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The Effect of Corrosion on Bond in Reinforced Concrete

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Summary

When reinforcement in concrete corrodes, splitting stresses are induced in the concrete. Thereby, the bond between the reinforcement and the concrete is influenced. This effect has been studied both experimentally and theoretically by many researchers. Here, this is investigated and described in a systematic way. An overview of the effect for various cases is given. Parameters defining the various cases are reinforcement type, existence of transverse reinforcement, and confinement due to concrete and boundaries. Preliminary recommendations for assessment of existing structures are given.

KEYWORDS
Corrosion, bond, concrete, reinforcement, anchorage

1. Introduction

During recent years, much research concerning durability aspects of reinforced concrete has been done. Lifetime design based on probabilistic approaches has been developed; see e.g. [1]. A rather common approach is to assume (on the safe side) that the lifetime is ended when corrosion is initiated. However, if the structural effects of corrosion are not checked in the lifetime design, initiation can only be allowed to occur with a very small probability. This will in many cases lead to unreasonably large concrete covers. To be able to use covers of more practical size, it is often necessary to include the structural effects of corrosion in the lifetime design. Hence there is a need for models of how corrosion affects the structure. These are also needed at assessment of existing structures. The most severe effect of reinforcement corrosion is the volume increase which causes splitting stresses in the concrete, and eventually spalling the cover. Due to the splitting stresses, the bond between the reinforcement and the concrete is affected. This has been studied by many researchers; for a state-of-the-art report see [2].

When starting to study bond between reinforcement and concrete, one easily becomes confused. Different bond mechanisms are often mixed with different failure modes. The confusion may grow when the effect of corrosion on bond is studied. 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 is given. Finite element modelling, using the bond and corrosion models presented in [3, 4], was used as a tool to provide the basic understanding. Furthermore, experiments from the literature were examined to check the validity of the overview. For detailed information about the analyses and references, see [5]. In this paper, the main findings are summarised. Recommendations for assessment of existing structures are also given.

2. Identification of important factors

To better understand the effect of corrosion on bond, several cases have been distinguished. This requires determination of the most important influencing factors. 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.

The choice of these factors can of course be discussed; for example, there are several further influential parameters. Some of them are: type of corrosion (general / pitting, due to chlorides or carbonation, wet or dry environment), amount of transverse reinforcement, placement of bar, possible effect of support pressure, and concrete strength. However, the three factors listed above were chosen because they were considered to have the greatest influence. Moreover, some of the listed possible parameters (such as support pressure and concrete strength) are indirectly included, as their main influence is on whether there will be splitting cracks at uncorroded pull-out or not. Another reason to use the chosen influencing factors is that these factors are rather clearly definable.

Still, for smooth bars, the choice of factors can be further discussed. For smooth bars, the cover generally does not crack at anchorage failure of an uncorroded bar. Furthermore, there is a large difference between top-cast and bottom-cast bars, as has been shown in experiments [6], [7]. This difference is more important for smooth bars than for ribbed bars. 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. Cairns *et al.* [6] found that the top-cast bars could withstand a higher corrosion level before cracking of the cover than the bottom-cast bars. Thus, it could be debated whether this is a more important factor for smooth bars than if the cover cracks at uncorroded pull-out. Still, here it was chosen to use the same factors as for ribbed bars. The main reason for this choice was to facilitate comparison with ribbed bars.

By use of the three factors above, an overview as shown in Fig. 1 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 [5]. In this paper, the main findings are summarised.

The scales in the bond-slip curves in Fig. 1 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. 1 is still believed to be of help in understanding the mechanisms, and for assessment of existing structures.

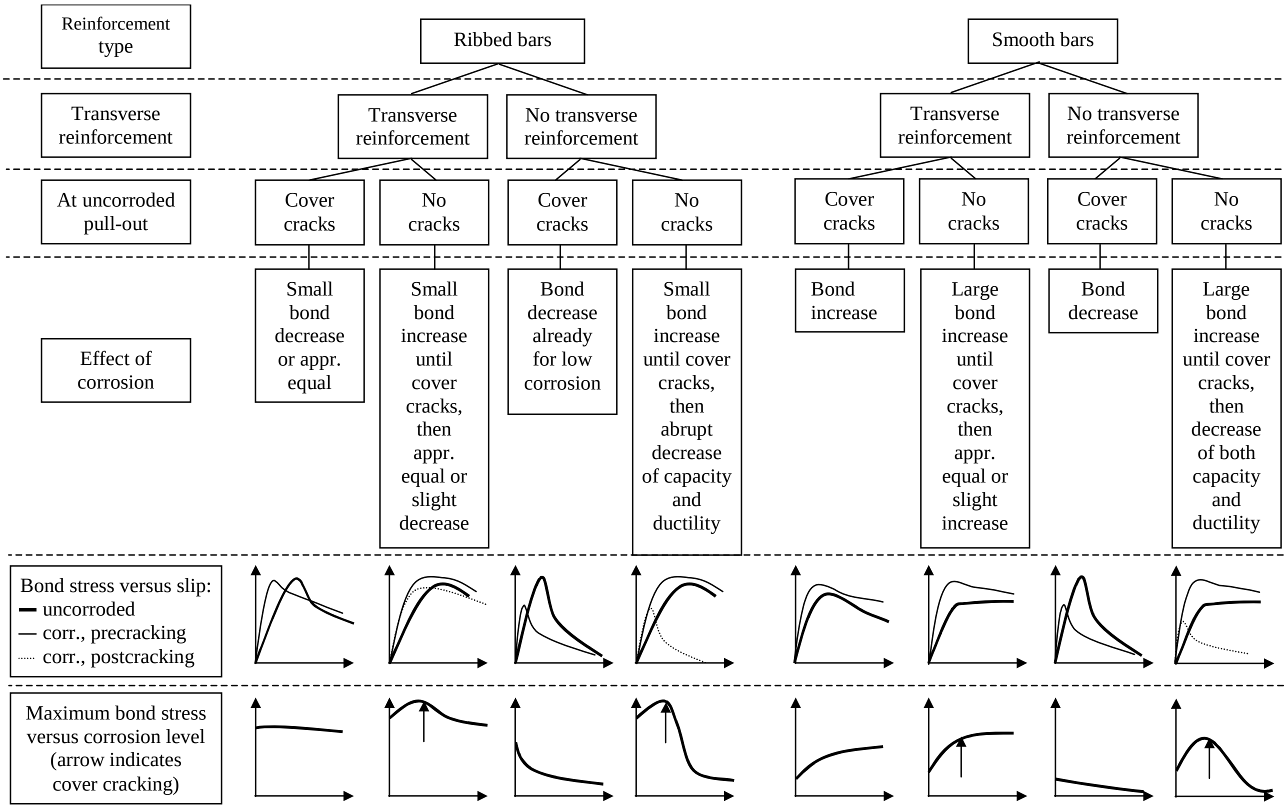

Fig. 1 Overview of effect of corrosion on bond. From [5].

3. 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 be increased to almost the same level as for ribbed bars. In short, the following conclusions can be drawn:

- For ribbed bars with transverse reinforcement, where the cover would crack for an uncorroded bar loaded in pull-out: 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: 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: 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: Corrosion causes small increase in bond capacity until the cover cracks; for larger corrosion levels the bond capacity decreases abruptly. Also the ductility decreases after cover cracking.
- For smooth bars with transverse reinforcement, where the cover would crack for an uncorroded bar loaded in pull-out: Corrosion causes small increase of bond capacity.
- For smooth bars with transverse reinforcement, where the cover would not crack for an uncorroded bar loaded in pull-out: Corrosion increases the capacity until the cover cracks.

This increase can be substantial, especially for large covers. Larger corrosion levels 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: Corrosion decreases the bond capacity.
- For smooth bars without transverse reinforcement, where the cover would not crack for an uncorroded bar loaded in pull-out: Corrosion increases the capacity until the cover cracks, while larger corrosion levels decrease the bond capacity and ductility.

4. Preliminary recommendations for assessment of existing structures

From the overview presented in the previous sections, preliminary recommendations were worked out for judgements concerning how serious corrosion is when assessing existing structures. These recommendations will be further discussed and verified in a European project called Sustainable Bridges. From drawings etc., it is supposed to be known what type of reinforcement that has been used, and whether transverse reinforcement is provided or not. In Fig. 2, the four various cases this leads to are listed in the order of how serious it is if corrosion takes place in anchorage regions; i.e. both at end anchorage and at splices. Each case is graded compared to statements when corrosion will become critical related to cracking of the cover due to corrosion: before the cover cracks, when the cover cracks, or first at a later stage.

It was concluded that ribbed bars without transverse reinforcement is most sensitive to corrosion. With that combination, the anchorage capacity can be reduced already before the cover is cracked due to corrosion. And, especially if the cover is thick, as soon as cracking of the cover occurs, the anchorage capacity will be very much reduced, and thus become critical. As cracking of the cover can occur between inspections, it is in new design advised to use transverse reinforcement in zones where ribbed bars are anchored. This advice is also given in [8]. In existing structures, it is advised to inspect at close intervals if ribbed bars are anchored without any transverse reinforcement and corrosion is likely to occur. Measures need to be taken as soon as there is any risk of corrosion.

Also for smooth bars without transverse reinforcement, the anchorage capacity will decrease when cracking of the cover occurs. However, the decrease will not be so abrupt as for ribbed bars, and furthermore, the anchorage length of smooth bars will be long already in the original design. Therefore, for this combination, it is judged that measures must be taken when there is any indication of corrosion.

For ribbed bars with transverse reinforcement, the anchorage of corroded reinforcement will depend on the amount of transverse reinforcement. Normally the transverse reinforcement corrodes as well as the main reinforcement; naturally it is then only the uncorroded part of the transverse reinforcement that can be accounted for. If the transverse reinforcement is sufficient, the anchorage will not be immediately critical, even if cracking of the cover occurs.

Finally, when smooth bars with transverse reinforcement corrodes, the anchorage is not a very critical issue. Of course, as for ribbed bars, one needs to consider corrosion of the transverse reinforcement. Furthermore, if significant spalling of the cover occurs, investigations are needed.

A general comment concerning smooth bars, is that they most often are provided with end hooks. In this case, most of the anchorage can be provided by the end hooks. The direction the hooks are bent in is most likely of importance; if they are bent into the structure, the anchorage is less sensitive to corrosion.

It is important to point out that these recommendations concern how critical corrosion is for the anchorage. At assessment of the load-carrying capacity, it is also important to take the effect of the area reduction into account. This includes reduction of the reinforcement area, both the main and the transverse reinforcement, but also reduction of the concrete cross-section, for example when corrosion has caused spalling of the concrete cover. The effect of the area reduction becomes more important when transverse reinforcement is present, as the anchorage is not as critical then.

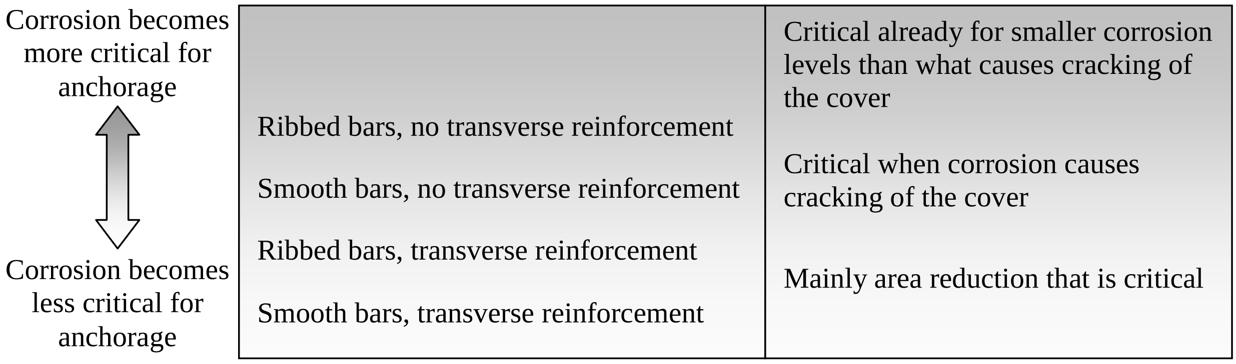

Fig. 2 Overview of how critical corrosion is for the anchorage capacity.

5. Conclusions

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. Another general observation is that corrosion increases the initial stiffness for all cases. The effect on the bond capacity varies more; an overview is shown in Fig. 1. One difference between smooth and ribbed bars is that corrosion can increase the bond capacity quite a lot for smooth bars, while only small increase can be found for ribbed bars. However, high corrosion levels will damage the bond, especially if transverse reinforcement is not supplied.

Preliminary recommendations for assessment of existing structures were given. In short, the following actions are recommended if corrosion takes place in anchorage regions; i.e. both at end anchorage and at splices:

- Ribbed bars without transverse reinforcement: Measures need to be taken as soon as there is any risk of corrosion.
- Smooth bars without transverse reinforcement: Measures need to be taken when there is any indication of corrosion.
- Ribbed bars with transverse reinforcement: Investigations need to be done when cracking of the cover due to corrosion occurs. If there is sufficient transverse reinforcement, the anchorage will not be critical immediately.
- Smooth bars with transverse reinforcement: Investigations need to be done when spalling of the cover due to corrosion occurs. If there is judged to be sufficient transverse reinforcement, the anchorage might not be critical.

It is important to point out that these recommendations concern how critical corrosion is for the anchorage. At assessment of the load-carrying capacity, it is also important to include the effect of reduced reinforcement and concrete cross-sections.

These recommendations can be of help at assessment of existing structures, as it is easy to visually inspect whether corrosion has caused cracking of the cover or not. Even though these recommendations do not provide any numerical absolute values, it can give guidance on when more thorough evaluation is needed, and when it can be postponed. Furthermore, from this, one can also conclude that at design of new structures, it is wise to use transverse reinforcement in anchorage zones, especially when deformed bars are used.

An issue for further studies is to give more detailed recommendations concerning how much transverse reinforcement that is needed to maintain the anchorage capacity. Furthermore, the combination of cyclic loading and corrosion needs to be studied; especially when ribbed bars and transverse reinforcement is considered. Finally, studies concerning how corrosion affects the anchorage of end hooks is needed.

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