually rust occurs on its surface.

Corrosion is an electrochemical phenomenon, in which the existence of an anode, a cathode, an electron pathway and electrolyte (ionic pathway) is required. The electrochemical reactions that occur during the corrosion process are presented as follows, in Eq. (1) and (2), [33]:

The anodic reaction (oxidation),



Since two electrons (2e^-) released in the above anodic reaction, there must be another reaction (cathodic reaction) in order to ensure the electrical neutrality on steel surface. This cathodic reaction, Eq. (2), consumes water and oxygen.

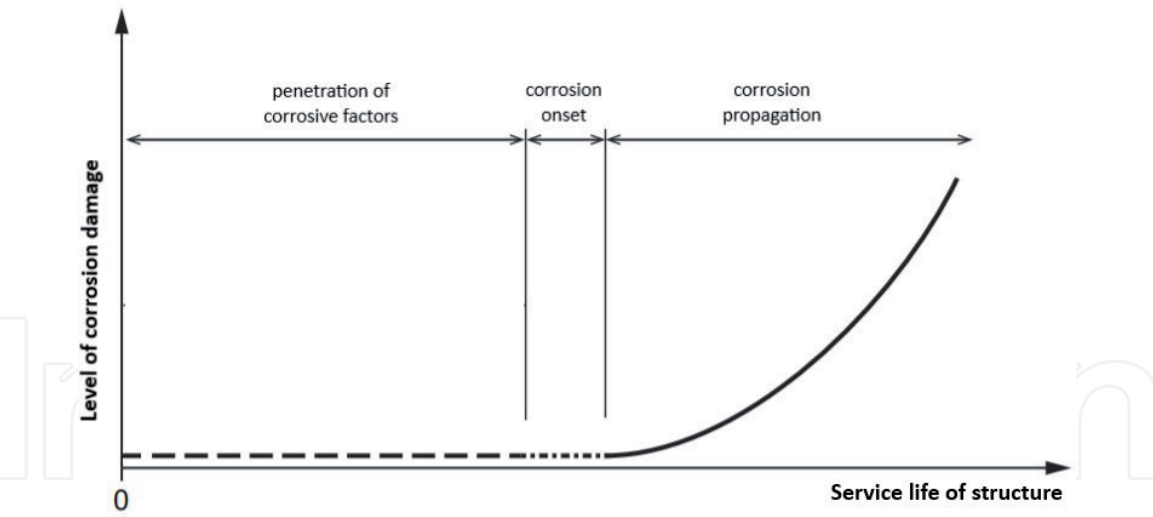


Figure 1.
Stages of corrosion in RC structures.

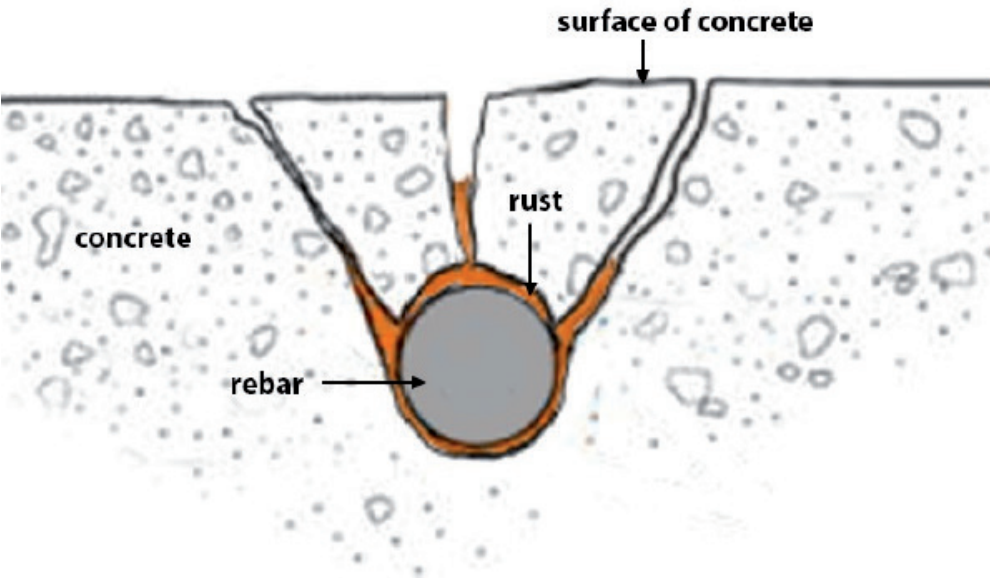


Figure 2.
Corrosion products (rust) cause tensile stresses in concrete leading to cracking and spalling of concrete cover.

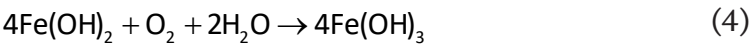
The cathodic reaction,



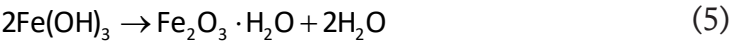
The above two chemical equations contain the basic reactions at the first stages of corrosion. Then, as corrosion propagates, hydration reactions are followed, Eq. (3) - Eq. (5), so as to form hydrated ferric oxide (yield red rust) $Fe_2O_3 \cdot H_2O$:



where is $Fe(OH)_2$ ferrous hydroxide,



where $4\text{Fe}(\text{OH})_3$ is ferric hydroxide and



where is $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$ hydrated ferric oxide (rust).

As shown in **Figure 2**, oxides (rust), which are formed due to corrosion on steel surface, occupy 2 to 6 times greater volume of the attacking mass [15], causing tensile stresses in surrounding concrete and, thereafter, leading to gradual concrete cracking development and spalling of the cover concrete. Hence, corrosion phenomenon affects significantly the steel reinforcement, reducing its initial cross-section, degrades its mechanical properties and bond between steel and concrete.

3. Laboratory testing

The capacity assessment of corroded reinforced concrete elements consists an engineering task of major importance, since the effects of steel corrosion have become more apparent. Nevertheless, the current international regulations and standards do not determine degradation rules of RC elements; thus, there is need to develop codes, taking into account the deterioration of materials and the subsequent reduction of structural capacity of RC members.

In order to study and quantify the consequences of corrosion, laboratory methods have been developed to simulate and accelerate the natural process. One of the most widespread accelerated corrosion techniques, used for the goals of many studies is impressed current density technique.

In this accelerated corrosion technique, the reinforcing steel bars (to be corroded) and stainless-steel bars are connected to the positive and the negative pole of a power supply, respectively, and are immersed in tanks, which are filled by a sodium chloride (NaCl) solution in content of 5% (by weight of water). In this way, an electric circuit is generated, since the reinforcing steel bars act as anode of circuit, the stainless-steel bars act as cathode and the NaCl solution is the electrolyte, which allows ions to flow into the circuit. Direct electric current is induced to the reinforcing steel bars through the power supply in order to accelerate the electrochemical reaction of corrosion [34]. This technique is in accordance with ASTM standards, although all the individual parameters needed to create a standard corrosive environment have not

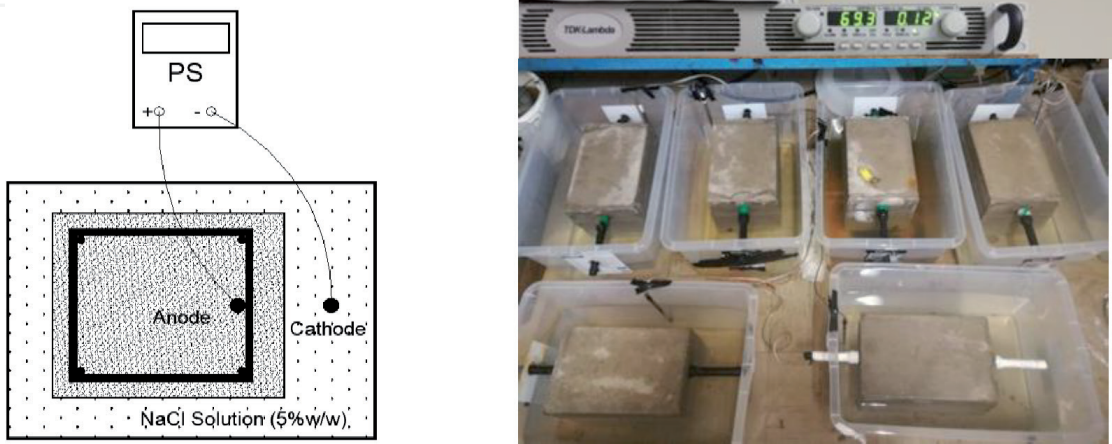


Figure 3.
Simplified procedure of accelerated electro-corrosion (left) - accelerated corrosion experiments on RC specimens via inducing current (right).

been determined yet. Nevertheless, the main advantage of this method is the ability to control the rate of corrosion, which usually varies due to changes in the resistivity, oxygen concentration, and temperature.

In **Figure 3** an indicative automatic system (found in Laboratory of Technology & Strength of Materials of University of Patras) is illustrated, which has been used for the performance of electrochemical corrosion tests. The specific system enables implementation of different corrosive conditions, in terms of impressed current density and ponding cyclic corrosion (wet/dry duration).

4. Differential aeration corrosion on steel reinforcement

In case of steel reinforcing bars, embedded in concrete, the corrosion damage is depicted in finite areas along their length, recording significant reduction of initial cross-section, as shown in **Figure 4**. Recent studies have indicated that the existence of voids and pores in concrete allows not only the penetration and diffusion of corrosive agents but also the higher oxygen concentration on steel bars' surface, consisting a favorable condition for differential aeration corrosion. The anodic dissolution rate depends solely upon the potential difference across the electrolyte-metal surface.

In order to further investigate and simulate the consequences of differential aeration corrosion, Apostolopoulos et al. [35] conducted accelerated corrosion experiments on bare reinforcing steel bars, taking into account different exposure to corrosion lengths. The results demonstrated that corrosion damage depends on the exposed to corrosion length, as short samples record higher mass loss percentages and more intense pitting, for the same corrosion duration. In particular, specimens with the short exposed to corrosion length demonstrated about 4 times greater percentage mass loss in contrast to specimens with the long exposed to corrosion length, for 300 h of accelerated corrosion time [35], which is due to Differential aeration corrosion.

In case of RC specimens of experimental study with weak concrete cover thickness, where bond forces are tested, differential aeration corrosion phenomena are detected on ribs. In particular, during the phase of concrete hardening, micro-cracks are recorded in the area of the edge of ribs, which lead to accelerate the penetration of aggressive agents to the steel reinforcement, starting from the damage from the ribs (as closer to the outer surface). Thus, ribs are more vulnerable to corrosion, resulting mainly in degradation of steel - concrete bond mechanism which leads to mechanical interlock's loss and rise of slippage. In that manner, corrosion primarily affects bond behavior of RC elements rather than their mechanical properties, even in low corrosion level. **Figure 5** illustrates intense pits on surface due to corrosion, which subsequently causes loss of ribs, especially on the outer half of the steel bar's circumference, adjacent to the external surface of RC specimens.



Figure 4.
Local reduction of cross-section due to corrosion.



Figure 5.
 Corrosion damage on steel surface. Inner half of steel bar's circumference (up) - outer half of steel bar's circumference (down).

5. Corrosion effect on bond strength

Corrosion factor is responsible for reduction of the cross-sectional area of steel reinforcement, degrading the mechanical properties [9–14], and causing cracks and spalling of the cover concrete, which leads to deterioration of steel - concrete interface and, subsequently, to bond loss between them. In order to assess the structural integrity of corroded RC members, many researchers have studied and quantified the consequences of mechanical performance of steel reinforcement due to corrosion and proposed degradation material laws [15–16]. However, as it is abovementioned, bond behavior is primarily affected by corrosion, as the transfer of forces between reinforcement and surrounding concrete weakens. Thus, the reference to degradation of mechanical properties of steel reinforcement is not a central issue in this chapter.

Regarding the interface characteristics in RC elements, Model Code 2010 [36] recommends the calculation of ultimate bond strength f_{bd} in the non-corroded condition, as presented in Eq. (6), in which concrete and steel class, steel bar diameter and the contribution of confinement via cover thickness and transverse reinforcement are taken into account.

$$f_{bd} = (\alpha_2 + \alpha_3) \cdot f_{b,0} + 2 \cdot p_{tr} \quad (6)$$

where $f_{b,0}$ is the basic bond strength, which depends on concrete and steel quality, bar geometry and the casting position of steel bar during concreting,

α_2 and α_3 are coefficients, which represent the influence of passive confinement from concrete cover thickness and from transverse reinforcement, respectively, in excess of their respective permissible minima, and.

p_{tr} is the mean compression stress perpendicular to the potential splitting failure surface at the ultimate limit state.

Prolonged exposure of reinforced concrete structures to a corrosive environment causes significant degradation problems in the steel-concrete bond mechanism, allowing relative slip to develop between steel and concrete and reducing the bond strength between them. Consequently, the bond loss effect due to the environmental action prevents the development of full bearing capacity of reinforced concrete elements until they behave as unreinforced members. From the abovementioned, it is obvious that bond mechanism is a main criterion in design of RC members. However, there is a gap in international codes, regarding the quantification of bond strength loss due to corrosion. In particular, even though range of values are proposed by Model Code 2010 for the estimation of reduced bond strength,

considering corrosion penetration and surface crack, nevertheless the influence of stirrups spacing as well as the impact of non-uniform type of corrosion damage on steel bar's surface through pits, which is the most common in practice, are not determined yet. Due to this, there is area of research so as to establish degradation models, including the effect of both density of stirrups and local reduction of cross-section in maintenance of bond strength of corroded RC elements. Moreover, the term corrosion penetration, which is found in many regulatory texts, refers to a uniform circumference loss of the circular cross section due to mass loss, case of uniform corrosion which is practically non-existent in real RC structures exposed to chloride induced corrosion.

On this basis, many researchers have studied the effect of corrosion on bond between steel and concrete [24–30]. As Maslehuddin et al. [27] reported, bond strength of RC specimens without transverse reinforcement increases slightly in low corrosion degree; however, sharp bond loss takes place with the propagation of corrosion. These findings are in agreement with the study of Auyeung [37], which demonstrated up to 80% bond strength loss due to only 2% reduction of steel cross-section. A more comprehensive study is presented by Lundgren [38] concerning the contribution of stirrups to the bond behavior of corroded RC elements. In real RC structures the estimation of corrosion penetration and mass loss of steel bars consists a difficult task, since steel bars are embedded in concrete and corrosion damage is non-uniform on steel's surface. However, cracks due to steel corrosion on concrete surface are visible and their width can be easily measured, as shown in **Figure 6**. For this reason, recent scientific studies tend to quantify the corrosion damage of the embedded steel reinforcement through the surface cracking width and, subsequently, estimate the local bond loss [10, 21, 24–30, 37–44]. An empirical correlation between the loss of steel bar's diameter and the average corrosion penetration has been proposed by Torres-Acosta et al. [39]. Moreover, studies of Andrade et al. [40] and Tahersamsi [10] link the surface cracking width

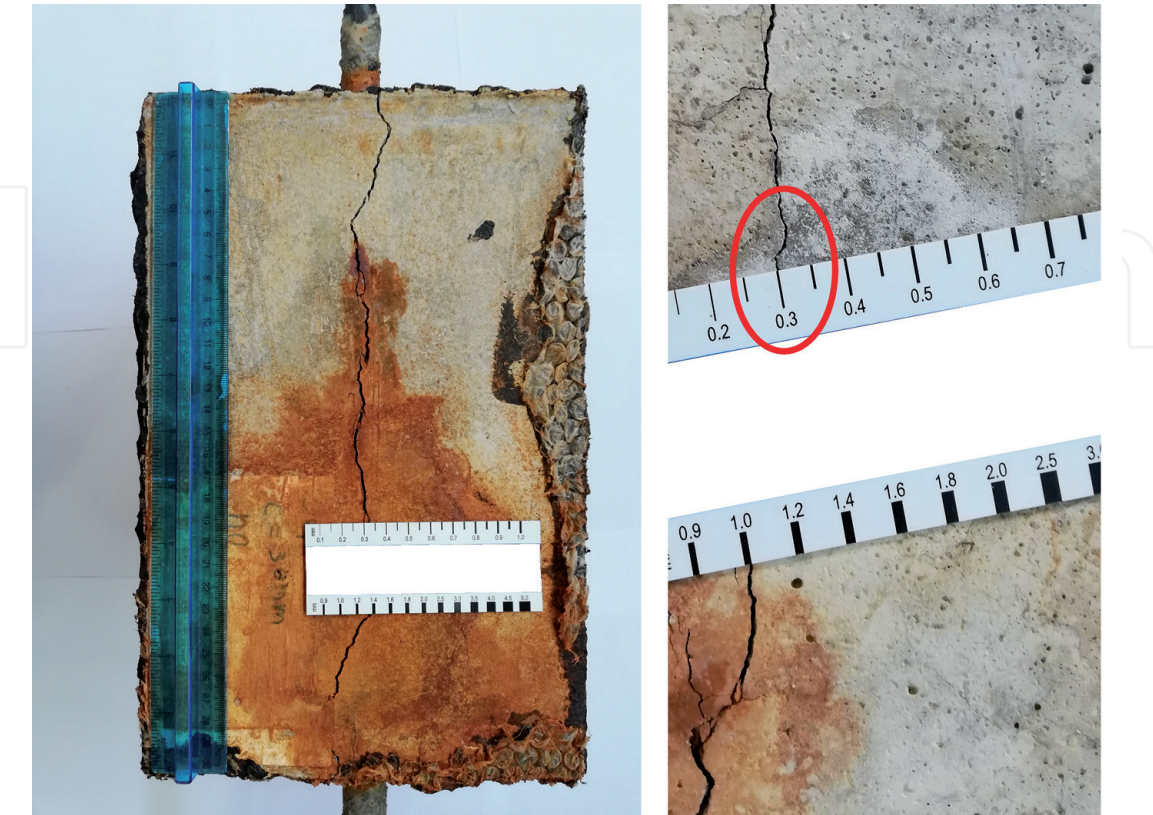


Figure 6.
Surface concrete cracking due to steel corrosion (left) -measuring of crack width on concrete (right).

with the corrosion damage of steel bar and the loss of bond strength. Recent experimental study of Lin et al. [29] investigated the influence of concrete cover thickness and stirrups on the occurrence of surface cracks and on the subsequent bond strength loss. Gathering various experimental data, a predictive model of bond strength loss as a function of surface concrete cracking has been suggested by Zhou et al. [41].

Based on the abovementioned, a broad and ongoing experimental research on corroded RC elements was conducted by Apostolopoulos and Koulouris [30], studying the influence of stirrups spacing (density) and concrete cover thickness on bond behavior of corroded RC specimens, in correlation with the surface cracking width due to corrosion. The results depict close correlation of bond strength with surface concrete cracking width.

The depassivation of protective layer on steel reinforcement leads to onset of corrosion, the propagation of which develops various range of surface concrete cracking along the reinforcing bars. As illustrated, firstly in the following **Figure 6** (Rigth) and thereafter in **Figure 7**, the surface cracking width varies depending on corrosion level, stirrups spacing and concrete cover thickness.

In the case of specimens with concrete cover of 25 mm, the values of average surface crack width followed a common path up to a low corrosion level of 3% (**Figure 7 Left**). It is noteworthy that the specimens with dense stirrups ($\Phi 8/60$ mm) demonstrated initially higher values of cracking width, since corrosion potential was higher due to the high percentage of steel reinforcement; however, as corrosion degree increases the confinement provided by dense stirrups limited the progressive development of surface cracking. On the other hand, the specimens without stirrups) recorded initially limited range cracking, due to the low percentage of steel, whereas in higher corrosion levels the absence of confinement lead to rapid growth rate of cracking width.

Similar results were recorded in the case of specimens with concrete cover of 40 mm (**Figure 7 Right**). More specific, specimens without stirrups and specimens with dense and quite dense stirrups ($\Phi 8/60$ mm and $\Phi 8/120$ mm respectively), for mass loss equal to 3%, depicted similar range of surface crack width. In contrast, specimens with stirrups $\Phi 8/240$ mm, for the same percentage of mass loss, recorded sudden and remarkable high range of surface crack. In this group pf specimens, namely with concrete cover thickness equal to 40 mm, the confined cross section is reduced in line to the specimens with concrete cover thickness equal to 25 mm. Hence, poor confinement level in conjunction with corrosion initiation impacts the uncontrolled propagation of surface cracking.

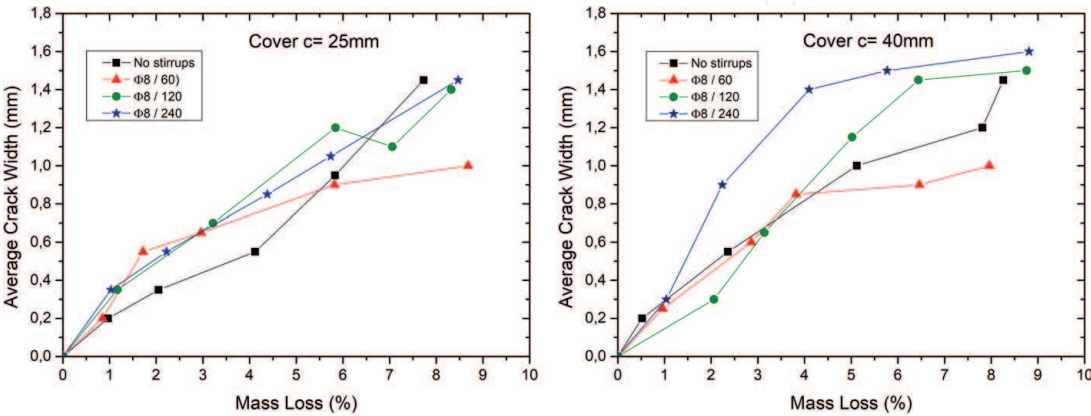


Figure 7.
Average crack width on concrete surface in function of percentage mass loss of steel bar. Cover thickness 25 mm (left) and 40 mm (right).

Nevertheless, with the evolution of corrosion, specimens with dense connectors, namely $\Phi 8/60$ mm, noted a significant decrement of surface cracking development. This particularly notable decrease, recorded in specimens with dense stirrups, was applied to both categories of specimens, one with concrete cover thickness of 25 mm and the other with concrete cover of 40 mm. More precisely, an average crack width equal to 1 mm has been recorded, for mass loss between 8.5% and 9%, respectively.

It is obvious that surface crack width is the outcome of corrosion damage of steel reinforcement; surface cracking is directly linked to various parameters beginning with the existence and amount of transverse reinforcement and cover concrete thickness. For both groups of specimens with different concrete cover (25 mm and 40 mm, respectively), the presence of dense stirrups ($\Phi 8/60$ mm) is preceded with a remarkable limitation of the surface cracking evolution to a width threshold of 0.90 mm, corresponding value to the abovementioned average mass loss of 8.5%–9.0%.

In order to investigate the bond behavior, pull out tests of uncorroded and corroded RC specimens conducted, the results of which confirmed that, in both cases of concrete cover thickness of 25 mm and 40 mm, the increase of the average range of surface cracking brought a dramatic decrease of bond strength between concrete and steel bar, **Figure 8**. Moreover, obtained by non-linear regression analysis, exponential predictive models of bond strength loss due to corrosion of steel reinforcement were given, derived from the correlation of bond strength loss of corroded specimens and surface cracking of concrete. The functions of predictive models are as follows, Eq. (7):

$$\frac{c_b^{cor}}{c_b^{uncor}} = e^{-A \cdot c_w} \quad (7)$$

where A is a parameter that depends on the concrete cover (c) and the amount of transverse reinforcement (stirrups spacing or absence of stirrups). The values of parameter A for each predictive model, and the corresponding values of the R^2 coefficient, are presented in the following **Table 1**. As shown by the predictive curves, stirrups spacing is main influencing factor of bond strength degradation due to corrosion. Hence, there is need to determine specific models of bond loss in order to enhance the current technical codes.

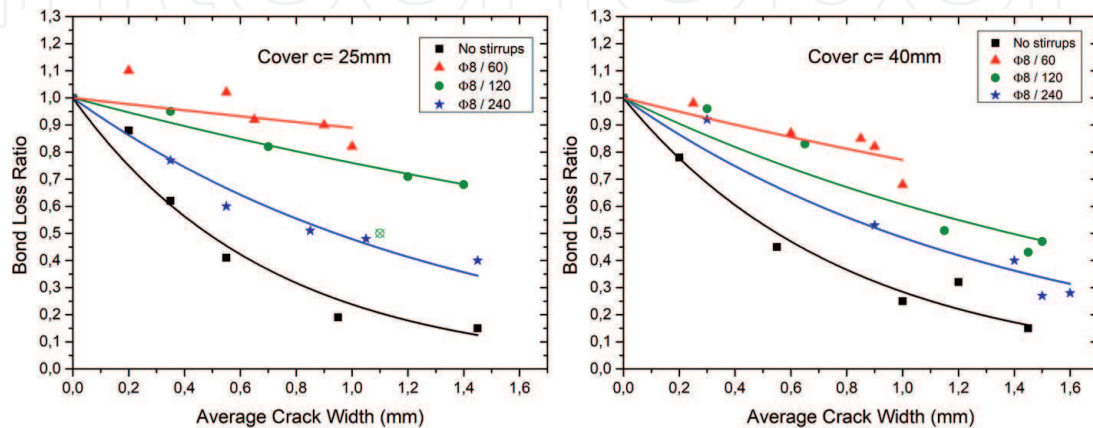


Figure 8. Predictive models of bond strength loss correlated to the average surface crack width. Cover thickness 25 mm (left) and 40 mm (right).

Cover (mm)		No Stirrups	Φ8/240	Φ8/120	Φ8/60
25	A	1.435	0.736	0.274	0.117
	R ² (%)	96.2	96.5	97.7	45.9
40	A	1.257	0.724	0.499	0.260
	R ² (%)	97.5	96.0	91.9	80.1

Table 1.
Parameters (by regression analysis) for the exponential predictive model of bond strength loss.

Among specimens of the same concrete cover, it is clear that densification of transverse reinforcement slows down the progression of bond loss. In particular, specimens with concrete cover equal to 25 mm and dense stirrups Φ8/60 mm, the bond strength performance, even though its initial increase up to a threshold of 0.60 mm crack width, remained stable as in the case of non-corroded specimens. Moreover, among specimens of similar range of cracking, specimens without stirrups recorded a decline of bond strength performance equal to 57%, whereas specimens with wide stirrups (Φ8/240 mm) and quite dense stirrups (Φ8/120 mm) recorded a decrease of bond strength performance equal to 35% and 15%, respectively.

The wide stirrups spacing (Φ8/240 mm), in case of 25 mm cover thickness, degrades bond strength performance, leading to a residual bond strength equal to 40% of the non-corroded bond strength, corresponding to a crack width of 1.45 mm, whereas the absence of stirrups (specimens without stirrups) recorded bond loss equal to 16% of non-corroded value. The abovementioned outcomes transposed to former practices, as in the existing building stock, the use of transverse reinforcement accounts for four pieces per linear meter, i.e. Φ8/250 mm. Thus, loss of bond strength seems to be inevitable.

In the case of cover thickness of 40 mm, the absence of stirrups deteriorates rapidly bond strength contrary to the dense fitting of stirrups (Φ8/60 mm) where this benefits, thereby delaying bond strength degradation.

The bond strength between steel and concrete demonstrates a denoting drop when increasing the range of surface cracking; it follows from the assessment of both cases of concrete cover that as the range of surface cracking raises, the threshold of bond strength performance reduces. These results come in good agreement with results of former studies, to name Lin et al. [29], Fischer and Ozbolt [42], Almusallam et al. [43] and Rodriguez et al. [44].

Given the tendency to approach the issue of bond strength between concrete and steel, exponential predictive models were developed in order to link the bond strength loss of corroded specimens to the average width of concrete surface cracking. The exponential model introduces an adequate approach of bond strength loss and comes to agreement with previous studies [43, 44] as corrosion evolves. Hence, so as to assess the bond loss, besides the traditional method of chlorides' measurement, surface cracking measurement occurs as an emerging methodology. Notwithstanding the efforts of the scientific community to correlate experimental results of current literature, the issue of dispersion is pertinent due to several parameters, to cover thickness, concrete class, nominal diameter of steel reinforcement, presence of stirrups. It is also noteworthy that, in existing experimental literature, exponential models are proposed as predictive models of bond behavior of corroded RC elements, regardless of the differences denoted in all parameters to-be-tested in comparative studies.

Extending the investigation of bond behavior of corroded RC members and focusing on values of maximum pull-out force and, subsequently, bond strength, and not on bond loss, the role of stirrups spacing is more highlighted, where bonding between steel and concrete degrades due to corrosion and the developed maximum pull-out force drops. The usage of dense transverse reinforcement contributes to bond behavior, not only reducing the bond loss rate, but leading to greater values of maximum pull-out force due to confinement, **Figure 9**.

In an effort to estimate that influence of stirrups spacing on non-corroded condition, the presence of wide stirrups ($\Phi 8/240$ mm) present maximum bond strength equal to 7.04 MPa, whereas quite dense ($\Phi 8/120$ mm) and dense stirrups ($\Phi 8/60$ mm) equal to 9.10 MPa and 9.53 MPa, respectively. The percentages attributing the increase of bond strength against specimens without stirrups are 35.9%, 75.6% and 84%, respectively. It is noteworthy that, quite dense stirrups spacing ($\Phi 8/120$ mm) result in sufficient bond strength levels, whereas further densification leads to minor increase of bond strength, nevertheless delays the bond loss. Extrapolating the abovementioned on real RC structures, stirrups' densification above a certain threshold, is considered inappropriate since it could lead on the one hand to substantial increase of costs and on the other hand to rapid rise of corrosion rate, due to potential increase.

Moreover, bond stress - relative slip curves are exported from pull-out tests for each corrosion level and for each category of stirrups spacing, respectively. Typical curves of uncorroded and corroded specimens are shown in **Figure 10**.

The harmful influence of corrosion phenomenon on bond behavior between steel and concrete can be seen examining the bond stress - slip curves of **Figure 10**, and in particular group of specimens without stirrups. Uncorroded specimens - where no surface cracking had been initially observed - showed a quasi linear relationship between bond stresses and relative slip till the point of bond strength's development. During this phase, cracks were occurred, parallel to the axis of steel bar, and gradually were developed due to the radial stresses, which are transferred from steel to concrete. After the development of bond strength, sharp decline of bond stresses and complete bond loss followed. In the case of corroded specimens (without

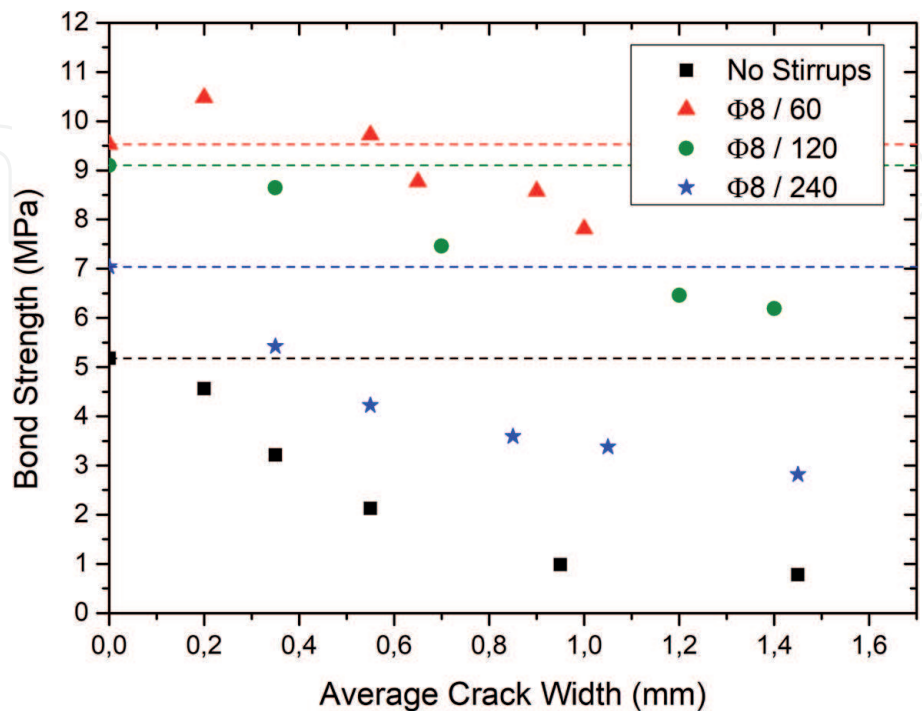


Figure 9.
Bond strength values in function with average crack width.

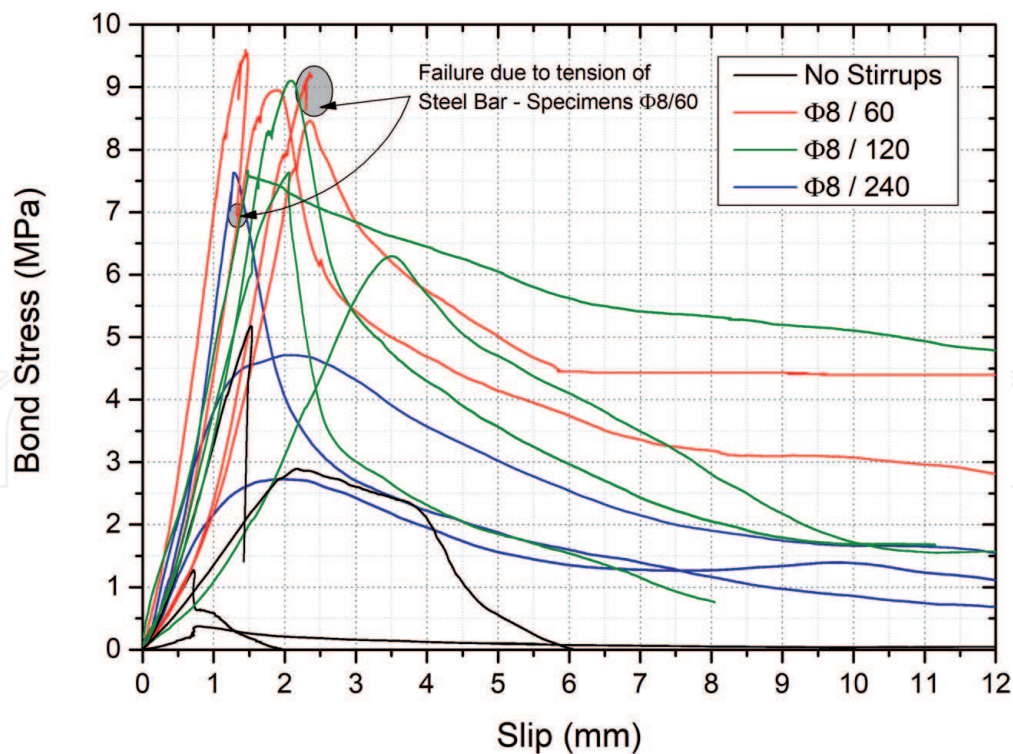


Figure 10.
 Bond stress - slip curves obtained from pull out tests.

stirrups) intense surface concrete cracking was recorded, due to steel corrosion, even in low mass loss levels. As a result of this cracking, bond behavior degrades dramatically, as confirmed by the corresponding curves of **Figure 10**, since both the steel-concrete interface is damaged by the corrosion oxides and the confinement level is deteriorated by the cracks in concrete cover.

On the other hand, as shown by the groups of specimens with stirrups, surface cracking and degree of bond loss is strongly correlated with stirrups spacing. In particular, specimens with quite wide stirrups ($\Phi 8/240$ mm) showed that transverse reinforcement has a positive impact on bond behavior in uncorroded condition, as greater values of bond stress indicated. However, when corrosion occurs, accompanied by surface concrete cracking, bond resistance degrades as reflected in responding curves, where bond strength reduces significantly, and subsequently low values of residual bond stress are recorded.

Greater contribution of stirrups to bond behavior was noticed on specimens with quite dense stirrups spacing ($\Phi 8/120$ mm), where even higher bond strength values are indicated, and while bond behavior degrades due to corrosion damage nevertheless does not demonstrate a massive drop mainly due to confinement. In addition, in the case of wide stirrups ($\Phi 8/60$ mm), full use of bond behavior, even after corrosion damage, occurs, with residual bond stress recorded after the peak of bond strength. It is also noteworthy that specimens of this category had finally ended due to failure under tension. Thus, that densification of stirrups make full use of bearing capacity of steel reinforcing bars and subsequently of RC elements. From the aforementioned, it becomes obvious that the use of dense stirrups ($\Phi 8/60$ mm) leads to full bonding between steel and concrete, in uncorroded and corroded conditions respectively, marking both high bond strength and high residual bond stress after the ultimate pull out force.

To conclude, existence of stirrups contributes to bond behavior, and subsequently, greater density of stirrups affects both the reduction of bond loss' degradation rate due to steel corrosion, as well as the increasing of bond stresses values due to greater confinement. The use of wide stirrups ($\Phi 8/240$ mm) enhances the

bond strength, in uncorroded conditions, about 35.9% in comparison with group of specimens without stirrups. However, when corrosion occurs, the subsequent surface cracking degrades significantly the confinement and the bond between steel and concrete, about 60% reduction against of uncorroded specimens with $\Phi 8 / 240$ mm. Specimens with quite dense stirrups ($\Phi 8 / 120$ mm) indicated higher bond strength values, and while bond behavior degrades due to corrosion damage nevertheless does not demonstrate a massive drop mainly due to confinement, about 32%. Finally, Dense stirrups spacing, specimens with $\Phi 8 / 60$ mm, ensure high level of bond behavior, either in terms of bond strength or of residual bond stress, both in uncorroded and corroded conditions. Furthermore, stirrups spacing of 60 mm results in full anchorage of steel reinforcing bars and make full use of their bearing capacity.

6. Conclusions

The present chapter presents an extensive and ongoing experimental research, which was conducted in Laboratory of Technology and Strength of Materials, in University of Patras, and comes to agreement with corresponding results of other scientific studies. The effect of steel corrosion on bond loss between steel and concrete was deeply investigated, including influencing parameters such as concrete cover thickness, density of stirrups and surface concrete cracking. The results of this research, the following outcomes were obtained:

- The width of surface cracking on concrete due to corrosion of steel reinforcement is closely related both to the cover thickness and to the amount of stirrups or their absence in RC element.
- Existence of stirrups contributes to bond behavior, and subsequently, greater density of stirrups affects both the reduction of bond loss' degradation rate due to steel corrosion, as well as the increasing of bond stresses values due to greater confinement.
- The development of surface cracking in concrete is associated with an exponential reduction of bonding forces.
- Based on the fact that presence of dense connectors, $\Phi 8 / 60$ mm, was accompanied by a clear limitation of the surface cracking development, it appears that the densification of stirrups (through the confinement) contributes positively to maintaining bond between steel reinforcement and concrete.
- In conclusion, there is a need for further improvement and strengthening of existing technical codes, introducing predictive models of bond loss in function with corrosion damage, cover thickness, surface concrete cracking and density of stirrups.

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