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DUCTILITY OF CONCRETE AFTER DECADES: PRELIMINARY RESEARCH ACTIVITY

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ABSTRACT

The effect of corrosion on steel to concrete bond is investigated through pull-out and beam tests on artificially corroded reinforced concrete specimens. The result of this preliminary experimental program is the definition of correct conditions for evaluation of corrosion effects close to those in existing structures.

KEYWORDS

Corrosion; bond tests; reinforced concrete; deformed bars; cracking.

INTRODUCTION

One of the recurrent sources of structural damage in reinforced concrete is the corrosion of the reinforcement bars. Even when confined to limited elements, corrosion has notable consequences both in the aesthetic and the structural realm. Potentially it may affect the safety conditions of the entire structure.

On a single element the structural effects are :
- a reduction of the resistant section of the bars;
- a reduction of the resistant section of the concrete caused by the formation of cracks, and the cover spalling or delamination;
- a reduction of the steel to concrete bond.

The aim of this present research work is to examine the last aspect, by measuring bond in reinforced concrete beams, in the presence of reinforcement corrosion. The reproduction in laboratory of a corrosive process, representative of what takes place in nature, has been the first target.

The influence of bond deterioration on the strength and ductility of reinforced concrete structures has been brought to notice more than 10 years ago. In a beam to column joint, when the flexural moment is accompanied by a shear action superior to 10 kg/cm^2 a decrease in resistance can be observed after a few load cycles, ascribed to the slips between reinforcement and concrete. The degradation is made evident by the "racketing" of the moment to curvature cycles.

In the laboratory repetition, bond degradation becomes evident when a few percent of the steel cross section is corroded, i.e. well before the reinforcing resistance is meaningfully affected. It is thus one of the first items to concern the structural durability of r.c. constructions.

EXPERIMENTAL ACTIVITY

Materials and tests

Three series of reinforced concrete specimens were prepared, each composed of 4 cubes for pull-out tests, and 6 pairs of beams, for beam tests.

The materials are:
- deformed Fe B44 steel bars, 14 mm in diameter;
- concrete, enriched with 2% chlorides to the weight of the cement, with the aim of accelerating the electrically induced corrosion;
- water/cement ratio 0.64;
- Portland cement CEM I 42.5, 250 kg/m^3;
- density at 28 days, 2450 kg/m^3;
- compression resistance at 20 and 90 days, respectively 360 and 418 kg/cm^2.

The cubes for the pull-out tests are 20 cm wide, one single bar cast into the concrete, with a 90 mm cover. Plastic tubes fixed round the bar keep the reinforcement adherent to the concrete in a central tract only, 6 cm in length, equal to 4 times the diameter of the bar.

The beam pairs for the beam test, in conformity to the ASTM (bond test on deformed steel bars) are confined by stirrups and supplementary longitudinal bars; this type of reinforcement has been prepared in two different percentages: 1) according to the ASTM provision, and, 2) reduced to 50% in the transverse and longitudinal bars. Specimens of this second series have been prepared with the intention of reproducing a confinement condition as close as possible to that of the of an operative condition. The volumetric percentage of confining reinforcement is thereby reduced from the 1.5 % (in the vertical and horizontal sense), as prescribed by the ASTM, to 0.75%. The concrete cover is 50 mm. By means of plastic tubing placed around the bar, the reinforcement is made to adhere to the concrete in a central tract only, 10 diameters in length.

Artificially accelerated corrosion

A direct electric current from the bar (Fig.1), anode, to the concrete, is used to accelerate corrosion, reckoning the penetration of corrosion by way of the circulated current. A current density equal to 1 mA/ m^2 causes a dissolvence of the steel to about 1.17 µm/year. By monitoring the current and the charge flowed, it is thus possible to control the speed and depth of the attack. However the current density should not exceed 0.5 A/ m^2. A higher density could damage, by mechanical effect, the cohesion between steel and concrete, therefore emphasising the effect of the selfsame corrosion, (Cabrera, 1991). By limiting the current density we achieve an attack depth of 10 µm/week, which value was checked subsequently by optical and ponderal measurement. The final corrosion levels were 50, 100, 150 µm in the first series of tests, and 50,100, 150, 200, 300 µm in the second and third series.

Corrosion conditions so obtained may differ from the natural ones, as a part of the products of corrosion tends to be distanced from the beam depending on the intensity of the flow of current and its uniformity. Comparative tests in natural corrosion conditions are being made, the results of which will begin to be available in two years' time.

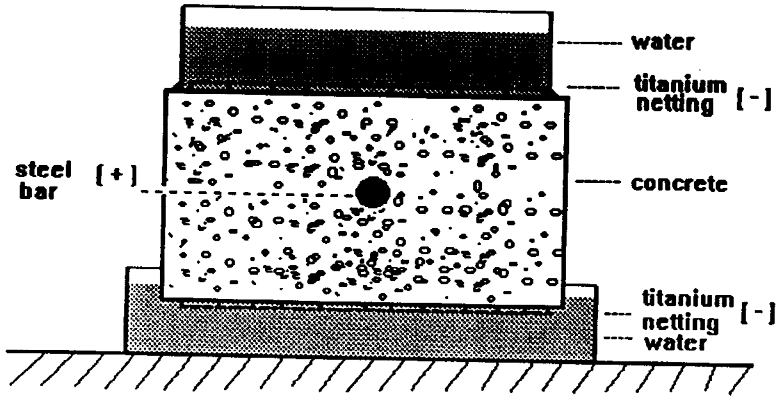


Fig.1: Set up for artificial corrosion.

Test apparatus

Bond has been calculated by different testing procedures. On the cubic specimens the pull-out test was carried out. The beam pairs were tested by two distinct procedures:
- the first, in conformity to the ASTM prescriptions (beam-test), uses both beams (Fig.2); the longitudinal reinforcement is submitted to a known tension at the center, and the free ends have no loading.
- the second procedure involves the single beam (Fig.2); the longitudinal reinforcement at one end undergoes compression and at the other end tension (push-in/pull-out). In theory compression and tension reach the same absolute value.

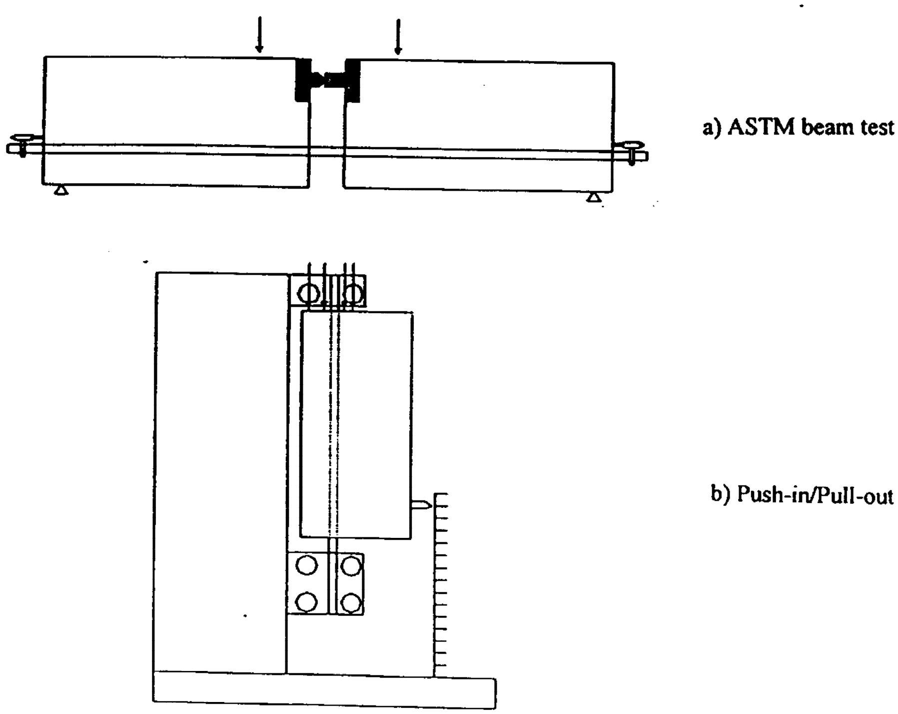
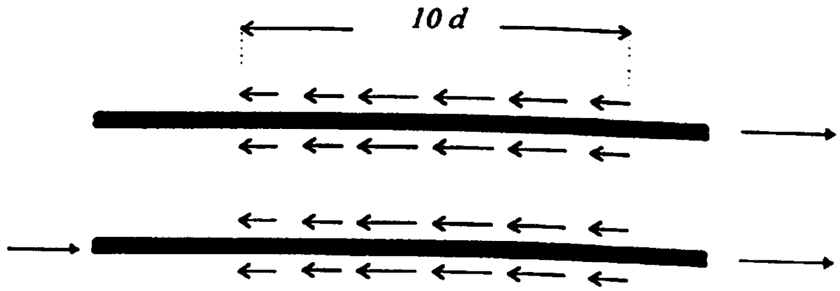


Fig.2: Test set up.

The forces and bond stresses acting on the bar are as follows:

1st procedure

2nd procedure



Loads are applicated by controlling the force. Transducers measure the relative slip of the bar with respect to the concrete. The load is increased until the maximum bond force is overcome. The specimens of the first series were subjected only to the pull-out tests and to the beam-test of the first procedure. The choice of the second procedure (push-in/pull-out), adopted for the specimens of the second and third series, is due to the fact that, with the chosen materials, the slip of the reinforcement in the beam test takes place around the yielding of the steel, and in some states of oxidation could not have taken place with the first test procedure.

RESULTS

Pull-out tests

Tab.1 summarises the results in relation to the level of corrosion. The nominal bond stress is calculated by assuming the bond stresses uniformly distributed along the adhering tract of the reinforcement:

$$\tau = P_{max} / (2 \pi r L) \tag{1}$$

where:
- τ = bond stress,
- P_{max} = maximum load during the test,
- r = nominal bar radius,
- L = length of the adherent tract

Tab.1: nominal bond stress (N/mm^2); pull-out tests results

corrosion (micron)	1st series	2nd-3rd series
0	10.98	10.96
50	18.18	17.05
100	28.04	28.42
150	31.83	31.07
200		34.10
300		29.36

The stress values show an increasing progress with the level of corrosion, whether in the first series (from 0 to 150 μm corrosion) or in the second and third series (from 0 to 300 μm corrosion). Only at the level of 300 μm, a marginal inversion of the tendency may be observed. The increase of bond with the level of corrosion is ascribed to the expansion of products of corrosion, that promote an internal pressure, and modify the morphology of the steel to concrete interface.

Beam-tests and push-in/pull-out

In the first test procedure (beam-test) the recorded bond stresses are corresponding to slip values equal to 0.01, 0.1, 1 and 3 mm, and the average of the first three values, according to the ASTM prescriptions.

Tab. 2: Nominal bond stresses (N/mm^2) 1st series (reduced confinement), beam-test procedure. Some tests were not considered significant as, in correspondence to the yielding of the steel, there was no slip of the reinforcement.

corrosion (μm)	$\tau_{0.01}$	$\tau_{0.1}$	τ_1	τ_3	τ_m
0	9.57 9.43	11.16 11.97	15.083 -	11.65	11.93
50	10.71 9.17	12.69 12.72	12.89 14.33	11.29 12.34	12.09 12.04
100	10.71 10.19	13.86 13.66	15.55 12.66	13.89 10.66	13.37 12.17
150	11.03 9.72	15.48 14.91	15.37 15.28	13.06 -	13.96 13.30

As regards the push-in/pull-out procedure the nominal stress values are shown in tab.3:

Tab. 3: Nominal bond stress (N/mm^2), 2nd and 3rd series, push-in/pull-out procedure.

Corrosion (μm)	reduced confinement	full confinement
0	21.17	19.48
50	23.126	-
100	23.98	-
150	25.62	-
200	26.71	-
300	28.3	28.42

With the increase of corrosion level the bond values increase, tab.2 and 3. The comparison between the results obtained through the beam tests and the push-in/pull-out at equal corrosion levels, shows higher values in the second test procedure, with an increase of about 100%. The increased resistance can be explained considering the distribution of the bond stresses in the two tests, as has come to light through numerical analyses. With equal values of τ_{max}, the average value in the second case is higher than in the first. In the second procedure, moreover, there is an induced compression orthogonal to the bar, that is more uniform in the longitudinal sense and of higher intensity than in the first procedure.

Malvar (1992) reports an increase in bond of compressed bars, due to the lateral expansion by the Poisson effect. This contributes to justify the increase in bond in the second procedure, where half of the bar is under compression with respect to the beam-test, where the bar is only under tension. This effect may be quite important when the bar is around yielding. The nominal stresses corresponding to tab.3 bond stresses are around 600 N/mm^2, so that the steel is well into the hardening range. The Poisson modulus reaches the theoretical limit value 0.5, and the lateral expansion (in the compressed portion of the bar) is emphasized.

Microscopic observation on corroded specimens

The superficial aspect of attack on reinforcement and the distribution of the products of corrosion inside the concrete, in the artificially corroded specimens, have been observed under microscope (Pedeferri *et al.*. 1993). The surface of the bar appears to be completely covered by corrosion products. The attack regards the whole surface in contact with the concrete. However it is not uniform, and there is evidence of small pitting.

The corrosion products generally tend to accumulate in an area around the reinforcement. They are distanced, by about half a centimetre, where there are micro-cracks, formed during the attack, or micro-cavities formed during the casting. Micro-cracks and the disposition of the products of corrosion allow us to assess that conditions similar to those in natural corrosion have been reached, which generally occurs as a result of the carbonatation of the concrete cover.

In addition to the micro-cracks formed in the vicinity of the reinforcement, observing the transverse section of samples corroded up to 150 μm, the presence of a longitudinal crack of a width around 1/10 mm has been noted. The crack is directed from the main reinforcement towards one of the longitudinal bars confining the specimen, close to one of the corners. Internally the corrosion products extend up to 2-3 cm from the bar. Observation of a beam corresponding to a level of corrosion at 300 μm evidences the presence of numerous cracks of this type, as shown in Fig.3.

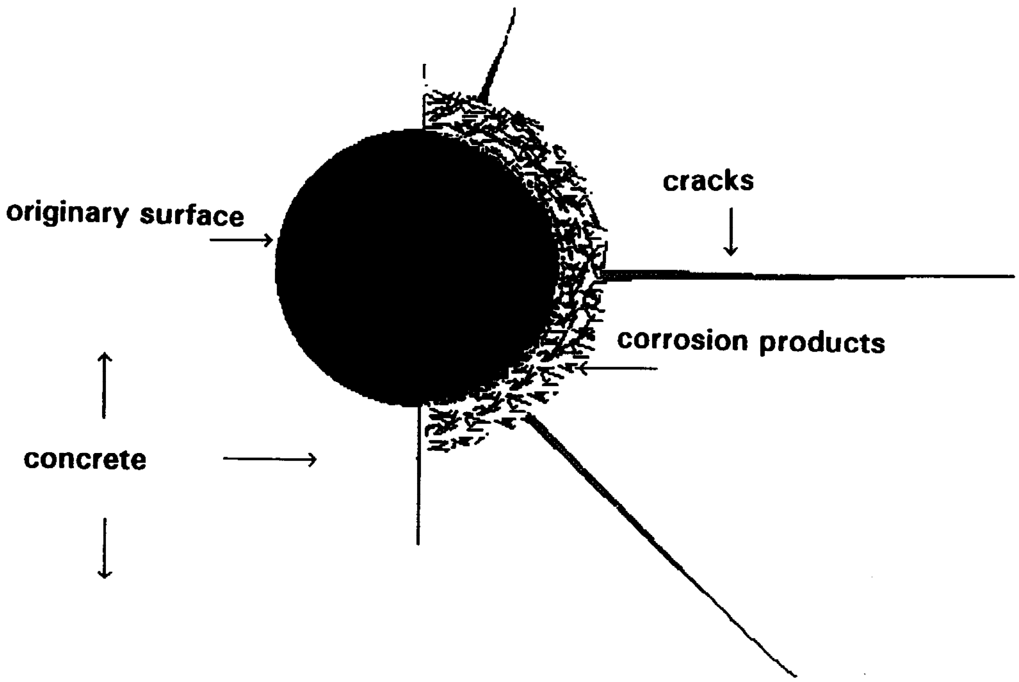


Fig.3 : Corrosion product distribution around the bar.

Alongside this type of crack in which corroded products are present, cracks void of products, and thus produced by mechanical action during testing, can be identified. These cracks are principally orientated in three directions, towards the two lateral faces and to the lower face of the sample.

Observations carried out on sections of cubes subjected to pull-out testing have shown that corroded matter tends to remain around the reinforcement. Only in the case of 300 μm corrosion levels a few small cracks have been observed, fanning out from the reinforcement, about 1 cm in length, and containing corrosion products.

COMMENT ON RESULTS

An important yield of the research has been that of defining experimental conditions able to reproduce corrosion conditions similar to those encountered in nature. Moreover the experiment has revealed the limitations to the bond testing procedure. From a practical viewpoint they are scarcely representative of conditions to which bars are exposed in buildings. This, both as regards the formation of cracks due to corrosion, or to the effects of slip caused by bond deterioration. Both effects principally depend on the extent to which a bar is confined, and therefore on the thickness of the concrete cover, and on the lateral reinforcing. In working conditions it is necessary for the flexural reinforcement to be close to the surface of the element, and therefore to have a limited covering. In both standard tests the bar has respectively 9 and 5 cm cover, and in these conditions corrosion does not cause cracks which extend to the surface.

Moreover there are uncertainties which are intrinsecal to the measurement of such effects. Andrade *et al.*. (1993), found experimentally that with 2 cm cover and ϕ 16 bars, in the absence of transversal confinement, 15 μm corrosion are sufficient to produce the first crack visible on the surface. In similar experimental conditions, but with 8 mm bars and 16 mm cover, Clark *et al.*. (1994), found that the level of corrosion that can produce cracks on the surface is about 100 μm. Basing our calculations on these results we can estimate that in our experimental conditions we would obtain cracks on the surface with about 400 μm corrosion, which value tallies with estimates drawn from our experience.

As for the effects of corrosion on bond, the results reported by various authors differ greatly, principally because of the conditions of corrosion obtained (Fig.4).

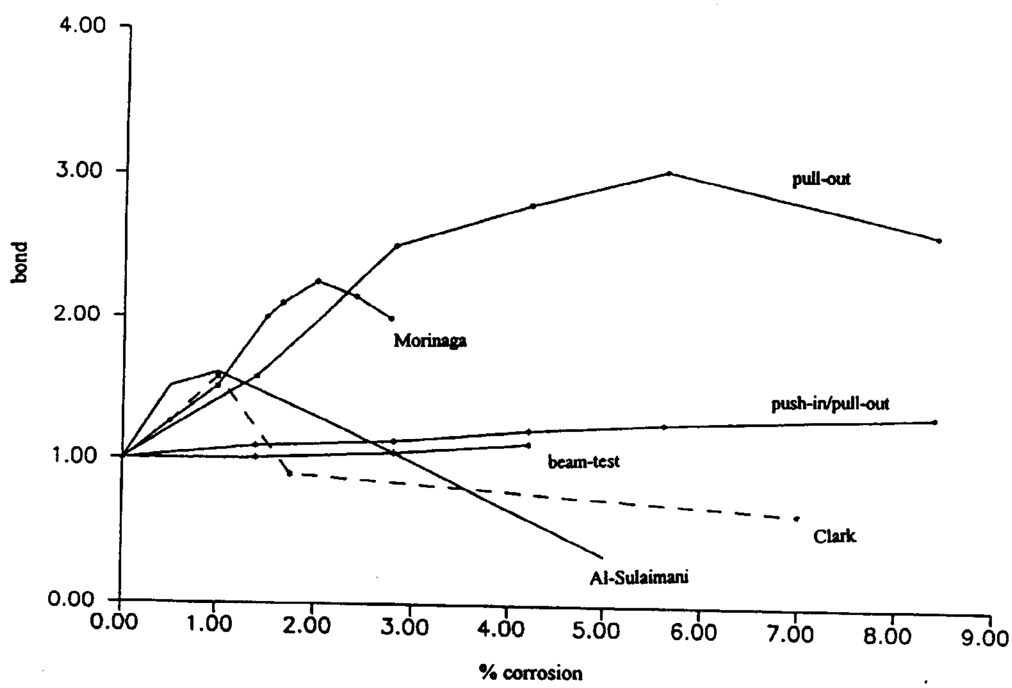


Fig.4 : Nominal stress values (normalized to the value without corrosion) in relation to corrosion levels (% loss in volume).

Al Sulaimani *et al.*. (1990), Cabrera *et al.*. (1992), Clark (1994), Morinaga (1988), report that within a certain level of corrosion there is an increase in bond resistance, with values 1.7-2 times the original. Beyond that corrosion level bond diminishes rapidly, below the value which corresponds to a new bar. This level is equal to 80 μm according to Clark and Al-Sulaimani, with 16 mm coverage, and equal to almost the double according to Morinaga.

In the present experience, for each type of test (pull-out, beam-test, push-in/pull-out), an increase of bond with the level of corrosion is observed. A variation of tendency can be observed with corrosion levels at around 300 μm.

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