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The Bond Behaviour between Concrete and Corroded Reinforcement: State of the Art

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ABSTRACT

The corrosion of reinforcing steel bar embedded in concrete leads to the bond deterioration. This literature review summarises the influence of corrosion on bond strength and bond-slip behaviour. The influence of corrosion on bond strength has been intensively investigated and the main influencing parameters, including the corrosion conditions of steel bars, the geometry and the corrosive environment, have been well recognized. Based on the previous investigations and the author's experimental work, an improved bond strength model, which can account for various parameters and is proved to agree well with experimental results in the literature, is developed. The literature survey also indicates that the surface crack width is appropriate to be the governing parameter for the evaluation of bond strength. For the bond-slip behaviour of corroded RC, the published experimental results indicate that the bond-slip mechanism is similar to that of non-corroded RC, however, the researchers have different views regarding the influence of corrosion on some of the parameters that shape the bond-slip curves. A comprehensive bond-slip model for corroded RC has been developed by the authors considering various parameters, such as the confinements and the corrosion conditions of stirrups. This paper also reviews the bond behaviour of corroded RC under repeated loading. The research by the authors suggests that the repeated loading shows no significant influence on the bond strength of corroded RC, and the bond-slip behaviour is characterized by the progressive increase of residual slip, which is the same to that of non-corroded RC. To better understand the bond behaviour of corroded RC, the further studies are needed with respect to the influence of environment on the bond deterioration, the correlations between the bond behaviour and the surface crack width, and the bond-slip behaviour of corroded RC under repeated loading with various loading scenarios.

Keywords: Bond strength; steel bar; corrosion; bond stress-slip; repeated loading

1.0 INTRODUCTION

The bond behaviour of RC structures is the complex interaction between concrete and reinforcing steel bar, which enables the force transfer and the compatibility of deformation between reinforcing steel bar and the surrounding concrete. It is made up of three components: chemical adhesion, friction and mechanical interaction. For deformed steel bars, bond depends primarily on the mechanical interaction (Tepfers, 1979) (see Fig. 1). The bond behaviour has a prominent influence on the crack width, crack spacing, stress distribution and hysteretic behaviour under severe seismic excitations of RC members. To get satisfactory performance of RC structures at serviceability limit state or ultimate limit state, adequate bond between concrete and steel bar should be guaranteed.

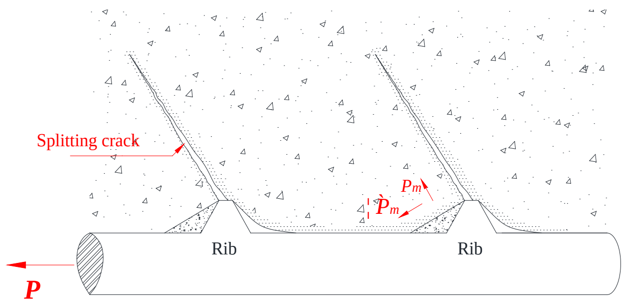


Fig. 1. Mechanical interaction between concrete and deformed steel bar

However, during the long-term service, RC structures exposed to aggressive environmental conditions are usually threatened by corrosion, which is generally induced by chloride contamination or carbonation. The corrosion products have higher volume than the original steel and can cause damage of concrete cover. In the initial stage of corrosion, the bond property is improved because of the increased roughness at the steel bar surface. Afterwards, the further corrosion of reinforcing steel bar leads to the concrete cover cracking and the bond property begins to deteriorate due to the substantial reduction of the rib area, the loss of the confinement provided by the concrete cover, and the existence of the lubricant corrosion products at the steel-concrete interface (Lin and Zhao, 2016). The influence of corrosion on bond strength is schematically shown in Fig. 2.

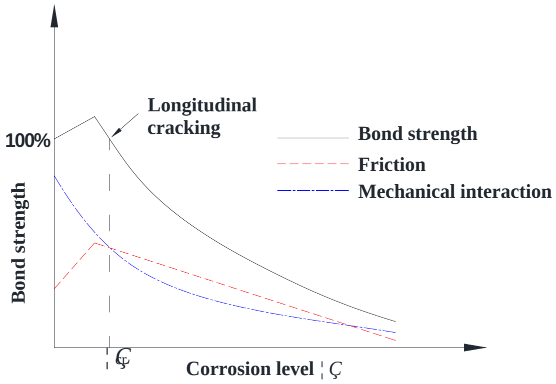


Fig. 2. Schematic illustration of the influence of corrosion on bond strength (Kivell, 2012)

The bond deterioration due to corrosion can significantly affect the mechanical properties or serviceability of RC structures, and its negative influence on structural behaviour can be as remarkable as the degradation of material properties. The experimental and numerical investigations by Yuan *et al*. (2001) on corroded RC beams suggest that the reduction of the loading capacity is mainly caused by the degradation of the material properties of reinforcing steel bar at the first stage, however, if the steel bar is seriously corroded, the bond stress developed at the steel-concrete interface is not enough to ensure the maximum performance of the reinforcing steel bar and the loading capacity is primarily determined by the bond deterioration. Test results by Chung *et al* (2008) on flexural slabs with corroded reinforcement confirmed that bond deterioration instead of loss of cross-sectional area of reinforcing steel bars is the major contributor to the reduction of moment capacity. The above conclusion that the considerable reduction in flexural strength is due to the significant reduction in bond strength is also demonstrated by the theoretical model developed by Nepal and Chen (2015; 2013) for evaluating the structural condition of corrosion damaged RC structures. Similarly, the mechanical properties of RC columns are also affected by bond deterioration. The theoretical investigation by Chen *et al*. (2008) revealed that the deterioration of bond behaviour can result in the change of the failure mode as well as the reduction in the ultimate capacity. The existing studies all prove that the mechanical behaviour of RC members or structures are closely related to the bond conditions at the steel-concrete interface. To better estimate the load-carrying capacity of corroded RC structures, it is therefore essential to fully understand how corrosion affects the bond behaviour. Improving the understanding of the effects of corrosion on the bond behaviour is also of great significance for predicting the remaining service life of corroded RC structures and for decision-making in terms of the repair, strengthening, and demolition of corrosion damaged structures.

Until now, many studies have been undertaken by various researchers to investigate the bond behaviour of corroded RC. This paper presents a comprehensive state-of-the-art review on the experimental results concerning the bond behaviour of corroded reinforcement.

2.0 BOND BEHAVIOR OF CORRODED RC UNDER MONOTONIC LOADING

2.1 Bond Strength

<u>Influence of the Corrosion of Longitudinal Steel Bar</u>
For the past several decades, the deterioration of bond strength has become a major concern for researchers worldwide. Extensive investigations have been conducted in this respect, among which experimental studies based on accelerated corrosion method are in the majority.

Al-Sulaimani *et al*. (1990) are among the first ones who conducted investigations on the bond deterioration due to the corrosion of longitudinal steel bar. Their tests results on beam specimens and central-pullout specimens all showed that the bond strength increased initially with the corrosion level and afterwards decreased consistently with the further increase in corrosion. This conclusion is further verified by many other studies carried out by Almusallam *et al*. (1996), Mangat *et al*. (1999), Stanish (1999), Zhao *et al*. (2013), Yuan *et al*. (1999). An overview of the literature reveals that the vast majority of bond tests regarding bond deterioration of corroded reinforcement in the early times are based on specimens without stirrups, while for most cases the stirrups are present in RC structures. Indeed, the bond deterioration of specimens confined by stirrups shows a considerable difference with that of specimens without stirrups. Fang *et al*. (2004) and Fischer *et al*. (2010) found that the influence of corrosion on bond strength was very limited when the stirrups were present. Similarly, both Rodriguez *et al*. (1994) and Hanjari *et al*. (2011) found that specimens confined by stirrups showed higher bond strength than specimens without stirrups based on test results of beam-end specimens. The test results by Berra *et al*. (1997) and Tondolo (2015) even showed that corrosion had no negative influence on bond strength at all. Instead, the bond strength of specimens with stirrups was increased due to corrosion. The noticeable effect of stirrups on preventing bond deterioration was also documented by some other researchers including Al-Sulaimani *et al*. (1990), Castel *et al*. (2016), Cabrea (1992), and Xia (2010).

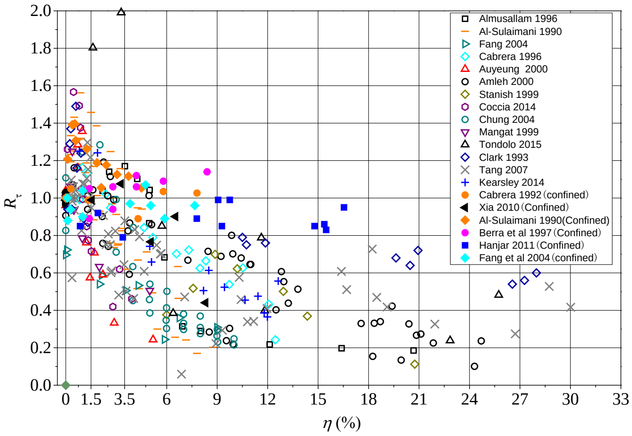


Fig. 3. Summary of tested bond strength in the literature

In Fig. 3, published test results based on specimens with or without stirrups are depicted to illustrate the influence of corrosion on bond strength (Almusallam *et al*., 1996; Amleh, 2000; Auyeung *et al*., 2000; Berra *et al*., 1997; Cabrera, 1996; Cabrera and Ghoddoussi, 1992; Chung *et al*., 2004; Clark and Saifullah, 1993; Coccia *et al*., 2014; Fang *et al*., 2004; Hanjari *et al*., 2011; Kearsley and Joyce, 2014; M and Clark, 1994; Mangat and Elgarf, 1999; Stanish *et al*., 1999; Tang and Eng, 2007; Tondolo, 2015; Xia, 2010). The solid points in Fig. 3 correspond to specimens confined by stirrups, whereas other points refer to specimens without stirrups. As expected, the test data particularly the data of specimens without stirrups, exhibit a considerable scatter due to the large variations in materials, specimen geometries, corrosion conditions, test setup and loading procedures adopted by researchers. For specimens without stirrups, the relative bond strength, i.e. the bond strength of the corroded reinforcement divided by the reference bond strength, increases in the initial stage of corrosion and peaks at the corrosion level around 0.5%-1.5%. In some cases, the relative bond strength can reach as much as 160%. After the peak, a rapid decline of the bond strength with corrosion can be observed. Compared with specimens without stirrups, specimens with stirrups show higher bond strength and the influence of corrosion is not as prominent.

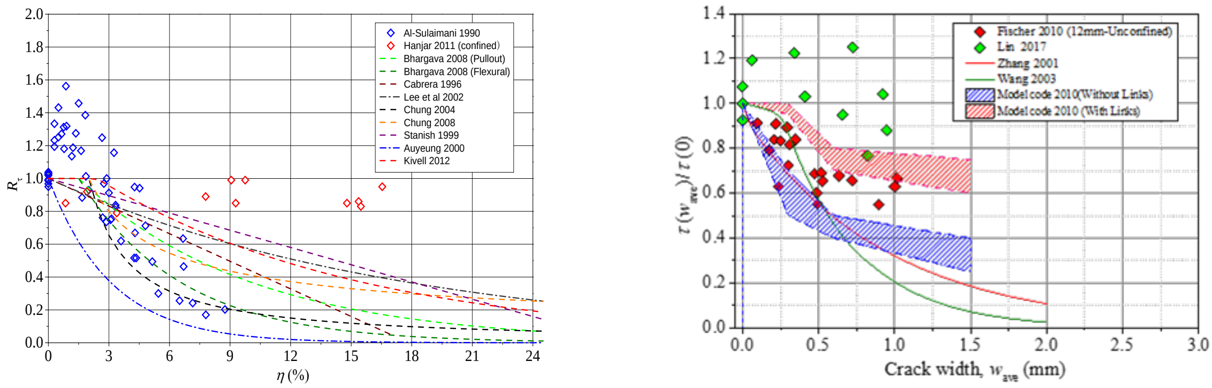
Extensive mathematical models for estimating the bond strength of corroded reinforcement have been developed by previous researchers, as shown in Table 1. These models are usually derived from specific test results and do not take account of the influence of various parameters, such as confinements, corrosion rate, location of reinforcement steel bar and loading method, making it difficult for them to be widely accepted. In Fig. 4(a) some empirical models in the literature are selected for comparisons with test results by Al-Sulaimani *et al*. (1990) and Hanjari *et al*. (2011). The pullout tests by Al-Sulaimani *et al*. (1990) were conducted on 150 mm cubic concrete specimens with 10, 14, and 20 mm-diameter deformed steel bars embedded centrally, while the pullout tests by Hanjari *et al*. (2011) were carried out on beam-end specimens confined by stirrups. As can be observed, the predicted curves show a great variation. For the test results by Al-Sulaimani *et al*. (1990), the model by Chung *et al*. (2004) and Bhargava *et al*. (2008) can provide relatively good estimations; however, for the test results by Hanjari *et al*. (2011), none of the models can give reasonable predictions, the predicted bond strength by the models is generally below the tested values. In Fig. 4(b), some empirical models with the surface crack width as the variable are compared with the test results by Fischer *et al*. (2010) and Lin *et al*. (2017a). The pullout tests performed by Fischer *et al*. (2010) were based on beam-end specimens which had a dimension of 200mm×200mm×300mm. Eccentric pull-out specimens confined by stirrups were used by Lin *et al*. (2017a). Like Fig. 4(a), for specimens without stirrups the predictions agree relatively well with tested bond strength, but for specimens confined by stirrups large discrepancies can be observed.

Influence of Corrosion Rate

Accelerated corrosion techniques have been widely used in laboratories for the accelerated corrosion of RC elements. Compared with natural corrosion, the durations of the corrosion period can be substantially reduced from the order of years to the order of weeks or months. In addition to saving in time and cost, the desired corrosion degree can also be easily controlled. Therefore, accelerated corrosion techniques have been widely used for bond tests. However, the difference with respect to the deterioration of bond strength between natural corrosion and accelerated corrosion should be considered. In field environment, the measured corrosion current density generally varies from 0.1μA/cm^2 to 1μA/cm^2(Lin and Zhao, 2016), while in the laboratories the corrosion current densities adopted by researchers can be 100 or even more times greater. Compared with natural corrosion, the fast corrosion rate in accelerated corrosion tests can result in different level of oxidation and accordingly different components of corrosion products.

Table 1 Mathematical models for bond strength of corroded reinforcement

Literature	Normalised equation	Type
Bhargava *et al*., 2008	$\tau_u(\eta)=\tau_u(0)e^{-19.8(\eta-1.5\%)}\le 1.0$	Flexural test
	$\tau_u(\eta)=\tau_u(0)e^{-11.7(\eta-1.5\%)}\le 1.0$	Pullout test
Cabrera, 1996	$\tau_u(\eta)=\tau_u(0)(1-5.6\eta)$	Pullout test
Lee *et al*., 2002	$\tau_u(\eta)=\tau_u(0)e^{-5.61\eta}$	Pullout test
Chung *et al*., 2004	$\tau_u(\eta)=\tau_u(0)0.0159\eta^{-1.06}\le 1.0$	Flexural test
Chung *et al*., 2008	$\tau_u(\eta)=0.116\tau_u(0)\eta^{-0.55}\le 1.0$	Pullout test
Stanish *et al*., 1999	$\tau_u(\eta)=\tau_u(0)(1-3.5\eta)$	Flexural test
Auyeung *et al*., 2000	$\tau_u(\eta)=\tau_u(0)e^{-32.51\eta}$	Pullout test
Kivell, 2012	$\tau_u(\eta)=\tau_u(0)e^{-7.6(\eta-2.4\%)}\le 1.0$	Pullout test
Yuan *et al*., 1999	$\tau_u(\eta)=\tau_u(0)(1-(10.544-1.586(c/d))\eta)$	Beam-end test
Pan *et al*., 2000	$\tau_u(\eta)=\begin{cases}\tau_u(0) & (\eta\le 0.6\%)\\ \tau_u(0)-a_\tau(\eta-0.006) & (\eta>0.6\%)\end{cases}$	Pushout test
Saifullah and Clark, 1994	$\tau_u(\eta)=\tau_u(0)(A_1+A_2\eta)$	Beam-end test
Wang *et al*., 1996)	$\tau_u(w)=\tau_u(0)e^{-2.1w}\left(0.13+0.5\frac{c}{d}\right)$	Pushout test
Zhang *et al*., 2003	$\tau_u(w)=0.9495\tau_u(0)e^{-1.093w}$	Beam-end test
Castel *et al*., 2016	$\tau_u(\eta)=\begin{cases}\tau_u(0) & (\Delta A_s<\Delta A_{s0})\\ \left(1-\frac{2}{\theta}\varphi_{st}\log\left(1+0.25(\Delta A_s-\Delta A_{s0})\right)\right)\tau_u(0) & (\Delta A_s\ge\Delta A_{s0})\end{cases}$	-
Zhao and Jin, 2002	$\tau_u(\eta)=\begin{cases}(1+7.0x_p)\tau_u(0) & (x_p\le 0.05)\\ (1.46-2.3x_p)\tau_u(0) & (x_p>0.05)\end{cases}$	Pullout test

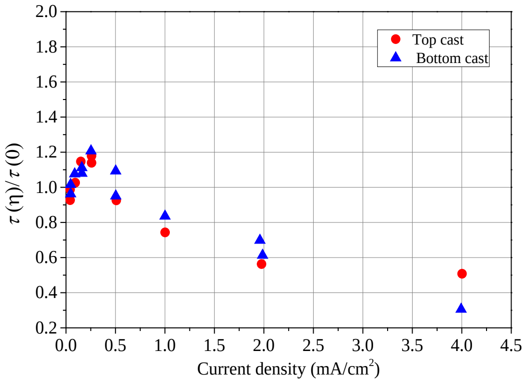


(a) Based on mass loss

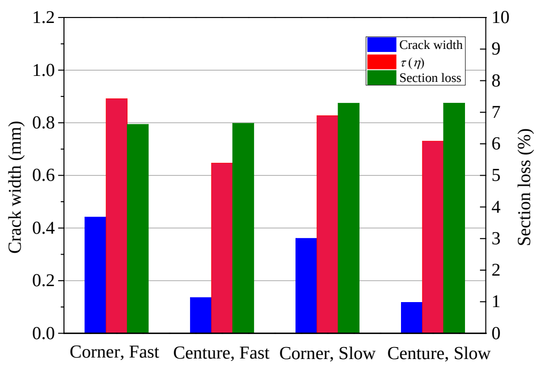
(b) Based on surface crack width

Fig. 4. Comparisons of model predictions with test results in the literature

Moreover, fast corrosion also means less time for corrosion products to spread through the concrete pores or the cracks. The different corrosion process will consequently lead to different deterioration of bond strength. Therefore, the suitability of the technique to model the bond deterioration under natural corrosion has been questioned.



(a) Saifullah and Clark (1994)



(b) Ayop and Cairns (2014)

Fig. 5. Influence of corrosion current density on the deterioration of bond strength

Saifullah and Clark (1994) found that for corrosion current density ranging between 40 μA/cm^2-4000 μA/cm^2, the bond strength increased with the current density (i.e. corrosion rate) up to about 150-250 μA/cm^2 and then decreased with further increases in current density (see Fig. 5a). The adverse effect of large corrosion rate on bond strength was also confirmed by Ayop and Cairns (2014), who adopted two different current densities 80 μA/cm^2 and 400 μA/cm^2 which identified as 'slow' and 'fast' current for accelerated corrosion process. The results indicated that the 'fast' current tended to have wider crack than the 'slow' current. Also, 'fast' specimens had lower residual bond strength compared with 'slow' current, as shown in Fig. 5(b). As the natural corrosion is characterized by very small corrosion rate, some researchers have further compared the laboratory test results with the test results from real concrete structures. In the review by Sæther (2007), it was concluded that the current laboratory investigations predict lower load-carrying capacity of beams and higher reduction of the bond strength compared with available field results from concrete bridges damaged by natural corrosion. Yuan *et al* (2007) found that the reinforced concrete beams subjected to the galvanostatic method showed more severe bond deterioration than those subjected to artificial climate environment which is an alternative method of inducing corrosion developed to model natural corrosive environment. Through naturally corroded RC beams taken from a bridge in Sweden and had been exposed to natural corrosion for 32 years, Tahershamsi *et al*. (2015; 2016) found that the corrosion level and reduction in bond capacity related to crack width were both lower in the naturally corroded specimens than the artificially corroded tests in the literature, and the provisions given in fib Model Code 2010 are on the safe side. Horrigmoe *et al*. (2007) conducted pullout tests on original concrete specimens from a bridge in Norway which was demolished after 29 years of service. The results indicated that maximum bond strength was unaffected by corrosion up to corrosion levels of 10% weight loss while the results obtained from laboratory experiments with different current densities showed similar trends as reported by several authors from different investigations.

The above investigations all suggest that the bond deterioration induced by accelerated corrosion techniques might not be the same as that caused by natural corrosion depending on the corrosion rate adopted. However, relevant studies with respect to the bond behavior of naturally corroded specimens are comparatively few. Therefore, it is of great significance to carry out more bond tests on naturally corroded RC members to extend the knowledge concerning the structural behavior of naturally corroded RC structures.

Models for Bond Strength Developed by the Authors

After a summary of current studies, the authors found that the confinements provided by the concrete cover and the stirrups, and the corrosion current density have non-negligible influence on the bond strength of corroded RC and should be reflected in the mathematical models (Lin and Zhao, 2016). Based on own test results and database in the literature, a comprehensive model for bond strength was previously proposed:

$$\tau_u(\eta) = \tau_u(0) R_\tau \tag{1}$$

where $\tau_u(0)$ and $\tau_u(\eta)$ are the bond strengths of non-corroded and corroded specimens, respectively, R_τ is the relative bond strength:

$$R_\tau = \begin{cases} 1 & \eta \le 1.5\% \\ e^{-\delta(\eta - 1.5\%)} & \eta > 1.5\% \end{cases} \tag{2}$$

in which δ is the degradation coefficient:

$$\delta=\begin{cases}\dfrac{k_1+k_2(c/d)}{k_4\xi_{\mathbf{st}}+1} & i_{\mathrm{corr}}\le 200\mu\mathrm{A/cm^2}\\ \dfrac{k_1+k_2(c/d)}{k_4\xi_{\mathbf{st}}+1}\left(k_3\ln(\dfrac{i_{\mathrm{corr}}}{200})+1.0\right) & i_{\mathrm{corr}}>200\mu\mathrm{A/cm^2}\end{cases} \quad (3)$$

where k_1, k_2, k_3 and k_4 are coefficients; c/d is the ratio of concrete cover to diameter; i_{corr} is corrosion rate.

It is worth mentioning that a reasonable model for bond strength of corroded reinforcement should also take account of the influence of the corrosion of stirrups. Field investigations and tests on RC members reveal that the stirrups are more seriously corroded than the longitudinal steel bars, especially at the intersection point, and in some cases complete section loss of stirrups is observed. The serious corrosion of stirrups can accelerate the bond deterioration caused by the corrosion of longitudinal steel bars. Unfortunately, research in this respect is very scarce. The authors previously carried out a series of pull-out tests based on eccentric pull-out specimens with corroded stirrups and developed a model to take account of the negative influence of the corrosion of stirrups on the bond strength (Lin *et al*., 2016). The reduction of bond strength due to the corrosion of stirrups can be reflected by the scale factor:

$$D_{\mathrm{st}}=1-0.68\eta_{\mathrm{stave}} \quad (4)$$

where η_{stave} is the average mass loss percentage of stirrups. For specimens with corroded longitudinal reinforcement and stirrups, the bond strength can be evaluated through the following equation:

$$\tau_{\mathrm{u}}(\eta,\eta_{\mathrm{stave}})=\tau_{\mathrm{u}}(0)D_{\mathrm{st}}R_{\tau} \quad (5)$$

An overview of the current studies regarding the deterioration of bond strength indicates that the main focus of researchers is the evaluation of bond strength through the mass loss, the section loss or the attack penetration depth of the corroded reinforcement. Although many models have been developed, they are not suitable for practical use because the governing parameters involved, such as the mass loss and the section loss, are very difficult to be measured in existing structures that are under service conditions. To solve this problem, researchers such as Fischer *et al*. (2013), and Tang *et al*. (2011) tried to directly correlate the bond deterioration to the surface crack width. A rough correlation between bond strength reduction and surface crack width is also suggested by Model Code 2010. Based on a large amount of pullout tests, an empirical model for estimating the bond strength from the measured surface crack width of longitudinal cracks and lateral cracks was previously formulated by the authors (Lin *et al*., 2017a), allowing for the consideration of the pronounced limiting effect of stirrups on bond degradation. The model is expressed as follows:

$$\tau_{\mathrm{u}}\left(w_{\mathrm{ave}},w_{\mathrm{stave}}\right)=\tau_{\mathrm{u}}\left(0\right)D_{\mathrm{st}}\left(1.0-0.9e^{-20\rho_{\mathrm{st}}}\left(1.0-e^{-1.73w_{\mathrm{ave}}e^{-56.6\rho_{st}}}\right)\right) \quad (6)$$

Where $\tau_u(w_{ave}, w_{stave})$ is the bond strength of corroded specimens; w_{ave} is the average longitudinal crack width; ρ_{st} is the stirrup index; D_{st} has the same meaning with Eq. (4), but it is determined by the average lateral crack width w_{stave} instead of η_{stave}:

$$D_{\mathrm{st}}=1-0.68\left(\frac{w_{\mathrm{stave}}d_{\mathrm{st}}}{-0.29c_{\mathrm{st}}+1.58d_{\mathrm{st}}}+1-\left(1-\frac{\theta}{d_{\mathrm{st}}}(7.53+9.32\frac{c_{\mathrm{st}}}{d_{\mathrm{st}}})10^{-3}\right)^2\right) \quad (7)$$

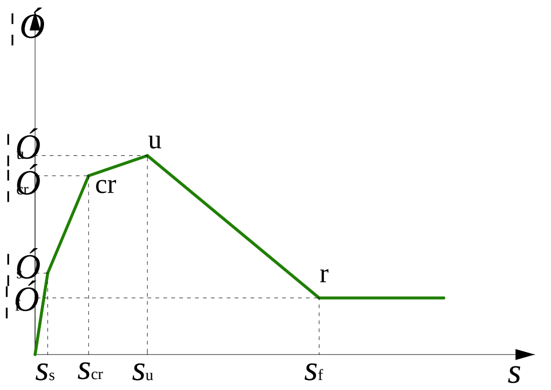
where c_{st} is the concrete cover of stirrups; d_{st} is the diameter of stirrups; α is the pit concentration factor.

Comparisons of Eq. (5) and Eq. (7) with a large amount of test results in the literature were carried out by the authors to validate the accuracy of the proposed models. The comparison with various experimental results confirm that both models can provide realistic predictions (see the literature Lin and Zhao, 2016; Lin *et al*., 2016; Lin *et al*., 2017a).

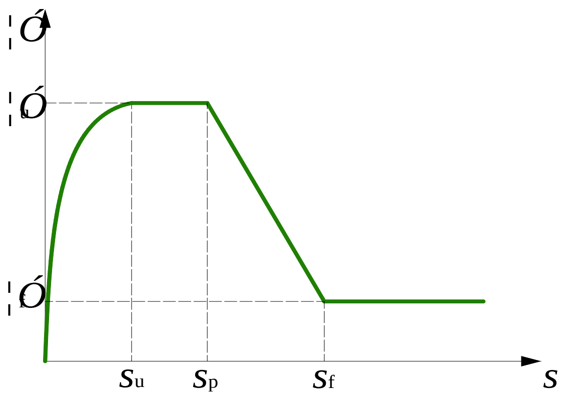
2.2 Bond-Slip Relationship

The structural performances are highly dependent on the bond-slip relationship at the concrete-steel interface. With a realistic local bond-slip relationship model, which can reflect the overall bond characteristics at the interface, it is possible to accurately reproduce the nonlinear behaviour of RC elements or structures through numerical or analytical methods. Numerous empirical, semi-empirical or analytical bond-slip models for non-corroded reinforced concrete have been proposed, however, research on the bond-slip model of corroded reinforcement is fewer in number and reliable mathematical model is still beyond reach.

Based on experimental observations, both Yuan *et al*. (1999) and Zhang *et al*. (2001) concluded that the bond-slip mechanism of corroded reinforcement was hardly affected by corrosion and the shape of the bond-slip curves can also be divided into five stages: the micro-slip stage, the slip stage, the splitting stage, the descending stage and the frictional stage. With mass loss or surface crack width as the variable and each stage described by straight line, five-stage bond-slip model for corroded reinforcement was developed by Yuan *et al*. (1999) (see Fig. 6a) and Zhang *et al*. (2001), respectively. By accounting for the effects of corrosion on some critical parameters, such as the peak bond stress and the frictional bond stress, a bond-slip model for corroded reinforcement, which was in the same form as that proposed by Eligehause *et al*. (1982), was developed by Kivell (2012) (see Fig. 6b). In the latest research work by Jiang (2017), the bond deterioration at the concrete-steel interface was ascribed to material weakening and confinement degradation, and a mathematically continuous bond-slip model was developed through modifying a unified bond-slip model for non-corroded specimens. Different with other researchers, Lundgren *et al*. (2012) reformulated the model given in the CEB-FIP Model Code 1990 into the format of theory of plasticity and modelled the effect of corrosion by shifting the bond-slip curve of uncorroded reinforcement along the slip axis, and finally developed a plasticity model for bond-slip response of corroded reinforcement.



(a) Yuan *et al*. (1999)



(b) Kivell (2012)

Fig. 6. Bond-slip model for corroded reinforcement

Due to the limited test results in the literature, the effectiveness of the aforementioned models has not been verified. Indeed, inconsistent conclusions can be found among the existing studies regarding the qualitative effect of corrosion on the various parameters in the bond-slip model. For instance, different trends regarding the influence of corrosion on the rupture slip which can significantly influence the bond stiffness are reported by various studies. In the bond-slip model by Kivell (2012) the rupture slip corresponding to the peak bond stress is not affected by corrosion, while in the model by Yuan *et al*. (1999) the rupture slip decreases rapidly with corrosion. Conflict test results were also derived by other researchers. In accordance with Yuan *et al* (1999), Auyeung *et al*. (2000), Almusallam *et al*. (1996), Christos *et al*. (2011) also observed the reduction of rupture slip due to corrosion, Lundgren *et al*. (2012) further concluded that the effect of corrosion on the rupture slip could be assumed to be similar to that produced by bar loading. However, Mangat and Elgarf (1999), Al-sulaimani *et al*. (1990) had opposite observations.

To clarify some of the existing problems with respect to bond-slip relationship of corroded reinforcement, the authors previously performed a series of pullout tests on confined eccentric specimens and the test results revealed that the rupture slip reduced drastically with corrosion (Lin *et al*., 2017b). The authors attributed this phenomenon to the loss of confinement resistance caused by concrete cover cracking. Moreover, it was confirmed that the ratio of frictional bond stress to peak bond stress was barely affected by corrosion. On the basis of previous research works, a bond-slip model for corroded reinforcement was proposed by the authors:

$$\tau(\eta,s)=\begin{cases}\tau_{u}(\eta)\left(\dfrac{s}{s_{u}}\right)^{\alpha} & s\le s_{u}\\ (1-k_{f})\tau_{u}(\eta)\left(\dfrac{s}{s_{u}}\right)^{\beta}+\dfrac{(1-\psi)k_{f}\tau_{u}(\eta)}{s_{u}-s_{f}}(s-s_{u})+k_{f}\tau_{u}(\eta) & s_{u}<s<s_{f}\\ (1-k_{f})\tau_{u}(\eta)\left(\dfrac{s}{s_{u}}\right)^{\beta}+\psi k_{f}\tau_{u}(\eta) & s_{f}\le s\end{cases}\tag{8}$$

where α is 0.24; s_u is the rupture slip related with corrosion and confinements; s_f is the clear distance between the ribs; β is a parameter determined by concrete cover and steel bar diameter; k_f and ψ are parameters that shape the descending branch (Lin *et al*., 2016).

3.0 BOND BEHAVIOR OF CORRODED RC UNDER REPEATED LOADING

Previously, most of the studies focused on the bond deterioration under monotonic loading, and the bond deterioration under repeated loading has not been given sufficient attention. In fact, a large number of RC structures, e.g. industrial constructions, offshore structures or bridges, are subjected to repeated loading when they are in service. Existing studies indicate that repeated loading can lead to a progressive deterioration of bond and may cause premature failure. Verna and Stelson (1962) investigated various failure models of RC beams under repeated loading. They concluded that the bond failure was the most susceptible to fatigue in flexural members. Test results by Edwards and Yannopoulos (1978) revealed that the bond-slip curves under repeated loading were characterized by residual slip at zero load and hysteresis loops formed by the loading and unloading paths. Moreover, the effectiveness of bond depends mainly upon the given stress level and the magnitude of the previous peak stress, and to a lesser extent upon the number of cycles. Similar phenomenon was also documented by other researchers. Rehm and Eligehausen (1979), and Oh and Kim (2007) further pointed out that if no fatigue bond failure occurred, the repeated loading showed no significant influence on bond strength and the slip at bond failure. As a summary of the current studies, the dominant effect of repeated loading is the progressive increase of slip, as shown in Fig. 7. Due to the slip growth, repeated loading leads to the increase of crack width and deflection of flexural members, which under aggressive environment conditions strongly affect durability of RC structures. Therefore, great care should be taken for RC structures subjected to repeated loading.

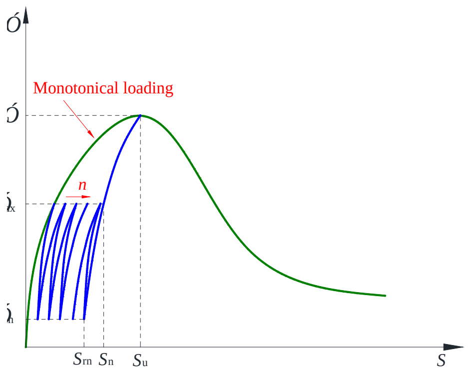


Fig. 7. Slip increase due to repeated loading

In spite of various studies on the effect of corrosion or repeated loading on the bond behaviour, to the authors' best knowledge, investigations regarding the combined effects of corrosion and repeated loading on the bond behaviour is rarely seen in the literature, only Al-Hammoud *et al*. (2010), Rteil *et al*. (2011) and Soudki *et al*. (2007) have carried out investigations in relation to the influence of corrosion on the fatigue of bond. Through reinforced concrete anchorage-beam specimens subjected to repeated loading, it was found that corrosion could result in the decrease of fatigue bond strength, whereas the use of CFRP sheets for beam repairs could increase the fatigue bond strength.

The authors have previously conducted a series of pull-out tests to investigate the bond deterioration due to repeated loading and corrosion (2017b). The test results revealed that the repeated loading exhibited no significant influence on the bond strength or the slip at peak bond stress, but could result in progressive increase of residual slip regardless of whether the reinforcement was corroded or not. Moreover, the reduction of bond strength due to corrosion could lead to an increase of applied stress level, which in turn resulted in the substantial decrease of the fatigue life of bond. Based on the research work by other researchers, the authors developed empirical equations for the residual slip (see Fig. 7), which is available for both corroded or non-corroded reinforcement, they are as follows:

$$s_n = s_u\left(F_{n1}\frac{\tau_{max}}{\tau_u} + F_{n2}\right)n^{\left(t_1\frac{\tau_{max}}{\tau_u}+t_2\right)} \tag{9}$$

$$s_{rn} = s_u\left(F_{rn1}\frac{\tau_{max}}{\tau_u} + F_{rn2}\right)n^{\left(t_1\frac{\tau_{max}}{\tau_u}+t_2\right)} \tag{10}$$

where F_{n1}, F_{n2}, F_{rn1}, F_{rn2}, t_1 and t_2 are empirical parameters. According to Eq. (9) and Eq. (10), the authors further established a model for bond-slip relationship of non-corroded and corroded specimens after repeated loading, as shown below:

$$\tau = \begin{cases} 0 & s \le s_{r(n-1)} \\ \tau_u\left(\dfrac{s - s_{r(n-1)}}{s_u - s_{r(n-1)}}\right)^{\alpha_n} & s_{r(n-1)} < s \le s_u \\ (1-k_f)\tau_u\left(\dfrac{s}{s_u}\right)^{\beta} + \dfrac{(1-\psi)k_f\tau_u}{s_u - s_f}(s - s_u) + k_f\tau_u & s_u < s < s_f \\ (1-k_f)\tau_u\left(\dfrac{s}{s_u}\right)^{\beta} + \psi k_f\tau_u & s_f \le s \end{cases} \tag{11}$$

where τ_n is the bond stress after n loading cycles, $s_{r(n-1)}$ is the residual slip after n-1 loading cycles, and the exponent α_n varies between 0 and 1.

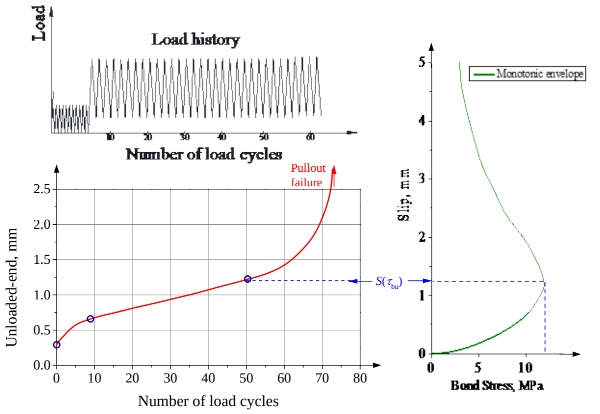


Fig. 8. Determination of bond fatigue failure (Balazs, 1992)

The previous research by Balazs *et al* (1992) concluded that if the slip reached s_u, a pullout-type bond failure might occur without applying the monotonic ultimate bond stress, as shown in Fig. 8. It was therefore suggested that the slip s_u at peak bond stress could be used as a safe fatigue failure criterion. Then the number of loading cycles at bond fatigue failure can be obtained based on Eq. (9):

$$n_f = \left(F_{n1}\frac{\tau_{max}}{\tau_u} + F_{n2}\right)^{\frac{-1}{t_1\frac{\tau_{max}}{\tau_u}+t_2}} \tag{12}$$

In general, current studies on the bond behaviour of corroded reinforcement subjected to repeated loading are far from enough. There are still gaps in the understanding of the influence of various parameters, such as the bond length, the confinements, the loading scenarios and the surface crack width, on the fatigue of bond. More tests are needed to develop comprehensive models, including the bond-slip models, the fatigue life models, that are essential to assess the performance of RC structures under repeated service load as well as to predict the residual strength of these structures.

4.0 CONCLUSIONS AND OUTLOOK

In the past several decades, a great deal of research effort has been devoted to the understanding of the deterioration of bond behavior due to reinforcement corrosion. As a result, numerous experimental investigations have been conducted by researchers worldwide. This paper has presented a comprehensive review of the existing studies regarding the bond deterioration of specimens subjected to monotonic or repeated loading, where the influence parameters have been discussed and the empirical models for bond strength or bond-slip relationship have been summarized. Based on this study, the following conclusions can be drawn:

(1) The deterioration of bond strength is closely related to the confinements, the corrosion conditions of stirrups and the corrosion rate. However, none of the current models for bond strength can well reflect the influence of the parameters, except the one proposed by the authors. Further studies are still needed with respect to the deterioration of bond strength under different corrosion current densities or natural corrosion.

(2) Although several empirical models that bridge the surface crack width with bond strength of corroded reinforcement have been developed by researchers, more bond tests are still needed to further improve and validate the effectiveness of these models.

(3) Researchers have contradictory findings on the bond-slip relationship of corroded reinforcement. More bond tests are required to further explore the influence of corrosion on bond-slip mechanism, bond stiffness, rupture slip and frictional bond stress.

(4) Repeated loading can worsen the bond deterioration induced by corrosion, which is characterized by the progressive formation of residual slip. Models for bond-slip relationship and bond fatigue life have been developed by the authors, but these models should be further improved to consider the influence of more factors such as the confinements, the bond length and the loading scenarios.

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