What do we know about concrete, steel, and bond-slip relation for corroded bars?

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Abstract

Reinforcement corrosion influences the deformation and load capacity of steel rebars. Further, it generates splitting stresses that weaken the concrete and strongly affect the bond between reinforcement and concrete. Here, a recently published engineering model to determine the deformation capacity of rebars with pitting corrosion is described. Further, the effect of corrosion on bond is described in a systematic way, with an overview of the effect for various cases depending on reinforcement type, existence of transverse reinforcement, and confinement due to concrete and boundaries. Finally, an engineering model to determine bond-slip relationships for ribbed bars is presented.

1 Introduction

Corrosion of reinforcement affects the structure in two ways: volume expansion that may crack and spall the concrete cover and affect the bond between reinforcement and concrete, and area reduction and ductility change of the reinforcement bars. Both effects reduce the safety of the structure; therefore, they are important to understand and control. Further, engineering methods to estimate capacity and safety for existing corrosion-damaged structures are of major societal value. This is the focus area of this paper.

In reinforced concrete elements, reinforcing steel is the main component carrying tensile stress. Thus, the mechanical properties of corroded rebars is essential for reliable assessment of corroded structures. It has been widely reported that, compared to the loss of load capacity, the ultimate strain decreased more markedly with increasing corrosion levels [1-7]. Empirical relationships which fit the ultimate strain to corrosion level have been suggested, however, they vary significantly between different studies. This is most likely attributable to variations in the type of corrosion condition and type of steel, plus different evaluation methods used in quantifying corrosion levels and mechanical properties, see [2-4, 6-8] for example. In this paper, a recently published engineering model to determine the ultimate strain for rebars with pitting corrosion is described [9].

A large number of studies on the effect of corrosion on bond has been carried out. General conclusions such as how a certain degree of corrosion affects the bond to a certain degree vary quite a lot, and it is difficult to get an overview. It is well-known that parameters such as the surrounding structure and type of reinforcement have a strong influence both on the bond behaviour for uncorroded structures, and on the effect of corrosion on bond. In this paper, these influencing parameters are organised in a systematic way, and an overview of how corrosion affects the bond behaviour for both smooth and ribbed bars is given. Finally, an engineering model to determine bond-slip relationships for ribbed bars is presented.

2 Ulitmate strain of corroded rebars

As mentioned, corrosion seriously decreases deformation and ductility behaviour of rebars; even more than the loss of load capacity [1-7]. Many studies [1, 2, 5, 6] have proposed an exponential decaying function for the ultimate strain versus the corrosion level, with different studies suggesting different empirical coefficients. One reason for this variation is different corrosion morphologies [6]. Furthermore, different extensometer gauge lengths influence the ultimate strain, as the local yielding elongation over the failure zone may be very different compared to the total elongation of corroded rebars [8], [9].

In recent work, a simplified way to calculate the ultimate strain for reinforcement suffering from pitting corrosion was derived [9]. The ultimate strain in the following is defined as the strain at maximum force. Further, the maximum cross-sectional area loss percentage of a bar is used to define maximum local corrosion level, μ_{max}:

$$\mu_{max} = \frac{A_0 - A_{min}}{A_0}, \tag{1}$$

where A_0 is the original cross-sectional area and A_{min} is the minimum remaining cross-sectional area.

From equilibrium of a bar with a corrosion pit, it is found that a critical corrosion level exists, above which the bar outside the pit would not yield upon failure. This critical corrosion level, denoted μ_{crit}, can be calculated as:

$$\mu_{crit} = 1 - \frac{f_{y0}}{f_{u0}}, \tag{2}$$

where f_{y0} is the yield strength of uncorroded bars and f_{u0} is the ultimate strength of uncorroded bars.

The sound steel is assumed to have a stress strain-behaviour with a linear elastic part, yield plateau and strain-hardening curve described by a power function as in [10]. By again looking at equilibrium of a bar with a corrosion pit, the following relationship between the ultimate strain outside the pit, ε_u^{out}, and maximum local corrosion level, μ_{max}, can be expressed:

$$\varepsilon_u^{out} = \begin{cases} \varepsilon_{u0} - (\varepsilon_{u0} - \varepsilon_{sh0})\left(\frac{f_{u0}}{f_{u0} - f_{y0}}\mu_{max}\right)^{\left(\frac{1}{P}\right)}, & \mu_{max} < \mu_{crit} \\ \in [\varepsilon_{y0}, \varepsilon_{sh0}], & \mu_{max} = \mu_{crit} \\ \frac{f_{u0}\varepsilon_{y0}}{f_{y0}}(1 - \mu_{max}), & \mu_{max} > \mu_{crit} \end{cases} \tag{3}$$

where ε_{u0} is the ultimate strain of uncorroded bars, ε_{sh0} is the strain at the onset of hardening of uncorroded bars, P is the strain-hardening power of uncorroded bars, and ε_{y0} is the strain at the onset of yielding of uncorroded bars. Note that all parameters except maximum corrosion level can be determined from mechanical testing of uncorroded bars. Further, the decreasing trend in ultimate strain outside the pit with increasing maximum local corrosion level follows exactly the full constitutive law of uncorroded steel, with the stress replaced by $f_{u0}(1 - \mu_{max})$, as shown in Fig. 1. As the strain in the pit is larger than outside, the ultimate strain outside the pit can on the safe side be used as a measure of the ultimate strain of the reinforcement. Thus, in engineering practice, a measure of the ultimate strain for bars damaged by pitting corrosion can be found from the maximum corrosion level and the properties of the sound reinforcement simply by use of the consitutive curve as shown in Fig. 1.

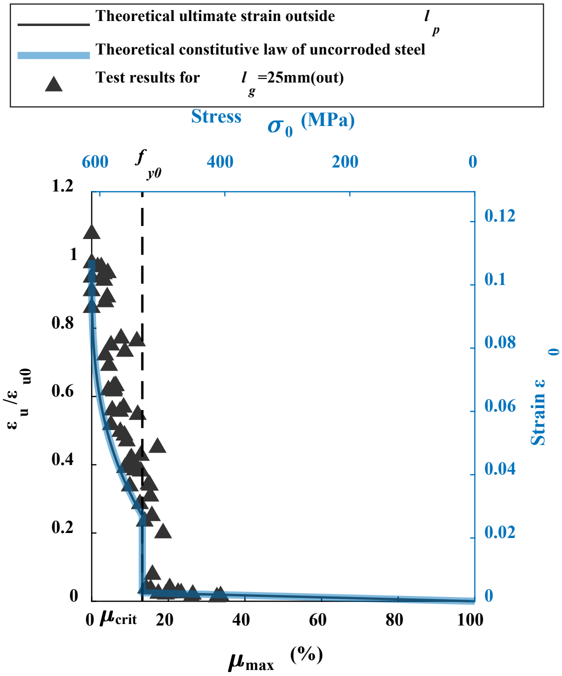

Fig. 1 Comparison of the theoretical relationship between the ratio of ultimate strain for corroded and uncorroded bar ($\frac{\varepsilon_u}{\varepsilon_{u0}}$) and maximum local corrosion level (μ_{max}), and experimental results [9]. Notations: l_p is the pit length, and l_g=25mm (out) refers to the extensometer placed outside the pit, with gauge length 25 mm.

3 Overview of how corrosion affects the bond behaviour

3.1 Identification of important factors

To better understand the effect of corrosion on bond, important influencing factors were used to define different cases. In the overview here, it was decided to include three factors:

- reinforcement type (ribbed or smooth),
- whether transverse reinforcement is present or not,
- whether there are splitting cracks at uncorroded pull-out or not, i.e. whether splitting cracks would occur for anchorage failure if the reinforcement was uncorroded.

For smooth bars without transverse reinforcement, a fourth factor was also considered : top-cast or bottom-cast. This factor is more important for smooth bars than for ribbed bars [11]. The bond capacity for uncorroded smooth bars is lower for top-cast than for bottom-cast bars. Furthermore, there is a difference in the tendency to split the cover due to corrosion: top-cast bars could withstand a higher corrosion level before cracking of the cover than bottom-cast bars [12, 13].

By use of the factors described, an overview as shown in Fig. 2 can be sketched. This overview was at first established as a hypothesis. By investigating each of the separate cases in detail, it could be validated, see [14]. Here, the overview is slightly further elaborated for smooth bars, based on recent test results of naturally corroded smooth bars [13, 15].

The scales in the bond-slip curves in Fig. 2 are varying, to make all graphs clearly visible. The scales in the maximum bond stress versus corrosion level graphs are, however, intended to be the same, to enable comparisons. Naturally, this summary is a simplification; for example, if the amount of transverse reinforcement is small, the behaviour will become close to that of specimens without transverse reinforcement. Also, of course, the transverse reinforcement can corrode; however, in general, larger corrosion penetrations are needed to substantially change the bearing capacity of the transverse reinforcement than to affect the bond of the main reinforcement. Granting these limitations, the summary in Fig. 2 is still believed to be of help in understanding the mechanisms.

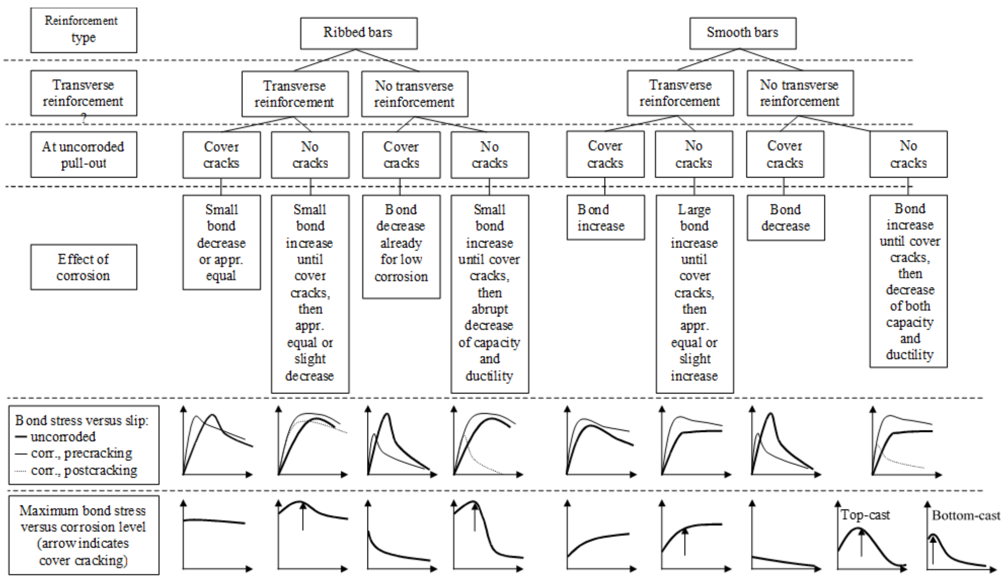

Fig. 2 Overview of effect of corrosion on bond. Modified from [14].

3.2 Effect of corrosion on the bond

One general observation for all cases is that corrosion increases the initial stiffness in the bond-slip relation. The effect on the bond capacity varies more, depending on the presence of transverse reinforcement and the failure mode for uncorroded pull-out. For both ribbed and smooth bars, transverse reinforcement makes the bond behaviour much less sensitive to corrosion. This is logical, as the transverse reinforcement will limit the splitting cracks that may arise due to the corrosion. Generally, the bond capacity of smooth bars is less than for ribbed bars; however, for corrosion penetrations that do not crack the cover, the bond capacity can increase to almost the same level as for ribbed bars. Each case is commented upon in the following:

- *For ribbed bars with transverse reinforcement, where the cover would crack for an uncorroded bar loaded in pull-out:* A typical such case is ribbed bars with large diameters combined with small concrete covers and no boundaries that provide restraint to prevent cracking. This is a common situation, which is also commonly combined with transverse reinforcement. In this case, corrosion has only a minor effect on the bond behaviour. As the cover cracks for pull-out already without corrosion, the transverse reinforcement is keeping the structure together already for uncorroded specimens. If the cover cracks due to corrosion, this does not have any major influence. For large corrosion penetrations, a small decrease in bond capacity can be seen, probably mainly because the ribs are being corroded. Thus, in short : Corrosion causes small bond decrease, or does not influence the bond capacity

- *For ribbed bars with transverse reinforcement, where the cover would not crack for an uncorroded bar loaded in pull-out:* Typical such cases are large covers combined with small reinforcement bars. It can also be larger bars or smaller covers, if the boundaries provide cracking restraint when, e.g., there is support pressure acting. For this case, the effect of corrosion will be slightly different depending on whether the corrosion penetration will crack the cover or not. For corrosion penetrations that do not cause cracking of the cover, the maximum bond capacity will remain almost unaffected, or even increase slightly, due to the increased normal pressure between rebar and concrete. At the corrosion penetration that causes cracking of the cover, the maximum bond capacity will decrease to a smaller level, which will decrease only slightly for larger corrosion penetrations. This smaller level depends on the amount of transverse reinforcement. Thus, in short : Corrosion causes small increase in bond capacity until the cover cracks; for larger corrosion levels the bond capacity decreases or remains approximately equal.

- *For ribbed bars without transverse reinforcement, where the cover would crack for an uncorroded bar loaded in pull-out*: Typical such cases are small covers combined with large reinforcement bars ; for these the cover will crack at anchorage failure for uncorroded bars. As no transverse reinforcement is present, the bond capacity will be limited already for uncorroded bars. Further, very limited corrosion will crack the cover. Thereafter, corrosion will decrease the bond capacity in a detrimental way. Thus, in short: Bond capacity decreases already for low corrosion levels.

- *For ribbed bars without transverse reinforcement, where the cover would not crack for an uncorroded bar loaded in pull-out:* This case can either consist of large covers combined with small reinforcement bars, or have boundaries that provide cracking restraint as e.g. when support pressure is acting. In this case, corrosion causes small increase in bond capacity due to the increased normal pressure between rebar and concrete. However, when corrosion cracks the cover, the bond capacity decreases abruptly. Also the ductility decreases after cover cracking. Thus, this is a dangerous case for real situations. Fortunately, it is rare to anchor reinforcement without presence of transverse reinforcement.

- *For smooth bars with transverse reinforcement, where the cover would crack for an uncorroded bar loaded in pull-out*: It can be noted that this is an uncommon case in real structures ; as smooth bars generate far lower splitting stresses than ribbed bars, this case thus is relevant only for very small covers. In this case, corrosion causes small increase of the bond capacity.

- *For smooth bars with transverse reinforcement, where the cover would not crack for an uncorroded bar loaded in pull-out:* As smooth bars do not generate any great splitting stresses, the covers do not need to be so large to prevent cracking at a pull-out loading of an uncorroded bar. Thus, this case is therefore a common situation in real structures. In this case, corrosion increases the capacity because of the increased normal pressure between rebar and concrete until the cover cracks. This increase can be substantial, especially for top-cast bars which typically gain bond when corrosion products fill up voids close to the rebar. Larger corrosion levels (than causing cracking) cause small bond increase or do not further influence the bond capacity.

- *For smooth bars without transverse reinforcement, where the cover would crack for an uncorroded bar loaded in pull-out:* As mentioned, this will be relevant only for very small covers. It can be noted that the pull-out failure will become rather brittle due to the splitting failure already for uncorroded bars. Very limited corrosion will crack the cover and decrease the bond capacity.

- *For smooth bars without transverse reinforcement, where the cover would not crack for an uncorroded bar loaded in pull-out:* First, it can be noted that this is a rather common situation. For small corrosion levels, the bond capacity increases due to the increased normal pressure between rebar and concrete. Corrosion levels cracking the cover decrease the bond capacity and ductility. Top-cast bars typically have smaller bond capcaity than bottom-cast bars when uncorroded, but can withstand larger corrosion levels before cracking, with subsequent large increase in bond capacity. This is due to smaller density of the concrete surrounding the top-cast bars. Bottom-cast bars are surrounded by denser concrete, and accordingly crack the cover for smaller corrosion levels, and lose bond capacity already for small corrosion levels.

4 Engineering model describing bond-slip behaviour

In the following, an engineering model to determine bond-slip relationships for ribbed bars is presented; for details see [16]. The model is refered to as “ARC model”. It can be used in analyses on different levels of detail [17]: in nonlinear finite element analyses, and also in simplified analyses where the one-dimensional differential equation is numerically solved; in this way the anchorage capacity can be calculated from an available anchorage length. The “ARC model” was calibrated versus a database containing 500 pull-out and beam tests reported in 21 research works; for details see [16]. Most of these tests were artificially corroded, and thus mainly included general corrosion.

The “ARC model” makes use of the observation that the local bond stress-slip curve of corroded reinforcement can be approximated by shifting the uncorroded curve in the slip direction, see Fig. 3. This can be expressed as:

$$s_{eff} = s + s_{eq} \tag{4}$$

where s_{eff} is the effective slip, s is the mechanical slip and s_{eq} is the equivalent slip to account for the effect of corrosion. The equivalent slip can be estimated as in [16]:

$$s_{eq,nostir} = 2.9\mu_{ave} \quad \text{without stirrups} \tag{5}$$

$$s_{eq,stir} = 13.6\mu_{ave} \quad \text{with stirrups} \tag{6}$$

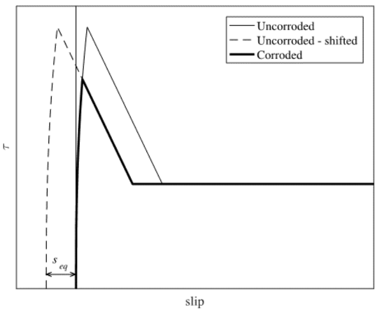

Fig. 3 Illustration of the equivalent slip, s_{eq}, to account for the effect of corrosion in a sample bond stress-slip curve, where splitting strength governs the maximum bond stress.

where μ_{ave} is the corrosion level (weight loss) in decimals and the equivalent slip is output in mm. For cases without stirrups there is data up to around 15% corrosion, and for cases with stirrups up to approximately 20% corrosion. Therefore, the domains for Equations 5 and 6 are 0-15% and 0-20% corrosion weight loss, respectively.

Increasing corrosion levels will ultimately crack the concrete cover. The corrosion penetration leading to cracking can be estimated as [16]:

$$x_{cr} = 11 \cdot \left(\frac{f_{cm}}{40}\right)^{0.8} \cdot \left(\frac{c}{\phi_m}\right)^{1.5} \cdot \left(\frac{\phi_m}{16}\right)^{0.5} \tag{7}$$

where f_{cm} is the mean cylinder compressive strength in MPa, ϕ_m is the diameter of the anchored bar in mm, and c is the concrete cover. The influence of corrosion on cracking of the cover is accounted for by using the reduced splitting strength [16]:

$$\tau_{bu,split,red} = \eta_2 \cdot 6.5 \cdot \left(\frac{f_{cm}}{25}\right)^{0.25} \cdot \left(\frac{25}{\phi_m}\right)^{0.2} (1 + k_m \cdot K_{tr}) \tag{8}$$

where η_2 is 1.0 and 0.7 for “good” and “all other” bond conditions, respectively, f_{cm} is the mean cylinder compressive strength in MPa, ϕ_m is the diameter of the anchored bar in mm, and k_m and K_{tr} are the confinement coefficient and the amount of the transverse reinforcement, respectively, defined in [18].

A modified expression of the residual bond capacity for specimens with low stirrup content is proposed for both the corroded and uncorroded cases [16]:

$$\tau_{res,mod}(K_{tr}) = \begin{cases} (0.16 + 12K_{tr}) \cdot \tau_{bu,split,red} & \text{for } 0 \leq K_{tr} \leq 0.02 \\ 0.4 \cdot \tau_{bu,split,red} & \text{for } 0.02 < K_{tr} \end{cases} \quad (9)$$

An earlier version of this engineering bond-slip model was developed in in earlier work [19], and applied in practice in a pilot study including two bridges [20]. The model proved to be easy to use in practical design work. Both bridges could be shown to have sufficient capacity, and costly strengthening could be avoided; the economical saving was around 27 million SEK for the two studied bridges only. The model is now included in the Swedish requirements for assessment [21].

5 Conclusions and outlook

Two engineering models for use at assessment of corroded concrete structures were presented: one for the deformation capacity of rebars with pitting corrosion, and one for what bond-slip relationship to use for ribbed bars. Further, the effect of corrosion on bond was described in a systematic way, with an overview of the effect for various cases depending on reinforcement type, existence of transverse reinforcement, and confinement due to concrete and boundaries.

Both the presented engineering models use the corrosion level as an important input parameter. However, reliable information about the corrosion level in existing structures is typically difficult to get; commonly used methods, such as measuring the corrosion rate and calculate the corrosion level from that, include major uncertainties. At inspections, splitting cracks are typically the first sign of ongoing corrosion. A possibility may be to judge the severity of the corrosion attack from the corrosion crack width: how much corrosion takes place before the cover cracks, and can the width of splitting cracks be linked to the corrosion level? Regarding the first question, for structures that are not submerged, it is known that already limited corrosion will induce visible cover cracks [22], [23], [13]. Thus, the main questions are if and how the corrosion level is linked to measured splitting crack widths. The wide scatter in prior experiments precludes a simple interpretation [23], indicating that we have not yet understood the involved phenomena. Further, recent studies indicate a strong interaction between corrosion and freezing [24]. These topics require further research.

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