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Corrosion of naturally corroded, plain reinforcing bars.

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Abstract

Reinforced Concrete is known to be susceptible to corrosion damages. Corrosion, by reducing strength and ductility of the reinforcing bar and modifying the steel/concrete interface, hinders the overall safety of the structure. This work investigates the bond of naturally corroded, plain reinforcing bars. Specimens were taken from an 80-year-old bridge and tested using pull-out and 3-point bending tests. Additionally, neutron and X-ray tomography is used to observe the distribution of corrosion products. Results highlight the influence of casting position on the bond of plain bars. Specifically, the distribution of corrosion products is influenced by the bleeding zone underneath top-cast bars. Corrosion products are shown to deposit in macro-pores and to adhere to the bar.

1 Introduction

Plain bars are an old type of reinforcement bars used in concrete structures, which has not been in use for at least 40 to 50 years. However, 16% of existing concrete bridges are estimated to be between 50 and 100 years old in Europe [1]. It follows that, although plain bars are no longer relevant for the design of new bridges, there is a need to assess structures with such reinforcements. Lack of knowledge on the behaviour of older structures is due to result, for some cases, in unnecessary demolition, which is neither economically nor environmentally sustainable.

The most common deterioration mechanism affecting reinforced concrete structures is corrosion of the reinforcement bars [2]. The cement paste provides a natural alkaline environment for the embedded steel bar, thus preventing the bar from corroding. However, the penetration of carbon hydroxide or chlorides into the cement paste can reduce the pH of the concrete environment. This results in the local depassivation of the bar, and, consequently, the initiation of the corrosion process.

Corrosion products originate from the combination of iron, oxygen and hydrogen, and can have different sizes, depending on the availability of the latter two. All corrosion products occupy a larger volume than the steel they originate from. Thus, the corrosion process results in increasing radial pressure on the reinforcing bar and on the surrounding concrete, eventually leading to cracking and spalling of the concrete cover. This, in turns, affects the bond behaviour.

The bond behaviour is the main difference between plain and deformed bars. Bond is generally characterized by three components, adhesion, friction and mechanical interlock [3]. Mechanical interlock contributes however only at the micro-level in the case of plain bars. Therefore, the bond of plain bars relies mostly on friction, which is particularly affected by the corrosion process: the increase in radial force generated by the expansive corrosion products has already been observed to initially increase the bond of plain bars. Such effect is less marked after the opening of corrosion-induced cracks, while loss of bond is generally observed after spalling of the concrete [4]-[5].

It is generally agreed that the formation of corrosion-induced cracks is strongly influenced by the presence of macro-scopic voids in the concrete paste, and by the porosity of the concrete [6]. In a concrete characterized by low porosity, small amounts of corrosion may already result in cracking and spalling of the concrete cover, and consequently, loss of bond strength. Higher porosity, combined with the presence of macro-scopic voids, allows for the corrosion products to expand without exceeding the tensile capacity of the surrounding concrete, and may thus result in longer time between the beginning of the corrosion process and the appearance of corrosion induced cracking. This, in turns, leads to an initial increase of bond capacity with the corrosion level.[7]

The porosity of the concrete surrounding the bar often depends on the casting position of the reinforcing bar itself. This is particularly true for the case of older infrastructure, where the concrete was tamped instead of vibrated. Additionally, top-cast bars are often surrounded by more porous concrete, as a result of settlements of aggregates and accumulation of bleed water below the bar [8]. This results in the formation of a bleeding zone underneath the bar, characterized by the presence of macro-scopic voids at the steel/concrete interface. The bleeding zone is likely to allow for the expansion of the corrosion products, without initially inducing cracking in the surrounding concrete. The size of the bleeding zone generally increases with the depth of the concrete below the bar; hence, the phenomenon prevalently affects top-cast bars.

The presence of a bleeding zone, and macro-scopic voids, is as well linked to the initiation of the corrosion process [9]. Macro-scopic voids can be filled or partially filled with water, providing both oxygen and hydrogen, which are essential for corrosion initiation. Although higher porosity may be beneficial to the concrete specimens in terms of maintaining, or even increasing, the bond capacity with the presence of corrosion process, corrosion induced cracks are often a good indicator for the presence of corrosion damages. If corrosion products have enough room to expand without cracking the concrete, large corrosion pits may form in the absence of external indicators. Thus, large, local reductions of the cross-section of the reinforcing bar could go undetected, hence compromising the safety of the entire structure. It is therefore important, for the assessment and safety of our structure, to fully understand how top-cast bars are affected by corrosion damages.

In this paper, we investigate in depth the behaviour of plain, top-cast bars subjected to natural corrosion. The paper examines and combines results from previous studies [4]-[5], with the aim of drawing a more complete picture of the corrosion damages observed in a naturally corroded, 81 years old bridge and their consequences for structural safety.

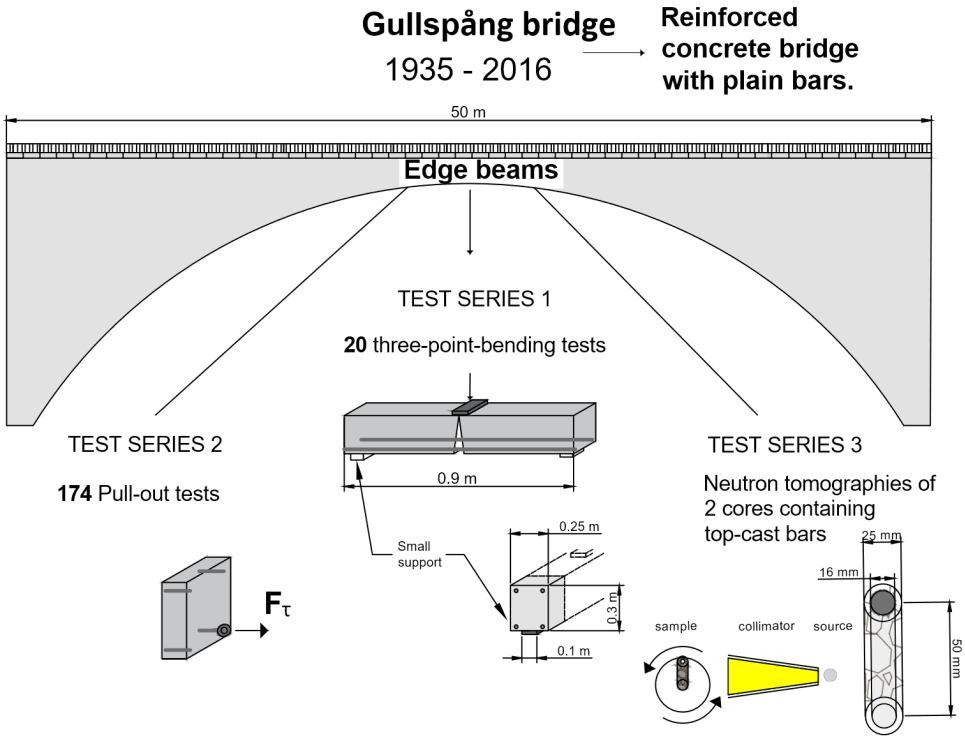

Fig. 1 Overview of previous test series on the specimens obtained from Gullspång bridge

2 Methodology

This work compiles previous individual studies focusing on the effect of natural corrosion in reinforced concrete structures with plain bars. Specifically, specimens were obtained from a decommissioned bridge. The bond strength of top-cast bars was assessed with 3-point bending and pull-out tests. The geometry of the corroded rebars was afterwards acquired via 3D scanning. The maximum loss of steel area in the tested bars was as well estimated. Finally, neutron tomographic images of a reinforced concrete cylindrical sample extracted from the same bridge were acquired. This allowed for observing the corrosion distribution without using destructive methods, and thus disturbing the sample. In Fig. 1, an overview of the tests conducted on the specimens is presented.

2.1 Gullspång bridge

The decommissioned bridge at the basis of this study was located in the Swedish town Gullspång, Västra Götaland. The bridge was built in 1935, and it was demolished in 2016, after heavy corrosion damage was observed on the structure. The edge beams were documented for existing cracks before being tested. Material tests were conducted on the edge beams; the compressive strength of the concrete was estimated to 45,6 ± 4,6 MPa, and the average yield stress of the reinforcing bars was 259,6MPa ± 10,1MPa. For 81 years, the edge beams were exposed to de-icing salts and weather conditions including wetting/drying and freezing/thawing cycles. The casting technique was by tamping the concrete, as common in the 1930s.

2.2 Three-point bending tests

Twenty, 900 mm long, beams were cut from the edge beams and tested in three-point-bending. Of these, eleven beams were tested upside down with respect to the original position on the bridge, to assess the anchorage capacity of top-cast bars. The beams had different levels of visible damages in the concrete surface, and were therefore classified in three categories: reference (R), for beams with no visible cracks in the anchorage zone, cracked (C), for beams with visible cracks in the anchorage zone, and spalled (S), for beams presenting spalling of the concrete cover in the anchorage zone. In all but two of these flexural tests, bending cracks were followed by yielding of the tensile reinforcement, and, thereafter, end-slip of the bars, one at a time, were observed. After structural testing, the bars were extracted from the beams, cleaned, and scanned, to evaluate corrosion level and yield penetration, and later tested in tension. Finally, the bond strength of the unyielded zone was evaluated [4].

The corrosion level was defined as the ratio between the corroded area of the reinforcing bar and the nominal area, calculated either from 3D scanning data obtained from uncorroded parts of the bar itself, or, when that was not available, from the average of a larger sample of uncorroded cross sections, calculated from all the scanned bars extracted from Gullspång bridge. The bond strength was averaged along the unyielded length of the bar, assuming a uniform distribution of the bond strength.

2.3 Pull-out tests

Direct pull-out tests were performed using 50, 75, and 100 mm thick sections of the edge beams from Gullspång bridge. An upper limit of 100 mm for the embedded length of the bar was chosen to avoid yielding of the bar. A total of 174 bars were tested, of which 95 were top cast. The specimens presented different levels of damage in the surrounding concrete, and were divided in three categories, following the same division used in the three-point bending tests.

The specimens were prepared for testing by drilling, threading, and inserting a threaded rod in the steel bar. Each bar was then pulled out using a hydraulic load cell and a special rig, designed with the aim of aligning the bar with the hydraulic load cell. After testing, all bars were extracted from the cross-sections, cleaned and 3D scanned [5]. The corrosion level was evaluated as in the three-point bending tests, and the bond strength was assumed uniformly distributed along the length of the bar.

2.4 Neutron tomography

One specimen was studied by neutron tomography; it was as well cut and cored from the edge beam of Gullspång bridge. It was 50 mm long, had a diameter of 25 mm, and contained a top-cast plain reinforcing bar with a diameter of 16 mm. The analysed sample was uncracked. The neutron tomographic data was obtained at the instrument D50 at the Institut Laue-Langevin (ILL) in Grenoble. The acquired

radiographies were reconstructed into the corresponding 3D volumes with the commercial software X-act (from RX-Solutions). The resulting images have a pixel size of 26 µm/px.

Neutron tomography is a non-invasive technique which enables to obtain a full 3D view of the concrete sample. Neutrons are particularly sensible to hydrogen, which is one of the main components of the corrosion products. Additionally, the attenuation of iron is remarkably lower than the attenuation of hydrogen, which allows for the scanning of reinforced concrete sample with an embedded, normal sized, reinforcement bar without compromising the acquisition of the steel/concrete interface.

Data showed in this study are part of a larger study, where multimodal registration was used to combine X-ray and neutron tomographic data, with the aim of characterizing corrosion products in naturally and artificially corroded samples.

3 Results and Discussion

In Fig. 2, the bond capacity of top-cast bars classified as reference bars (i.e. without corrosion induced cracks in the surrounding concrete) is plotted against the peak (left) and average (right) corrosion level of the reinforcing bar. The 3D scanned surface of four cases is as well shown. The results from the 3-point bending tests are shown in blue, while the results from the pull-out tests are in red.

Pull-out tests results are more numerous and characterized by a high scatter. The results of the three-point bending tests may instead show higher bond capacity as a result of support pressure in the anchorage zone. However, both datasets are shown to follow a similar trend, i.e. the highest average bond strength is reached in bars with corrosion damages.

The surface of the bar with the highest bond strength in the pull-out tests is presented in Fig. 2: corrosion damage is clearly asymmetrically distributed with respect to the circular perimeter of the bar, but small pits are almost uniformly distributed along the length of the bar. Many bars with no corrosion damages have instead low bond strength. Corrosion damages, however, do not necessary increase the bond strength of plain bars, even in the absence of cracks in the surrounding concrete. Many bars with large corrosion pits, but not uniformly distributed corrosion damages along the length, do not show increased bond strength. Corrosion distribution, in these cases, is still shown to be asymmetric, but presenting more local, large corrosion pits.

It is to be noted that Fig. 2 shows results for reference specimens, i.e. without corrosion induced cracks in the surrounding concrete. It follows that in some cases large corrosion pits, that significantly decrease the cross section of the steel reinforcing bar, may form without inducing cracks in the surrounding concrete. This is likely linked to the size of the bleeding zone. The presence of corrosion induced cracks is a common indicator of the presence of corrosion damages currently in use at assessment of structures. However, in the presence of macro-pores and high porosity, these results show that it was possible to locally lose as much as 12 % of the cross section of the reinforcing bar without any external indicator of corrosion damages.

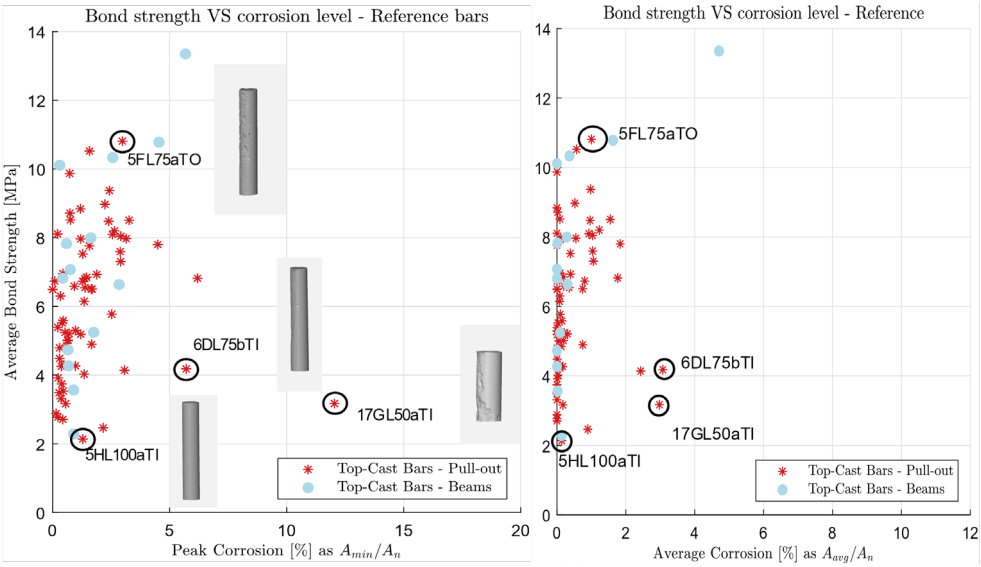

Fig. 2 The average bond strength of reference bars (i.e. without corrosion induced cracks in the surrounding concrete) plotted against peak and average corrosion levels.

In Fig. 3, the bond capacity of top-cast bars embedded in specimens classified as cracked (i.e. with corrosion induced cracks) is plotted against the peak (left) and average (right) corrosion level of the reinforcing bar. The 3D scanned surface of three examples is as well shown.

The effect of corrosion-induced cracks is not easily predictable. Many specimens are characterized by higher corrosion levels than the one evaluated for the reference specimens. If we compare pull-out tests results, the cracked specimen and the reference specimen with higher bond strength have similar characteristics: uniformly distributed corrosion along the length, but asymmetrically distributed along the cross section, without particularly large pits. The cracked specimens have higher average and peak corrosion, and, as well, higher bond strength: in this case, the presence of corrosion-induced cracks does not seem to decrease the bond capacity. This applies as well to the specimen with the largest corrosion pits (5EL75aTO), where both corrosion level and bond strength are higher when compared to the most corroded reference specimen. However, specimen 9EL75aTO, i.e. the specimen with corrosion-induced cracks with lower bond strength in the series of pull-out tests, presents similar characteristics to the specimen with the highest bond strength (5FL50bTO): both had uniformly distributed corrosion along the length of the bar, with comparable pit size. This shows that the scatter is large in the collected data, implying that other factors, such as the position of the corrosion induced cracks, their width, the number of such cracks, or the distribution of the voids around the bar, influence the bond strength.

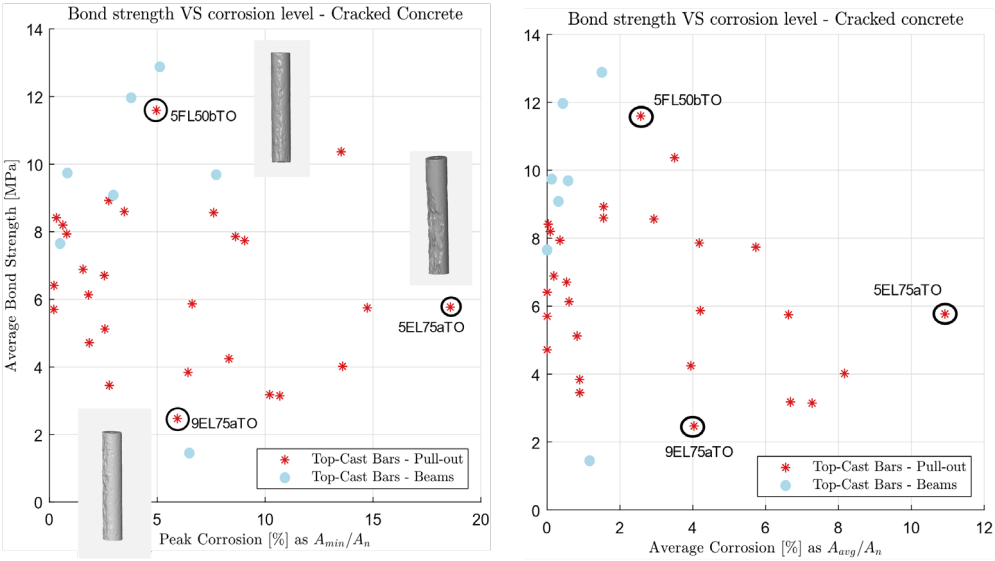

Fig. 3 The average bond strength of bars embedded in concrete with corrosion-induced cracks plotted against peak and average corrosion levels.

In Fig. 4 the cross section of a reference bar is shown, as captured with neutron imaging. Brighter values correspond to higher attenuation values. Corrosion products are hence in white, followed by cement paste, which contains hydration products, the plain reinforcing bar, aggregates and voids. Voids and aggregates have similar attenuation values and are therefore not easily distinguishable. However, the bleeding zone is easily recognizable in the bottom part of the bar, where corrosion products are as well concentrated. The concrete is shown to well adhere to the top part of the top-cast bar. The bottom part is characterized by the presence of macro-scopic voids, corresponding to where the corrosion process had started. However, the relatively large size of the bleeding zone allows for the expansion of the corrosion product without increasing stresses on the surrounding concrete. Additionally, the corrosion product is shown to adhere to the surface of the bar, possibly increasing the surface roughness. Thus, two factors could explain an increase in bond strength: the increase in radial pressure generated by the corrosion products, and an increased surface roughness.

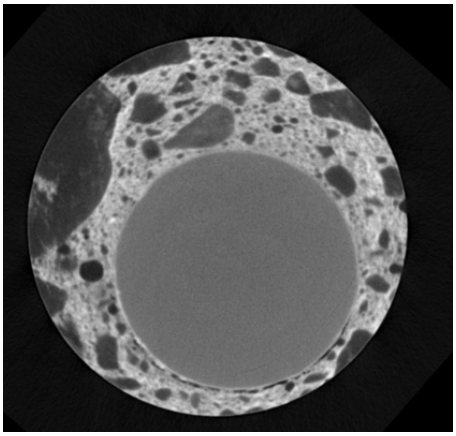

Fig. 4 Cross section of a reference bar as captured with neutron imaging.

4 Conclusions

In this work, the corrosion level and the bond strength of different specimens is presented, with the aim of gaining a deeper understanding on the corrosion process and its effects on the bond strength of plain, naturally corroded, bars. Corrosion damages are shown to be consistently asymmetric in the analysed bars. This has been linked to the presence of a bleeding zone underneath the top-cast bars, as shown by data acquired with neutron imaging. The bleeding zone is likely linked to corrosion initiation: when the reinforcing bar locally depassivates, corrosion initiates in correspondence of macro-pores, where enough oxygen and hydrogen are present to allow the formation of corrosion products. These, in turns, can expand without inducing excessive pressure on the surrounding concrete in this area (and consequently corrosion induced cracks), in some cases resulting in the formation of large, local pits. This observation is particularly of interest for the assessment of corrosion damages in structures with similar reinforcing bars and casting conditions: the absence of external cracks in a certain location does not necessary imply that the reinforcing bar is not damaged by pitting corrosion.

The bond strength is shown to increase with the corrosion level for specimens with uniformly distributed corrosion damages along the length of the bar, when no corrosion induced cracks are present. The presence of cracks can reduce bond strength but does not always necessarily do so.

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