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Anchorage in naturally corroded specimens taken from existing structures

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ABSTRACT: In an on-going project, the anchorage capacity of naturally corroded steel reinforcement was investigated experimentally. The beam specimens were taken from edge beams of Stallbacka Bridge in Sweden. The specimens showed different extent of corrosion induced damage; from no sign of corrosion to extensive cracking and spalling of the concrete cover. After consideration of different possible test setups, a four point bending test indirectly supported with suspension hangers was chosen. The beams were strengthened with transverse reinforcement around the suspension hangers to avoid a premature failure. Eight successful tests have been carried out so far; in all these, a diagonal shear crack preceded an anchorage failure. The anchorage behaviour was examined through monitoring the applied load, free-end slip and mid-span deflection. The test results can be used to extend our knowledge concerning the structural behaviour of corroded reinforced concrete structures to field conditions.

1 INTRODUCTION

Corrosion of reinforcement is one of the most common causes of deterioration in reinforced concrete bridges. Anchorage, prior to shear and bending moment resistance, is a main uncertainty in the evaluation of the structural behaviour of corroded reinforced concrete structures. The bond behaviour, i.e. the interaction between the steel reinforcement and the surrounding concrete, is decisive for both the load-carrying capacity and the ductility in the ultimate state, Zandi Hanjari et al. (2011) and Coronelli et al. (2004), as well for the stiffness distribution and deflection in the service state, Val et al. (2009). Thus, to assess the remaining load-carrying capacity of deteriorated existing structures, models to estimate the remaining bond and anchorage capacity are needed.

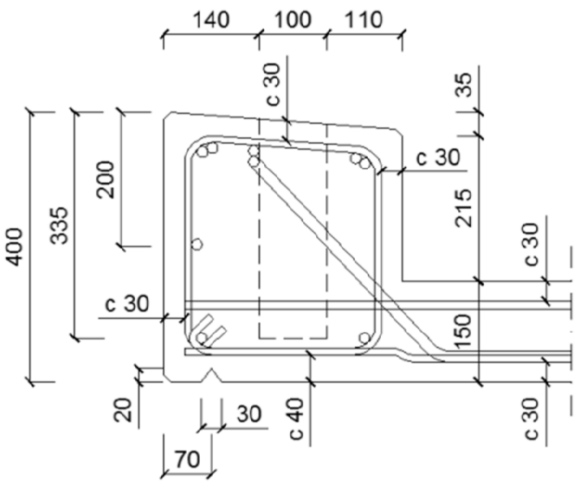
Existing analytical and numerical models of bond of corroded reinforcement have been developed based on experimental investigations of artificially corroded specimens. However, there are reasons to believe that the deterioration caused by natural corrosion does not have the same effects on the structural behaviour as the deterioration caused by artificial corrosion. Experimental evidences found in the literature show that common methods of accelerated induced corrosion may influence the bond capacity and change the anchorage behaviour, Saifullah et al. (1994), Austin et al. (2004). Remarkable reduction of the corrosion time from years to days is a rather strong justification for using accelerated induced corrosion in lab tests. However, a great care should be taken to interpret the results and extrapolate them to field conditions. In this study, the anchorage capacity of naturally corroded steel reinforcement was investigated experimentally. The test set-up was carefully chosen and designed by using non-linear finite element analysis, Berg & Johansson (2011). The bond and anchorage behaviour was examined through measurements of applied load, free-end slip and mid-span deflection.

2 EXPERIMENTS

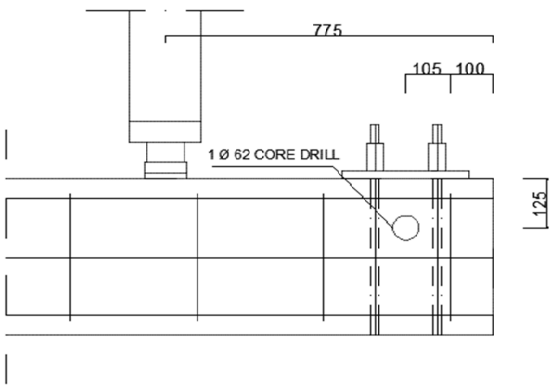
2.1 *Test specimens*

The test specimens were taken from the south side edge beams of Stallbacka Bridge in Sweden. The inauguration of the bridge took place in 1981, and it is thus only 30 years old. The severity of the deterioration has been increased by poor design of the bridge. The cantilevering parts of the bridge deck slab were too slender, and lack of secondary reinforcement in the slab forced the edge beams to work as load distributors, carrying more load than they were designed for. Loaded concrete structures normally crack; the edge beams are no exception. The cracks facilitate the chloride penetration of the deicing salt and the open cracks store up free water that increase the risk of severe frost damages. Cracks perpendicular to the construction joints of the slab accelerated the chloride penetration.

In Figure 1(a), the geometry of the edge beams is shown. They were 350 x 400 mm in cross-section, with a small inclination of the upper surface. The longitudinal reinforcement consisted of four bars Ø16 Ks60 bundled in pairs in the upper part, and two bars Ø16 Ks60 at the bottom. The transverse reinforcement consisted of Ø10 s300 Ks40. The longitudinal reinforcement bars closest to the upper inclined surface of the edge beams were more damaged than the other longitudinal bars as they were most exposed to de-icing salt. Therefore, they were considered to be more interesting in the investigation of bond and anchorage behaviour. The edge beams show different extent of corrosion-induced damage, from no sign of corrosion to extensive cover cracking resulting in spalling of concrete cover. Based on the damage patterns; the test specimens were categorized into three different groups: Reference (R) specimens, and Medium (M) and Highly (H) damaged specimens. The edge beams were reinforced, both longitudinally and transversally, with deformed bars, i.e. ribbed bars. In Figure 2, some examples of test specimens before testing are shown.

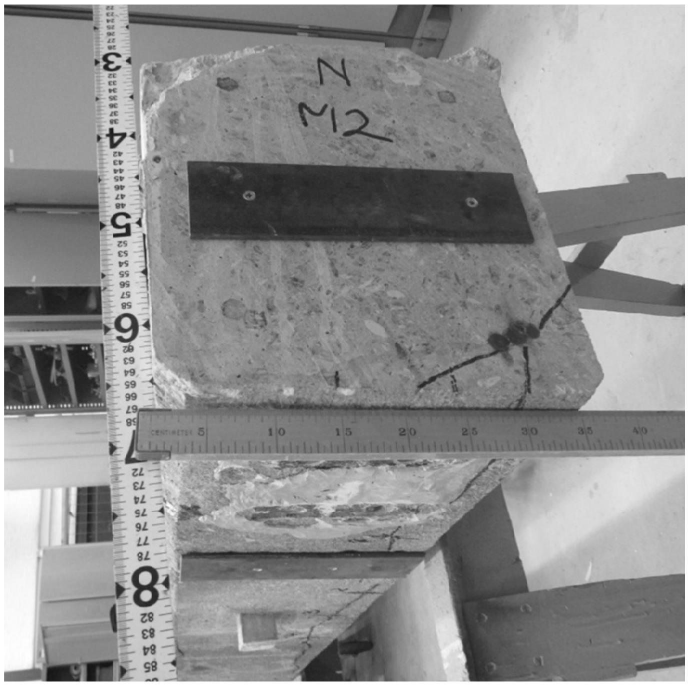


(a)

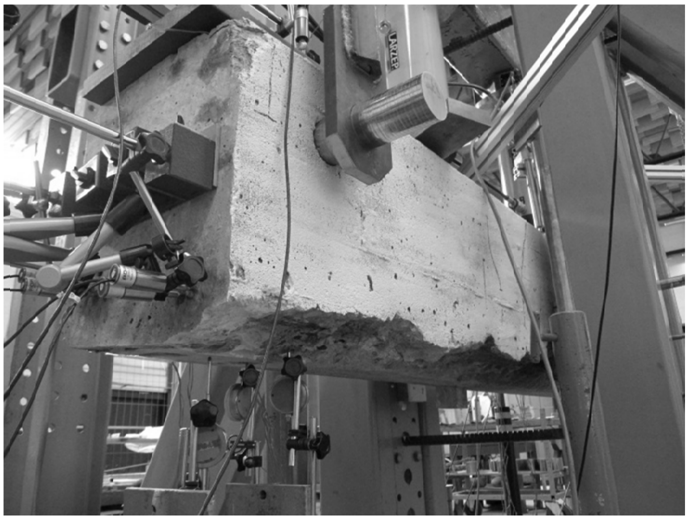


(b)

Figure 1. (a) Cross-section of the edge beams, (b) details of the test set-up and the strengthening bars.



(a) Medium Damaged M2



(b) Highly Damaged H1

(c) Highly Damaged H3

Figure 2. Photos of some of the test specimens before testing.

2.2 *Test set-up*

The test configuration was thoroughly designed to secure anchorage failure for beams with various corrosion damage levels in one common test set-up. Here only a short summary of the test set-up is provided; details of the test set-up design are given in Berg & Johansson (2011). For preparation of the test specimens, any significant modification to the geometry of the beams had to be avoided as it would have caused further damage to the concrete and steel/concrete interface. Consequently, many of anchorage test set-ups described in the literature were not practically feasible. Moreover, the corrosion-induced damage, i.e. cracking and spalling, appeared around the reinforcement for which the anchorage capacity was of interest. This means that no direct support against these surfaces was possible. In addition, the reinforcement bars in question were bundled, which made gripping of reinforcement for direct pull-out tests complicated. After consideration of different possible test setups, a four point bending test indirectly supported with suspension hangers was chosen, Figure 2.

The edge beams were positioned upside down when they were tested, thus the most corroded bars were loaded in tension. The chosen test set-up made it possible to evaluate anchorage capacity of beams with cover spalling. Moreover, there was the advantage of avoiding external transverse pressure acting in the anchorage region, i.e. along the transmission length. This was important as the major influence of corrosion on bond is that the confinement is reduced due to cracking and eventually spalling.

The edge beams were strengthened with transverse reinforcement around the suspension holes to avoid premature failure of the beam at the support suspension holes. Pre-stressing steel bars of Ø20 were used for strengthening. The strengthening bars were anchored at the top of the beam with hexagonal nuts and flat steel plates, Figure 1(b). The mechanical locking of the bars, by means of threaded coupling, was considered to provide adequate anchorage to avoid failure at the suspension hole. The bars were injected with epoxy.

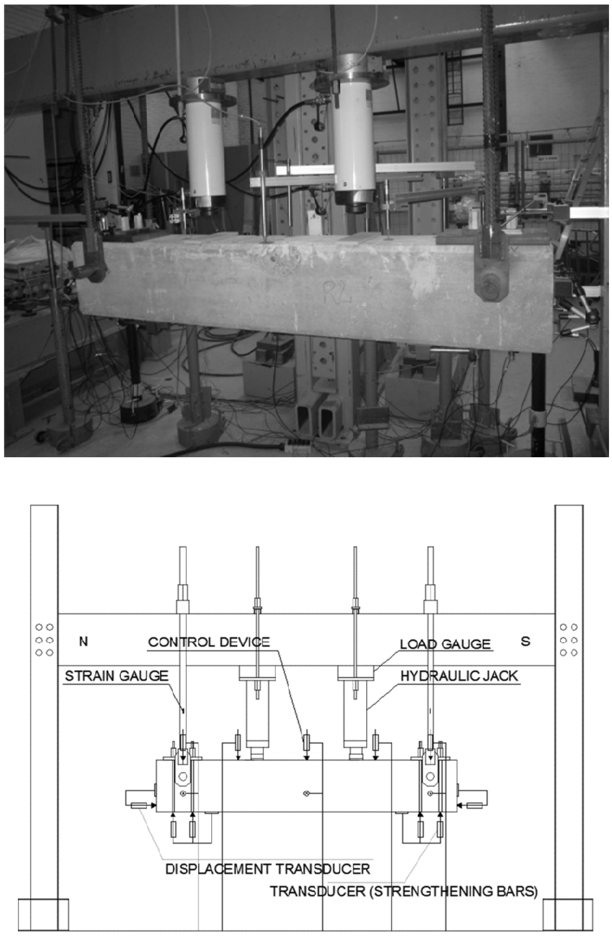
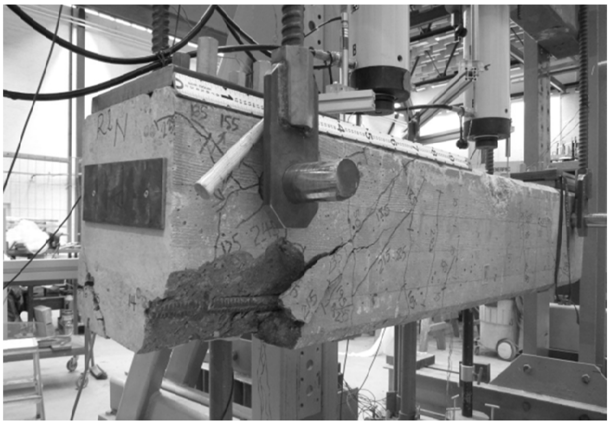


Figure 2. Photo and drawing of an indirectly supported four-point bending test.

3 RESULTS

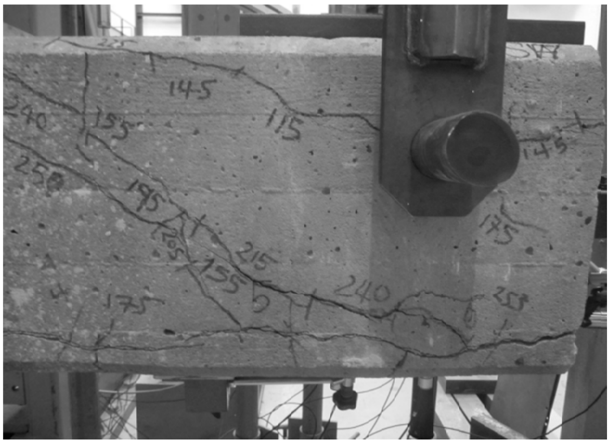
Eight test specimens were successfully tested. All the beams showed similar behaviour in terms of crack development and failure mode. The first flexural cracks occurred at around 80-110 kN near the centre of the beam. With increased loading, flexural-shear cracks then initiated in the shear span. The inclined shear cracks occurred at around 160-180 kN, see Table 1. Thereafter, the load continued to increase; this is when the anchorage was effectively loaded and the bond capacity came to play an important role.

The free-end of the tensile bars began to slip at a load level of about 190-200 kN and the final anchorage failure took place, on average, at a load level of 275 kN for the reference beams (R) and 240 kN for the damaged beams at both levels (M and H), see Table 2. As can be seen from the values of the failure loads in Table 2, the scatter was larger for the highly damaged beams. Photos of some of the beams after they were tested are shown in Figure 3; as can be seen splitting cracks occurred around the main bars at failure.



(a) Reference specimen R2

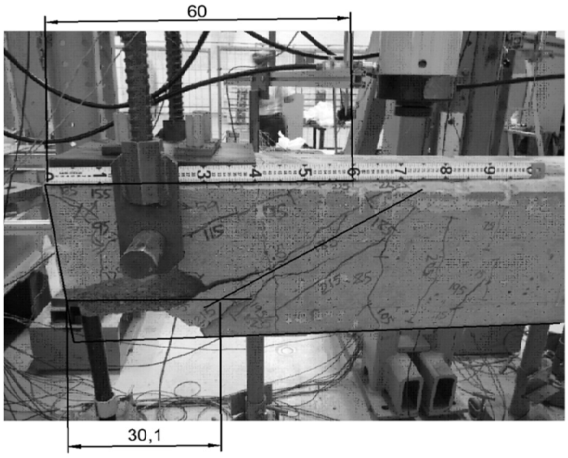
(b) Medium Damaged M2

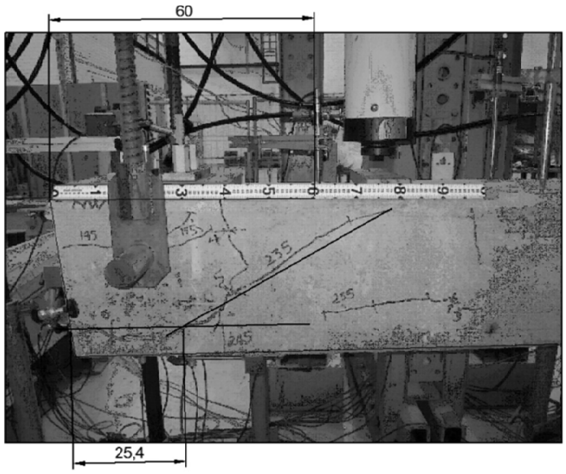


(c) Highly Damaged H3

Figure 3. Failure and crack pattern of some of the beams after testing.

After the tests, the available anchorage length was evaluated from the crack pattern. It was measured from the point where the main bars and the inclined shear crack intersect, to the end cross section, see examples in Figure 4. Only the half of the beam that failed was considered; however there the available anchorage length was evaluated on both back and front side. The average of back and front side are given in Table 3. As can be seen, the available anchorage length show only small variations; thus the position of the shear crack was governed more by the load arrangement than the corrosion level. Therefore, the variation in failure loads can be seen directly as variation in anchorage capacity. Thus, from the results in Tables 2 and 3 it can concluded that the anchorage capacity was reduced in the corroded specimens compared to the reference specimens, with around 10% higher anchorage capacity for the reference specimens than for the damaged ones. Furthermore, the scatter in anchorage capacity increased with increasing corrosion level.





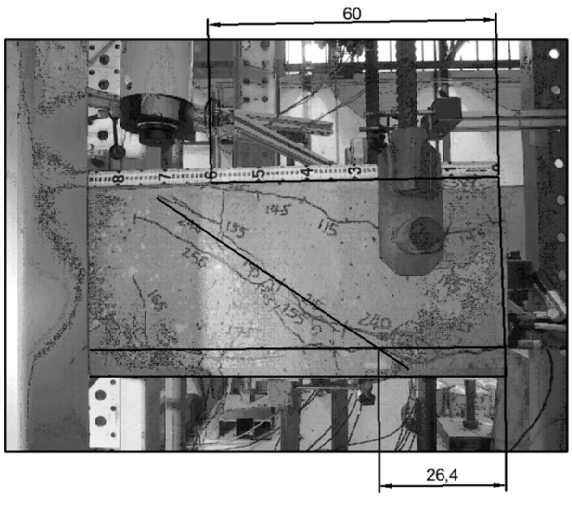


Figure 4. Available anchorage length in some of the beams; measured from the end cross section to the point where the main bars and the inclined shear crack intersect.

Table 1. Load levels corresponding with the initial inclined shear cracks observed during the tests.

Beam No.	(1)	(2)	(3)
Units		kN	
Reference beam (R)	160-170	175-185	-
Medium Damage (M)	185-195	225-235	215-225
Highly Damaged (H)	170-180	165-180	155-175

Table 2. Maximum failure loads obtained in the experiments.

Beam No.	(1)	(2)	(3)	Average	Standard Deviation
Units			kN		
(R)	270.1	281.2	-	275.6	7.9
(M)	234.9	243.8	250.2	243.0	7.7
(H)	255.4	225.1	244.4	241.6	15.4

Table 3. Available anchorage lengths in the experiments; the given values for each specimen are the average of the measured anchorage length on both edges of the failure zone.

Beam No.	(1)	(2)	(3)	Average
Units		cm		
(R)	29.4	30.5	-	30.0
(M)	31.4	27.2	34.1	30.9
(H)	32.2	29.7	27.3	29.7

4 CONCLUSIONS AND OUTLOOK

Eight edge beams with varying levels of natural corrosion damage were tested in indirectly supported four-point bending tests. In all tests, diagonal shear cracks preceded a splitting induced pull-out failure; i.e. anchorage failure was achieved as intended. The preliminary results show around 10% higher load-carrying capacity for the reference specimens than for the damaged ones. Since the available anchorage length was about the same for both corroded and uncorroded specimens, this corresponds to around 10% higher anchorage capacity in the undamaged specimens than in the corroded ones. Medium and highly damaged beams; i.e. beams with corrosion cracks or cover spalling respectively, had about the same average values of maximum failure loads, but with a larger scatter in results for the highly damaged group.

Since quite large scatter can be expected in this type of work with test specimens taken from an existing bridge, more tests will be carried out. In a second series, specimens from the north part of the Stallbacka Bridge will be tested. The tests will produce benchmark data of anchorage of naturally corroded reinforcement. They will be evaluated with detailed nonlinear finite element modelling, using the bond and corrosion model developed in Lundgren (2005) and further developed in Zandi Hanjari *et al*. (2011). Through comparing results such as load versus deflection and free end-slip, and crack pattern, more detailed information on how the local bond-slip is affected by natural corrosion will be obtained.

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