

# CORROSION PROPAGATION PHASE AND BOND STRENGTH DEGRADATION OF REINFORCED CONCRETE STRUCTURES: STATE OF THE ART

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## ABSTRACT

Corrosion causes damage to reinforcing steel in concrete structures and governs the service life of the structures. Currently, researchers are paying attention to modelling the behaviour of the bond between the concrete and steel interface of corroded reinforcement. The main objective of this paper is to study the recent research relevant to the bond behaviour at the interface between corroded ribbed bars and concrete and to identify the future research focus. Initially, the paper presents the mechanisms of corrosion damage of reinforced concrete by discussing corrosive agents, causes and effects. Then mechanisms of corrosion propagation, mechanical properties of corroded reinforcing steel and effects of corrosion on bond degradation of reinforced concrete are discussed in details. Thereafter, recent experimental researches on bond degradation between reinforcement and concrete are reviewed. Previous studies have proposed formulae, which depend on cover, reinforcing bar diameter, concrete strength and corrosion level, to predict the ultimate bond strength. Effect of other parameters (i.e. type of the bars, bar spacing, crack size, aggregate size, type of loading, stress state and etc.) on bond strength have not been properly studied in literature. Bond strength against biaxial bending or combined load action has not been investigated. Finally, the paper concludes with the significance of testing naturally corroded test specimens, compared to the artificially corroded specimens, as well as discussing loading situations.

*Keywords: bond degradation, corrosion, load capacity, reinforced concrete.*

## 1 INTRODUCTION

The deterioration of concrete structures can be recognized in different ways, such as by corrosion of reinforcement, freeze-thaw damage, etc. The corrosion of reinforcing steel is a major durability issue of existing concrete structures. Generally, reinforcing steel and the surrounding concrete area are damaged by corrosion. Finally, it affects both the serviceability and load-carrying capacity of existing reinforced concrete structures [1, 2]. Therefore, the understanding and modelling of reinforcing steel corrosion is very important when predicting the service life of reinforced concrete structures.

The reinforcing steel in concrete structures corrodes mainly due to carbonation, chloride ingress and any other chemical ingress. The deterioration process in reinforced concrete structures due to corrosion can be categorized into two phases, namely, initiation and propagation [3]. The initiation phase starts when chloride, carbonation or both begin to penetrate the concrete. The thin oxide layer formed on the surface of the embedded steel prevents from corrosion. The propagation phase starts by the passivation of the thin oxide layer on the surface of steel; this is the start of the active corrosion condition of the reinforcing steel. The corrosion of steel is getting in an active state when the pH value decreases. The summation of the time, from penetration until the threshold value is reached and the time from propagation until a maximum acceptable corrosion depth is reached, can be illustrated as the service life of the structure.

During the propagation phase of the corrosion, a reduction in the steel cross-sectional area, which affects both the ductility and the strength of the steel, and a volumetric expansion,

which causes spalling of concrete and loss of bond strength in between the concrete and steel (due to both a weak interface layer and the disengagement of ribs), can be seen [1, 4]. These effects may reduce the anchorage capacities and the composite interaction and change the geometric properties, due to a loss of the concrete cross section [5]. Finally, this causes changes in the overall stiffness of the structure, and a reduction in load carrying capacity can be observed. Several researchers have studied the relevant corrosion mechanisms and the corresponding structural behaviour of deteriorated reinforced concrete structures [6, 7]. They pay significant attention to the accurate modelling of the bond strength and the corresponding mechanisms of corroded reinforced concrete structures.

The main objective of this paper is to review the recent research and findings related to bond strength degradation due to corrosion propagation in reinforcing steel, by considering the overall reasons for and causes and effects of corrosion. More specifically, the experimental research studies, relevant to the bond behaviour of corroded bars, are reviewed. Initially, the paper presents the mechanisms of corrosion propagation and the effects of corrosion on bond degradation. Then recent experimental research on bond degradation between reinforcement and concrete is reviewed. Finally, taking into account notable issues and shortcomings in experimental research studies, a research gap has been identified in respect of modelling bond strength between corroded reinforcing steel and concrete.

## 2 CORROSION DAMAGE OF REINFORCED CONCRETE STRUCTURES: CAUSES AND EFFECTS

Chemicals, which are available in the environment or in the ingredients of concrete, are the main agents of the corrosion of reinforced concrete. Chloride in de-icing and seawater salts, carbonation and the reaction of sulphates with the tricalcium aluminate present in cement are some of the corrosive agents. The corrosion initiation phase starts when chloride, carbonation or both begin to penetrate the concrete [8]. The propagation phase starts when steel bars are active in corrosion.

During the propagation phase of the corrosion, the following can be observed: reduction of the cross-sectional area, loss of original shapes and disappearance of the reinforcement steel ribs [9–12]. This may also cause both a weak interface layer and finally the disengagement of the ribs [9, 13, 14]. The chemical reaction of the corrosion of steel bars produces rust materials, which expand the volume of the original steel. The previously mentioned loss of the steel bar section, volumetric expansion of the steel and a weak interfacial layer are the major causes of the deterioration of existing reinforced concrete structures.

The volumetric expansion places stresses on the concrete, leading to cracking [10]. This may finally cause spalling of the concrete cover area. This damage may accelerate the corrosion rate. In addition, it reduces the concrete cross section and finally reduces the overall stiffness of the structure. The disengagement of ribs due to volumetric expansion, cover cracking caused by spalling, and the weak interfacial layer affect the bond strength/mechanism, which is source for the interaction between the steel reinforcement and the surrounding concrete [9]. Then the bond between the steel and concrete significantly reduces the anchorage capacity and composite action of the steel and concrete, as shown in Fig. 1. The loss of the steel bar section can occur from either localized pitting corrosion, due to chloride ingress, or general (uniform) corrosion, due to carbonation. This may reduce the mechanical properties of the reinforcement, such as ductility and strength. General corrosion also affects the bond mechanism between the steel and concrete, as shown in Fig. 1. Finally, changes in the mechanical properties of the steel, anchorage capacity, composite behaviour, as well as the

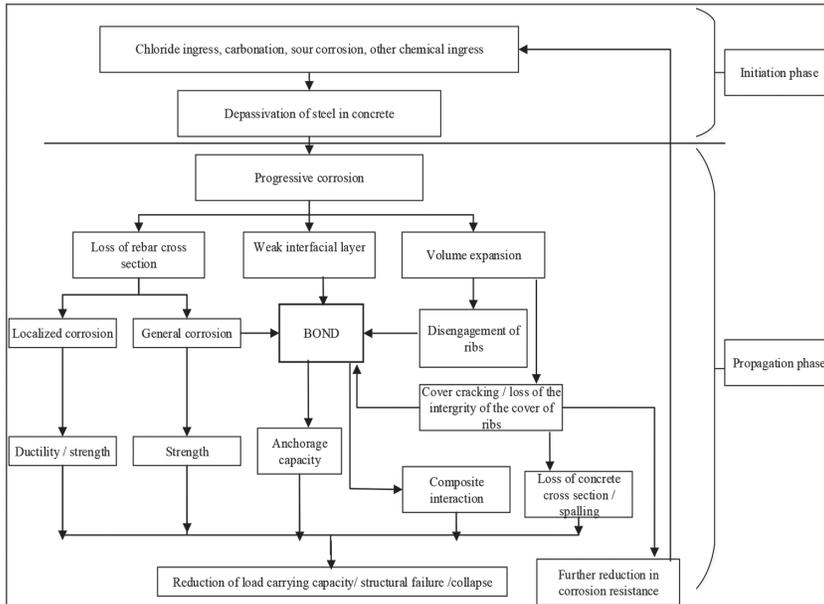


Figure 1: Fault tree for bond degradation and structural failure (adapted from [9, 16])

loss of the concrete cross section, have the effect of reducing the load carrying capacity and ductility in the ultimate limit state, altering the overall stiffness and structural response of the reinforced concrete structures.

### 3 MECHANISM OF CORROSION AND MECHANICAL PROPERTIES OF CORRODED STEEL BARS

This section describes the chemical reaction involved in the corrosion of steel and the development of corrosion products. Changes to the mechanical properties of corroded reinforcing steel bars are briefly discussed in the latter part of the section.

#### 3.1 Chemical Process During Corrosion of Steel Bars

The mechanism of corrosion in concrete can be described as follows: oxidation of iron takes place when the dissolution of iron produces ferrous iron ( $Fe^{2+}$ ) at the anode with the presence of chloride or carbon dioxide. At the cathode, oxygen produces hydroxide ions ( $OH^-$ ) which diffuses through the concrete. Then  $OH^-$  and  $Fe^{2+}$  react and form ferrous hydroxide ( $Fe(OH)_2$ ). Further oxidation of ferrous hydroxide produces the rust ( $Fe_2O_3 \cdot H_2O$ ), as shown in Table 1) [15, 16]. The resulting rust increases the volume of the steel, thus expanding the concrete. Moreover, the rust formation increases the volume to about six times that of steel. It has very little positive effect on the onset of the corrosion but a negative effect afterwards on the service life of the structure, especially with regard to bond strength. Finally, concrete cracking and spalling can be seen due to corrosion of the steel in concrete. This causes a reduction in the cross-sectional area, which affects the cross-sectional properties. This may cause the overall stiffness of the structure and the structural response (i.e. stress, displacement, dynamic characteristics, etc.) to change.

Table 1: Summary of experimental investigations regarding the bond strength

		Materials					
		Concrete properties		Reinforcement steel			
Author	Year	Type of test	Specimen	Avg. compressive strength (MPa)	Bar diameter (mm)	Characteristic Strength (MPa)	Corrosion process and corrosion measurement/level of corrosion
Al-Sulaimani <i>et al.</i> [22]	1990	Pull-out	150mm cubes	30	0.55	450	Accelerated corrosion: Constant current density 2000 $\mu$ A/cm <sup>2</sup> Corrosion percentage: 0%-7.8% (mass loss)
							Test information -Cover to bar ratio 7.5, 5.36, 3.75 -embedded length to bar diameter ratio is 4 -bar centrally embedded
Rodriguez <i>et al.</i> See Ref [6] for summary	1994	Pull-out	300mm cubes	40		590	Accelerated corrosion: 3% CaCl by weight of cement added to concrete mixture; 100 $\mu$ A/cm <sup>2</sup> current for few months Depth of corrosion: 0-0.377mm
Cabrera See Ref [6] for summary	1996	Pull-out	50mm cubes	-	0.55	460	Accelerated corrosion: NaCl 2% to the concrete mixture; 5% NaCl 28 days curing; voltage of 3V Corrosion percentage: 0%-12.6% (mass loss)

(Continued)

Table 1: (Continued)

Materials		Concrete properties				Reinforcement steel			Corrosion process and corrosion measurement/level of corrosion
Author	Year	Type of test	Specimen	Avg. compressive strength (MPa)	w/c ratio	Bar diameter (mm)	Characteristic Strength (MPa)	Test information	
Almusalam <i>et al.</i> See Ref [6] for summary	1996	Cantilever bond	Beam 152mm x 254mm x 279mm	30		12	Grade 60 high strength	Embedded length 102mm Inverted open stirrups were provided	Accelerated corrosion: Constant current 0.4A Corrosion percentage: 0%–80% (mass loss)
Amleh and Mirza See Ref [6] for summary	1999	Tension (i.e. pull-out)	100mm diameter and 1000 mm long cylinder	25	0.45	19.5	400	Centrally embedded Embedded length 1000mm	Accelerated corrosion: Curing 5% NaCl by weight of water; voltage of 5V Corrosion percentage: 0%–17.5% (mass loss)
Auyeung <i>et al.</i> [8]	2000	Pull-out	Concrete prisms 175mm x 175mm x 350mm	28		19		One long bar and one short bar -embedded length long bar: 175mm short bar: 125mm -centrally embedded -50mm separation of bars -pull-out in opposite direction	Accelerated corrosion: 3% chloride based admixture by weight of cement; 3% salt solution curing for 3 days; direct current applied Corrosion percentage: 0%–5.91% (mass loss)

(Continued)

Table 1: (Continued)

Materials		Concrete properties				Reinforcement steel		Corrosion process and corrosion measurement/level of corrosion
Author	Year	Type of test	Specimen	Avg. compressive strength (MPa)	w/c ratio	Bar diameter (mm)	Characteristic Strength (MPa)	
Chang [33]	2002	Pull-out	10 dia x 20mm		0.48 0.58 0.66	12.7	410	Accelerated corrosion: 3.5% NaCl solution; 1200 $\mu\text{A}/\text{cm}^2$
Lee <i>et al.</i> [32]	2002	Pull-out	8D per side cube (D is bar diameter)	24.7-42.1	0.45-0.65	13	315	Accelerated corrosion: 1.45% of cement to concrete; 3% NaCl solution curing during corrosion process; 1 A current Corrosion percentage: 0%-30% (mass loss)
Fang <i>et al.</i> [34]	2004	Pull-out	140mm x 140mm x 180mm	52.1		20	$f_y$ : 289.6 smooth bars; Both smooth and deformed bars 350.9 smooth bars With and without stirrups	5% NaCl curing 3 days before accelerated corrosion; fully immersed in NaCl; direct current 0-2A Corrosion percentage: 0%-9% (mass loss)

(Continued)

Table 1: (Continued)

Materials		Concrete properties				Reinforcement steel			Corrosion process and corrosion measurement/level of corrosion
Author	Year	Type of test	Specimen	Avg. compressive strength (MPa)	w/c ratio	Bar diameter (mm)	Characteristic Strength (MPa)	Test information	
Chung <i>et al.</i> [31]	2008	Pull-out	Beam	25	0.58	13	526.8	Centrally embedded 1 rebar 3D bond length	Accelerated corrosion: 3% NaCl solution; 24 V DC and 12 amps to achieve maximum corrosion level; chloride admixture used Corrosion percentage: 0%–8.8% (mass loss)
Yalciner <i>et al.</i> [7]	2012	Pull-out	150 cube	23-51	0.40, 0.75	14	606 $f_y=458$	Cover 15mm, 30mm, 45mm	Accelerated corrosion: Fully immersed in 3.5% NaCl solution before accelerated corrosion starts; direct current supply 60V; constant potential 0–5A; Copper plate in 5% NaCl solution Corrosion percentage: 0%–18.75% (mass loss)
Wu <i>et al.</i> [30]	2016	Pull-out	240mm x 150mm x 160mm	34		12, 16, 20, 25		Course aggregate/ fine aggregates 33% 25mm cover	Accelerated corrosion: By NaCl, HCl, MgCl <sub>2</sub> , NaSO <sub>4</sub> CO <sub>2</sub> , high temperature, high humidity

### 3.2 Mechanical Properties of Corroded Steel Bars

The corrosion of reinforcing steel bars can be categorized into two types named general corrosion and localized corrosion. Uniform corrosion is most commonly caused by carbonation whereas chloride ingress is the most common cause of pitting corrosion [9, 17, 18]. Both pitting and general corrosion degrade the mechanical properties of reinforcing steel bars [19].

In the presence of corrosion, usually in the pits, hydrogen-assisted stress-corrosion cracking can be seen (i.e. hydrogen embrittlement). The ultimate strain, therefore, is severely reduced, and researchers found that ductility may be reduced below the minimum required level specified by the design codes, as a result of around 10% of localized corrosion of the reinforcing steel bars [11]. The yield and ultimate strength are also significantly reduced by the effect of corrosion [11, 12, 19, 20]. The localized pit develops locations of stress concentration and may be subject to local bending on the pitted cross section, due to the displacement of the centroid of the remaining cross section of the steel bar [9, 20].

## 4 BOND STRENGTH BETWEEN REINFORCING STEEL AND CONCRETE

The flexural strength of reinforced concrete members relies on the transfer of tensile forces known as bond, between the longitudinal reinforcement and concrete. The bond between concrete and steel reinforcement provides better composite action in reinforced concrete structures [10]. The bond consists of three main mechanisms: chemical adhesion, friction and mechanical interlock between concrete and steel. Bond stress can be defined as the shear stress between the steel and the concrete interface [10]. The bond stress initially develops due to the chemical bonds between the steel and the concrete in the low stress ranges. Micro cracks in the radial direction originate after the loss of the chemical bond. Slipping of the reinforcement bar may occur when increasing stress is acting on the steel bar. In this case, the friction, especially in plain bars, governs the bond strength. For ribbed bars, the bond strength is governed by the interaction of both friction and mechanical interlocking between the ribs of steel and the concrete. The bond strength depends on the grade of concrete, type and size of the main reinforcement bars, concrete cover and amount of transverse reinforcement [18].

When the bond degrades because of corrosion of the reinforcing steel, the cohesion, due to the chemical bond and the mechanical interlock between the ribs of steel and the concrete weakens. This may cause a loss of bond strength, although the corrosion products increase the bond strength slightly at the beginning, by stressing the interlock between the steel and concrete [21, 22]. The bond strength drastically decreases with the increase in corrosion level, due to longitudinal and transverse cracks. The factors affecting the bond strength of corroded reinforced concrete structures are as follows: concrete grade, concrete cover, size and type of steel bar, confinement provided by transverse reinforcement, corrosion level and loading state/actual structural behaviour. The bond failure modes are generally recognized as splitting failure, pull-out failure and combined modes of failure [23]. Splitting occurs when transverse cracks lengthen to join up with cracks appearing from outside. Pull-out failure occurs when shear resistance (i.e. bond strength) exceeds the external force (i.e. when the load transfer mechanism fails).

## 5 MODELS FOR BOND DEGRADATION BETWEEN REINFORCEMENT AND CONCRETE

This section, which includes the models, describes the bond strength, bond stress-slip behaviour of corroded reinforced concrete members and the associated investigations. Initially,

different bond strength modelling approaches are briefly discussed. Then the recent experimental research on bond degradation between reinforcement and concrete is reviewed. Recently proposed, widely applicable bond strength models and bond-slip behaviour are summarized at the end of this section.

### 5.1 Bond Strength Modelling Approaches

The available models for bond degradation can be categorized as analytical, numerical and experimental/empirical models. Analytical modelling and numerical modelling have been developed using bond stress-slip theories and finite element approaches [24–27]. Empirical modelling based on experimental investigations has been found to be more realistic and versatile for bond strength degradation. The widely used tests to evaluate bond strength include both concentric and eccentric pull-out test and bond beam test (i.e. standard beam or cantilever). The RILEM Recommendations for the testing and use of constructions materials [28] is the testing standard used for pull-out tests. These tests simply can be divided into two categories, namely, pull-out tests and flexural tests. All the tests had prepared control specimens to determine the bond strength of the non-corroded bar. The tests were carried out with and without stirrups. These experimental studies are utilized to understand bond stress-slip behaviour and to develop empirical bond strength models [28, 29]. Therefore, previous experimental research studies have been critically reviewed and summarized in the following subsections.

### 5.2 Accelerated Corrosion Process/Artificial Corrosion Process

It is also important to discuss the corrosion process when the experimental research of reinforced concrete specimens is concerned. It is noted that mainly accelerated corrosion [7, 30–34] has been widely used for previous research purposes by different researchers, although it does not give the fully real behaviour, compared to natural corrosion. The current density applied to accelerated corrosion tests may significantly affect the bond strength [9]. The chemical composition of corrosion products and its escape or penetrate behaviour are the main reasons for above differences. A few studies have been performed to obtain a relation between both accelerated corrosion and natural corrosion [2]. In summary, the acceleration of the corrosion of steel reinforcement has been brought about by an electrochemical method. To that end, concrete specimens were immersed in a sodium chloride solution to provide a chloride environment and current was provided to start and accelerate the electrochemical process. The percentage of sodium chloride has been decided on being as close to the chloride content available in the air or in a marine environment (i.e. generally 3%–5%), to find the most realistic environmental condition, according to the requirement.

This process can be established by many methods, for instance, by full or partial immersion in salt water or by both sodium chloride being added to the concrete mixture and then samples being immersed in sodium chloride liquid, in order to accelerate the corrosion process in both ways [7]. The direct current or voltage used to accelerate the process is decided by considering the value closest to the natural corrosion process.

### 5.3 Experimental Investigations of Bond Strength by Pull-Out Tests

Previous experimental investigations regarding bond degradation are briefly summarized, as shown in Table 1. The table shows that how researchers have used pull-out tests to model the

bond strength by considering different parameters such as reinforcement with different diameters, with different rib patterns or without ribs and with different levels of strength. In addition, the diameter of the bar or the type, concrete compressive strength, concrete mix design or water-to-cement ratio are parameters considered for concrete [28]. Al-Sulaimani *et al.* [22] conducted a concentric pull-out test, as shown in Table 1, and ultimate bond strengths were presented as a function of percentage of corrosion. Bhargava *et al.* [6] presented average and standard deviations of bond strengths for different depths of corrosion (i.e. corrosion levels). Cabrera [6] also conducted a concentric pull-out test, as shown in Table 1, and bond strengths were presented as a function of percentage of corrosion, as in the work of Al-Sulaimani *et al.* [22]. The differences between these two experimental investigations are the reinforcement bar diameter, characteristic yield strength of the bar and the concrete grade. However, it is not possible to find a generalized relation (i.e. widely applicable) for bond strength, based only on the above tests, and therefore researchers have been motivated to perform further experimental studies. Almusallam *et al.* [29] conducted a bond strength test by using cantilever beams, as shown in Table 1, and ultimate bond strengths were presented as a function of degree/percentage of corrosion. The test represents a severe corrosion level. Amleh and Mirza [6] also performed a tension test on a concrete specimen of 100 mm diameter and 1 m length. The test was a concentric pull-out test, as shown in Table 1. Auyeung *et al.* [8] tests were conducted on concrete prisms, which were pulled out in opposite directions, with one long and one short bar at 50 mm spacing, as summarized in Table 1. Finally, the normalized bond strengths versus percentage mass losses were presented. In 2002, the maximum bond strengths were obtained as a function of the degree of corrosion and the grade of the concrete by Lee *et al.* [32]. Fang *et al.* [34] conducted a concentric pull-out test for a higher grade of concrete, as shown in Table 1, and the bond strengths were discussed as a function of the degree of corrosion for both smooth and deformed bars, in cases with and without stirrups. Chung *et al.* [31] experimentally investigated bond degradation by using two types of bar pull-out tests with prismatic concrete specimens. The first specimen type consisted of reinforcing bars, which were pre-corroded before casting. The reinforcing bar of the second type of specimen was corroded after the concrete casting. Based on the experimental data, a bond strength model was proposed as a function of the corrosion level. Yalciner *et al.* [7] found a valuable empirical model for bond strength as a function of concrete cover, strength and corrosion level, by conducting a series of pull-out tests, as shown in Table 1. The bond-slip relations were comprehensively investigated. In 2016, Wu *et al.* [30] proposed a simplified model for examining bond strength between the cracked concrete and heavily corroded deformed steel bars. The proposed model depends on the degree of corrosion, the compressive strength of concrete, the width of the cracks in the concrete and the friction factor between the deteriorated concrete and the corroded steel bars.

Reinforcing steel bar diameters, which were used for previous studies, vary from 10 to 25 mm. Both smooth and ribbed reinforcing bars have been used and their ultimate strength varies from 350 MPa to 606 MPa. This shows that effect of the chemical composition of steel reinforcement has been considered for the bond strength by previous studies. The average concrete compressive strength of tested specimens was in the range of 23 MPa–52 MPa. The current densities used for the accelerated corrosion process were in the range from 100  $\mu\text{A}/\text{cm}^2$  to 2000  $\mu\text{A}/\text{cm}^2$ . The considered NaCl percentage varies from 2% to 5% and this is closer to the NaCl percentage, which is generally available in the environment. The calculated mass loss due to accelerated corrosion were in the range of 0%–18.5% for most of the tests except one test, which was in the range of 0%–80%.

#### 5.4 Experimental Investigations of Bond Strength by Flexural Tests

Several researchers have also carried out experimental investigations of bond strength by means of flexural tests. Al-Sulaimani *et al.* [22] tested beams of 150 mm × 150 mm in cross-section and 1000 mm in length. The reinforcement details are one bottom bar of 12 mm, two top bars of 10 mm and 6 mm spacing, between stirrups at 50 mm. A four-point bending test was conducted, and bond strength was presented as a function of percentage of corrosion. The bond breakdown strengths and the ultimate bond strength were comprehensively discussed. Bhargava *et al.* [6] performed flexural tests on one-way slab specimens of 350 mm × 150 mm in cross-section and 1300 mm in length. A four-point loading system was utilized.

Normal and silica fume concrete were considered separately with 10 mm main reinforcement bars, spacing of 125 mm and 20 mm clear cover. The degree of corrosion was estimated by the mass loss of steel compared to the original mass of the bar; it varied from 0% to 20.7% during this series of the tests. Normalized bond strengths were presented as a function of percentage mass loss due to corrosion. Chung *et al.* [31] tested slabs of 500 mm × 90 mm in cross-section and 1000 mm in length. The slabs were reinforced with five 10 mm steel bars with 100 mm spacing, and the cover was 20 mm. The slabs were tested by four-point loadings, and the concrete was subjected to bending failure. The degree of corrosion varied from 0% for the control specimens to 15% for the other specimens. The bond strength was presented as a function of the percentage corrosion. The accelerated corrosion process was used for all the above flexural specimens, which were investigated by the previous researchers. However, researchers have recognized that the effect of natural behaviour differs from that of artificially corroded specimens (i.e. natural corrosion may affect structural behaviour in a different way from that of artificially corroded members) [9]. To overcome this problem to some extent, Tahershamsi *et al.* [9] carried out an investigation of the bond capacity of naturally corroded reinforcements. Beam specimens were extracted from a 32-year-old bridge and were tested by four-point loadings. Both gravimetric measurements and advanced 3D optical scanning were used to measure the degree of corrosion. The relation between degree of corrosion, splitting crack widths and bond strength was investigated, and the results were compared with accelerated corrosion tests. The comparison reveals that naturally corroded tests provide higher bond strength than the artificially corroded specimens. This study provides a platform for understanding the structural behaviour of existing structures due to the effects of naturally corroded reinforcements.

#### 5.5 Bond Strength Models and Bond Stress-Slip Relationships

Following a review of previous experimental bond strength investigations in Sections 5.3 and 5.4, it has been recognized that differences between the proposed bond strength relations may be due to various factors. These are such as: (1) the characteristic strength of the steel bars; (2) the difference in material properties of concrete due to different mix proportions or production processes (i.e. compaction and curing); (3) uneven salt solution; (4) corrosion process, natural or artificial, etc. However, this section summarizes a widely used mass loss relation to determine the degree of corrosion/corrosion level, a recently proposed realistic empirical bond strength model and bond-slip relationship.

The theoretical mass loss due to corrosion ( $m_c$ ) can be calculated by Faraday's law [1, 7] as shown below:

$$m_t = \frac{t \times I \times M}{z \times F} \tag{1}$$

where  $I$  is the current;  $M$  is the molar mass of iron, which is taken as 55.847 g/mol;  $z$  is the valency of the element, which is taken as two for steel;  $t$  is time; and  $F$  is the Faraday’s constant, which is taken as 96,487 coulombs. The actual mass loss ( $m_a$ ) due to the corrosion can be approximately obtained as [7]:

$$m_a = 0.703 \times m_t - 1.5(\text{gr}) \tag{2}$$

The corrosion level or percentage of actual mass loss ( $C_L$ ) can be calculated by obtaining percentage ratio of the difference between the initial and final weights of the steel as

$$C_L = \left( \frac{m_a}{m_i} \right) \times 100\% \tag{3}$$

where  $m_i$  is the initial mass of the reinforcement bars before corrosion,

The ultimate bond strength ( $\tau_{bu}$ ) of uncorroded specimens is given as a function of concrete cover and strength, as shown below [7]

$$\tau_{bu} = -2.7143 + 0.362 f'_c + 2.3296 \left( \frac{c_{nom}}{D} \right) \text{ (MPa)} \tag{4}$$

where  $c_{nom}/D$  is the nominal cover to bar diameter ratio and  $f'_c$  is the strength of the concrete. Three separate empirical relations have been proposed [7] to predict precisely the ultimate bond strength of corroded members, based on the  $c_{nom}/D$  ratios and corrosion levels.

$$\text{If } \frac{c_{nom}}{D} < 2 \text{ and } \begin{cases} 0 \leq C_L \leq 4 \text{ for } f'_c = 23 \text{ MPa} \\ 0 \leq C_L \leq 0.8 \text{ for } f'_c = 51 \text{ MPa} \end{cases}$$

$$\tau_{bu} = -0.40551 f'_c - 0.25306 \left( \frac{c_{nom}}{D} \right) + 0.97926 C_L \text{ (MPa)} \tag{5}$$

$$\text{If } \frac{c_{nom}}{D} \geq 2 \text{ and } \begin{cases} 0 \leq C_L \leq 1.4 \text{ for } f'_c = 23 \text{ MPa} \\ 0 \leq C_L \leq 0.68 \text{ for } f'_c = 51 \text{ MPa} \end{cases}$$

$$\tau_{bu} = e^{\left( -0.01572 f'_c + 0.22957 \left( \frac{c_{nom}}{D} \right) + 0.13946 C_L + 1.75913 \right)} \text{ (MPa)} \tag{6}$$

If the corrosion levels are different from the limits given in the above relations and if  $1 \leq \frac{c_{nom}}{D} \leq 3.2$  then:

$$\tau_{bu} = e^{\left( -0.01667 f'_c - 1.06499 W_{cr} + 0.20658 \left( \frac{c_{nom}}{D} \right) - 0.12928 C_L + 1.80139 \right)} \text{ (MPa)} \tag{7}$$

where  $W_{cr}$  is the crack width. This research investigation shows the possibility of predicting empirical relations for bond strength as a function of crack width and corrosion levels for different  $c_{nom}/D$  ratios and concrete strengths.

The bond-slip behavior was also investigated experimentally in 2012 [7]. The slip of uncorroded reinforcement bars was decreased by increasing the cover to bar diameter ratio ( $c_{nom}/D$  ratio) and

the compressive strength of the concrete. The slip was found to be less for lower concrete grades at lowest  $c_{nom}/D$  ratio for corroded reinforcement bars. In addition, the slip decreased for higher concrete grades at the same corrosion level, when the  $c_{nom}/D$  ratio was increased. The bond strength and bond-slip behaviour of corroded reinforcements with different concrete classes and  $c_{nom}/D$  ratios may provide a better platform for structural performance evaluation of existing reinforced concrete structures.

## 5.6 Discussion

The previous experimental investigations demonstrate that there are several parameters (as shown in Table 2), which significantly affect the bond strength and bond-slip behaviour of reinforced concrete structures during the corrosion propagation phase.

The previous majority of experimental studies of bond strength degradation were mainly based on pull-out tests with different parameters. During the pull-out test, reinforcing steel is in tension and concrete is compressed and therefore concrete does not crack. However, during the flexural test both concrete and the reinforcement are in tension and hence concrete cracks. In this case, the concrete cracking results in-and-out-stress distribution of bond stress. Therefore, the pull-out test does not generally represent the real behavior of reinforced concrete under bending. Recently few experimental studies have been done under flexural behaviour with beams and one-way slabs (i.e. uniaxial bending nature). Bond strength against biaxial bending or combined action (i.e. load interaction) has not been examined. The bond strength has not been widely studied under other cyclic or impact loading situations. Moreover, most of the laboratory load testing have been carried out after corroding the reinforcement. However, in reality, corrosion starts while structural members withstanding loads. Therefore, it is vital to study the behavior of bond strength in such situations as well.

It has been recognized that the effect of natural behaviour differs from that of artificially corroded specimens (i.e. natural corrosion may affect structural behaviour in a different way

Table 2: Bond behaviour governing parameters

Classification	Parameters
Reinforcement bar	Plain or smooth bars, bar diameter, rib size and spacing, embedded length, chemical composition
Concrete	Strength class, w/c ratio, aggregate type, cement type, additives, admixtures, permeability, porosity, concrete cover, crack size, production process, electrical properties of the raw materials
Stress state of concrete	Compression, tension, bending, combined action, static or dynamic, impact, uniaxial or multiaxial, position of reinforcement bars
Environmental factors	Temperature, humidity level, Cl or CO <sub>2</sub> availability in air
Corrosion process	Artificial or natural, rate of corrosion, percentage of NaCl for curing, percentage of NaCl in concrete mixture
Concrete structure	Size, functionality, loading state, loading history, age

from that of artificially corroded members). A proper correlation has not yet been identified between natural and artificial corrosion.

Gravimetric measurements have been widely used for determining the degree of corrosion of test specimens. Usage of this technique is difficult for existing structures. The corrosion propagation phase can be subdivided into stages with different corrosion levels, which can be measured with non-destructive measurements such as corrosion potential mapping, 3D optical scanning, etc. The application of these techniques is not widely reported in bond-strength degradation studies.

## 6 CONCLUSIONS

This paper has presented the mechanisms of corrosion propagation and the effects of corrosion on bond degradation of reinforced concrete structures. Previous experimental research into degradation of the bond between reinforcement and concrete has been reviewed, and a few recently proposed, widely applicable bond strength models and bond-slip relationships have been summarized. The parameters, which significantly affect the bond strength and bond-slip behaviour of reinforced concrete structures, have been listed. It is important to perform more experimental parametric studies to verify the simplified tests, which were used to provide empirical bond strength models for different loading situations. A proper correlation between natural and artificial corrosion should be proposed in future. More studies on role of confinement in bond degradation are recommended. It is very important that conclusions are drawn by repeating experimental investigations, which represent real behaviour, as concrete is a heterogeneous construction material. It is a matter of high importance and necessity to establish accurate propagation models, which can easily be applied by practising engineers.

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