Failure Of Prestressing Steel Induced By Crevice Corrosion In Prestressed Concrete Structures

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Summary: The application of prestressed concrete technology in civil structures is relatively recent. Therefore, the existing prestressed concrete members in such structure are still relatively young, and the corrosion and the concrete deterioration problems associated with this type of concrete members have became clearly evident only in the early 1980s. Damage during service, frequently appearing after several years or decades of exploitation, is usually most consequential. The lacking or insufficiently alkaline protection already from the beginning or its loss due to carbonation and/or depassivation after chloride attack are the major causes of later damage or even of a failure. Steel wire strands, due to their structure, usually consisting of steel wires helically laid about a core centre, frequently another wire, may be subjected to crevice corrosion even if they are well grouted with uncarbonated mortar but in presence of a little amount of chloride ions. Crevice can occur also in cable to duct (metal or plastic ducts) contacts. Crevice condition easily promotes a drastic change in local environmental composition, that is a pH reduction and an increase of chloride concentration. In such a condition steel strand failure due to hydrogen embrittlement can occur. Experimental results obtained in calcium hydroxide solution with added potassium chloride in simulated crevice condition on stressed steel strands, showed crack formation after only 1250 hours. Chloride concentration was lower than the critical amount to induce pitting corrosion or generalized corrosion at that pH (12.4), whilst was enough to induce extended crevice corrosion. In some case crevice attack was so intense to reduce drastically steel wire cross section.

Keywords: Prestressing steel, corrosion, crevice, cracks, failure

1 INTRODUCTION

The application of prestressed concrete technology in civil structures is relatively recent. Therefore, the existing prestressed concrete members in such structure are still relatively young, and the corrosion and the concrete deterioration problems associated with this type of concrete members have became clearly evident only in the early 1980s. Although prestressed concrete members were generally manufactured with concrete of relatively higher strength, time has shown that they are subject to the same adverse effects of reinforcement corrosion as reinforced concrete members are. Documented cases of prestressed tension members failure as a result of corrosion make this a most pressing problem. Since prestressed concrete members rely on the tensile strength of the prestressing steels to resist loads, loss of even few wires or strands per member could result catastrophic.

Damage during service, frequently appearing after several years or decades of exploitation, is usually most consequential. The lacking or insufficiently alkaline protection already from the beginning or its loss due to carbonation and/or depassivation after chloride attack are the major causes of later damage or even of a failure. Responsible for that are usually the failures caused by shortcomings in planning and/or execution as well as inaccurate or inefficient structural measures. Execution faults and construction errors concern e.g. the injection of the ducts with mortar in case of post tensioned concrete (a mortar-free section of prestressing steel is exposed to the risk of corrosion, when penetration of moisture is possible and oxygen can enter the duct space), the concrete technology (too small concrete cover and too low concrete quality, under certain conditions not protect prestressing tendons or prestressing steel), the procedure (technology) of the production of the structural elements, as well as waterproof sealing (not present or damaged) and drainage (damaged), that can lead to strong salt contamination of concrete, and very seldom the development of cracks outside and inside the coupling joint of prestressed bridges.

The up to then most spectacular damage in the prestressed concrete structures occurred in 1980. It was the collapse of the southern outer roof of the Berlin Congress Hall occurred 23 years after its constructing. The damage was primarily caused by corrosion-initiating and corrosion-promoting conditions in a part of the roof structure (Rehm *et al*. 1981).

Probably the most frequent occurrence of corrosion related problems on bridge structures as a consequence of planning and execution errors, is on post-tensioned precast segmental bridges. The first serious problem with corrosion of bonded post-tensioned bridges occurred in U.K. in the mid-1960 when the Bickton Meadows footbridge collapsed in Hampshire (Concrete Society 1996). This structure was a segmental post–tensioned construction type, and collapsed without warning under its own self-weight after only few years of service. Collapse occurred as a result of severe corrosion of the top tendons.

Then, in the 1980s, two bridges were found with serious problems: the Taf Fawr Bridge on the A470 in Wales and the Angel Road Bridge on the A406 North Circular in London. Soon, problems had been identified in other bridges, the most serious being the collapse of the single-span segmental post-tensioned Ynys-y-Gwas bridge in Wales in 1985 (Woodward and Williams 1988). The collapse of the bridge was due to corrosion of longitudinal tendons at the segment joints. The mortar at the joints was highly permeable and allowed moisture, chlorides, and oxygen ready access to the tendons. The structure was 32 years old with no evidence of distress prior to failure.

Finally, studies by the British Department of Transportation concluded in 1992 that there was currently no method to guarantee the grouting process and further work was needed. It was on 25 September 1992 that the Department of Transportation effectively banned post-tensioned grouted duct techniques from UK bridge construction. The moratorium was partially lifted only in the 1996 with the exception of segmental bridges constructed from precast segments, because there were still some reservations about the corrosion protection of the tendons where they cross the joints (Lewis 1996).

The UK was not the only place with problems. The post tensioned Melle Bridge built across Schelde in Belgium in 1956 collapsed early in 1992. The collapse was traced to corrosion of the ducted post-tensioning wires and, most worryingly, the bridge had been inspected, load tested, given a clean bill of health, re-waterproofed and restored to service just two years before (Concrete Society 1996).

Two very recent bridge collapses can be related to corrosion of prestressing steel: Saint Stefano bridge collapse in Italy in 1999 (Proverbio & Ricciardi 2000) and Lowe's Motor Speedway footbridge in North Carolina (USA) in 2000 (Goins 2000).

Failure of prestressing steel in prestressed concrete structures is usually induced by corrosion. The most simple failure case is present when the high-strength steel fails because its notched-bar tensile strength in the region of corrosion pits has been exceeded. In such a case the failure has a brittle character. In practice such a pure brittle failure in case of prestressed concrete it is relatively seldom. The necessary condition of notched-bar tensile strength being smaller than the actual steel stress requires namely pit depth of at least 1 mm.

Fracturing of prestressing steel in structures is predominantly attributed to hydrogen- induced stress corrosion cracking (Nurnberger 1997). Hydrogen formation and absorbtion on steel surface is promoted by different corrosion conditions:

- activation or depassivation of certain regions of steel surface;
- localized corrosion (pitting corrosion);
- presence of certain substances (so-called promoters), which hinder the recombination of the atomic hydrogen to molecular hydrogen (such as sulphur, arsenic, thiocyanate and selenium compounds, which are in practice frequently found in concrete constructions).

Studies on behaviour of prestressing steel (cold drawn eutectoid steel) in $NaHCO_3$ solution, simulating carbonated concrete, was carried out by Alonso *et al*. (1993), showing that such steel is very susceptible to stress corrosion cracking (SCC) in carbonate-bicarbonated environment as a function of bicarbonate content.

Steel wire strands, due to their structure, usually consisting of steel wires helically laid about a core centre, frequently another wire, may be subjected to crevice corrosion even if they are well grouted with uncarbonated mortar but in presence of a little amount of chloride ions. Crevice can occur also in cable to duct (metal or plastic ducts) contacts. Crevice condition easily promote a drastic change in local environmental composition, that is pH reduction and increase of chloride concentration. In such a condition steel strand fracture due to hydrogen embrittlement can occur. Aim of this work is to investigate, by deep microscopy investigation, the evolution of corrosion phenomena on stressed cold drown steel wires subjected to crevice condition in calcium hydroxide saturated solution in presence of chloride.

2 EXPERIMENTAL METHODS

The material used was a 3/8" seven steel wire strand in cold drawn and stress relieved state. The chemical composition and properties are described in Table 1

Table 1. Chemical composition and properties of the steel used

Chemical analysis (wt%)		Mechanical properties	
Carbon	0.81	Ultimate tensile strength	1940 MPa
Silicon	0.22	1 % proof stress	1750 MPa
Manganese	0.67	% elongation	5.5
Phosphorus	0.007		
Sulphur	0.004		
Copper	0.09		
Chromium	0.05		
Nickel	0.05		

Two different testing conditions were used. “Single wire” condition and a “bundle” condition. In the first case as received single steel wires (central wires extracted by a strand) with a diameter of 3.19 mm and a length of 150 mm were subjected to bending condition on glass reinforced plastic beams as shown in Figure 1. Wire deflection was imposed in order to reach in the middle section of the wire a stress equal to 0.8 time the UTS. Wires were kept bent by means of plastic strips, crevice condition were obtained by inserting a Teflon ring in the middle section of the wire. Samples were then immersed in a calcium hydroxide saturated solution (pH 12.4) closed to air (solution T), potassium chloride was added to the solution up to a concentration of 0.2 M. In such a condition it was obtained a OH^-/Cl^- ratio less than the critical value to induce pitting corrosion (Andrade *et al*. 2001), but a chloride concentration sufficient to allow crevice corrosion occurrence. An electrical connection shielded by epoxy resin coating was made on each wire in order to monitoring electrochemical potential during the time.

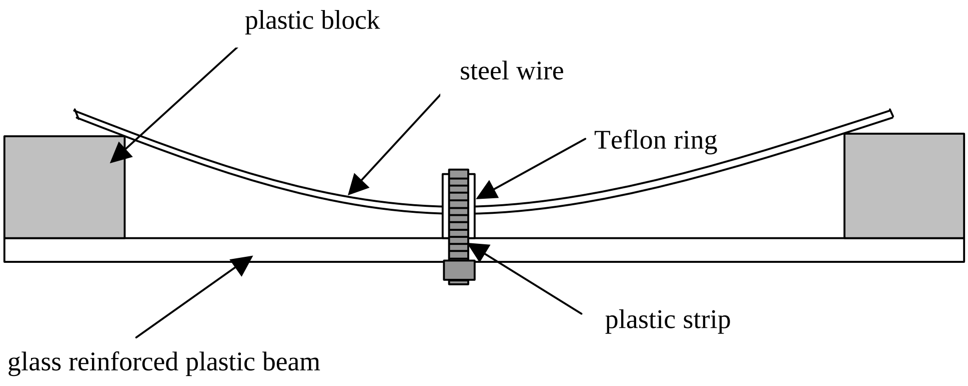

Figure 1. Scheme of steel wire loading and crevice induction set up

As a reference, in order to evaluate hydrogen embrittlement susceptibility, identical samples were immersed, at room temperature, in the solution A indicated in the ISO/DIS 15630-3 (Steel for reinforcement and prestressing of concrete – Test methods – Part 3: Prestressing steel). Test conditions are summarized in Table 2.

Table 2. SCC susceptibility test condition after ISO/DIS 15630-3

Solution composition	Test condition
5 g of $SO_4^{=}$ (as K_2SO_4), 0.5 g of Cl^- (as KCl)	Constant axial load equal to 0.8 UTS
and 1 g of SCN- (as KSCN) for 1 litre of solution	50±1 °C

Test in the bundle condition were performed by immersion in the solution T portion of seven steel wire strands, obtained by cutting 250 mm long pieces form the as received prestressing cable. Each bundle was secured on the extremities by plastic strips to avoid its opening. Such tests were performed to evaluate crevice occurrence between steel wires in condition similar to in field application.

3 EXPERIMENTAL RESULTS

Free potential versus time of steel wire during the tests is reported in Figure 2. After stabilization, and depending on crevice corrosion initiation time, free potential values ranged between –540 and – 470 mV (vs SCE). Such values lied well above the limit indicated by the equation proposed by Andrade *et al.* (2001) for critical chloride content for pitting initiation (Figure 3)

$$E_p = 310 \cdot \log\left[Cl^- / OH^-\right] - 15 .$$

No corrosion attacks were in effect evidenced on free steel surface after solution removal. Immersion test were ended after about 54 days (1280 h) even if no complete steel wire failures were observed. After removal of Teflon ring strong crevice attack was observed on some samples. Before samples observation corrosion products were removed by means of Clarke's solution (ASTM 1981).

A typical crevice attack was shown in Figure 4. Where crevice attack was particular intense complete disruption of steel occurred, corrosion being strongly influenced by steel drawing direction. No evidence of other type of corrosion damages were observed on such areas. Where crevice attack was less pronounced transversal cracks on steel surface were observed. Cracks were comparable for extension, and in some case for penetration depth, to those one observed on sample tested in solution A (thiocyanate solution) as shown in Figure 6.

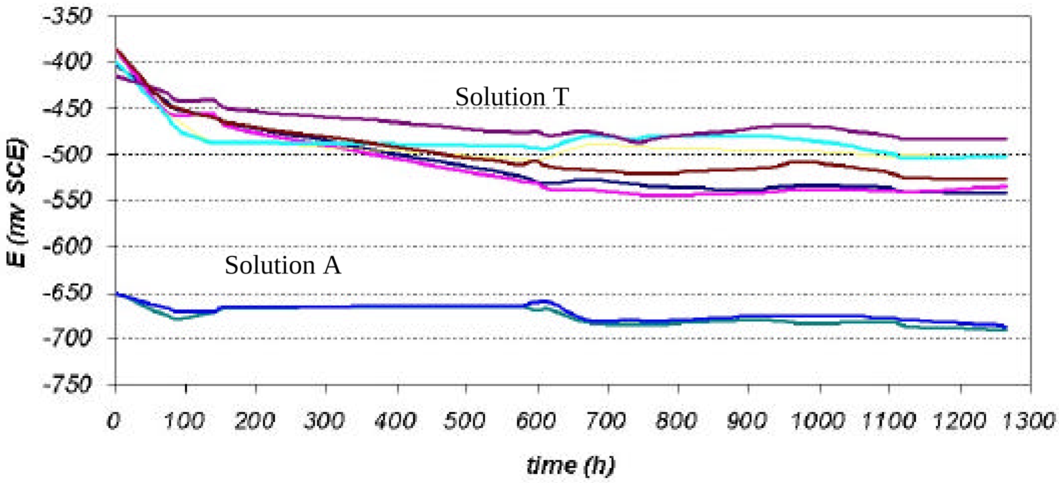

Figure 2. Free corrosion potential of steel wires in solution T and A.

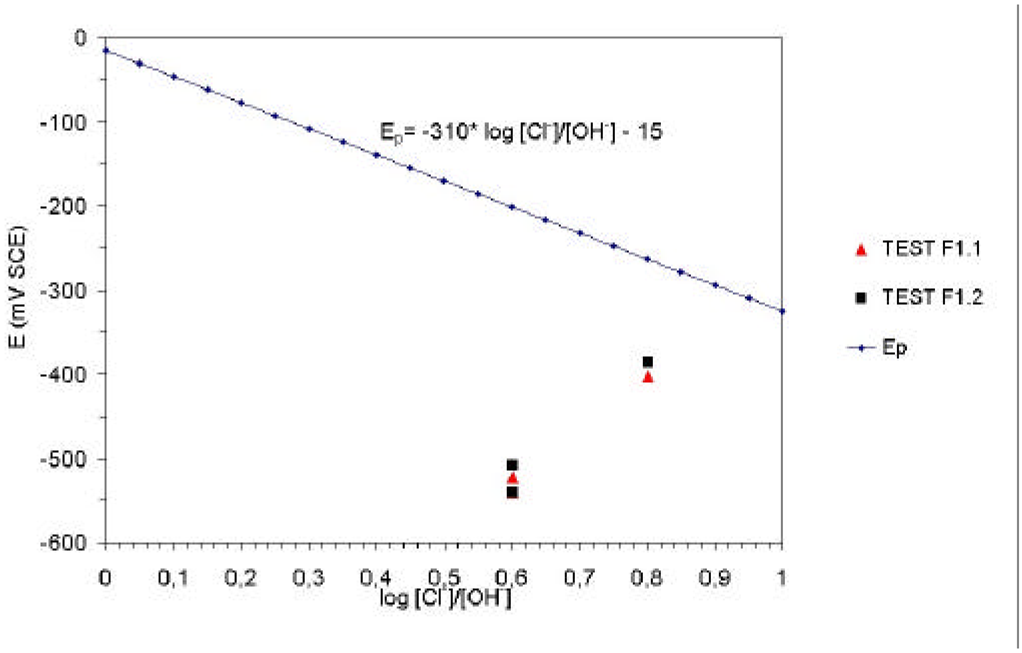

Figure 3. Free corrosion potential of steel wires in solution T vs log[Cl-]/[OH-]

No corrosion attack was observed on free steel surface of wire strand ("bundle" condition) as removed from solution T, unbinding steel wires revealed crevice corrosion development on contact surface between inner wires, corrosion attack being concentrated on an helical line following wires disposition (Figure 7). Strands were however not subjected to bending condition due to difficulties encountered in applying a sufficient stress to the samples without causing wire opening, so it was not possible to evaluate the influence of stress on evolution of corrosion attack for such type of samples.

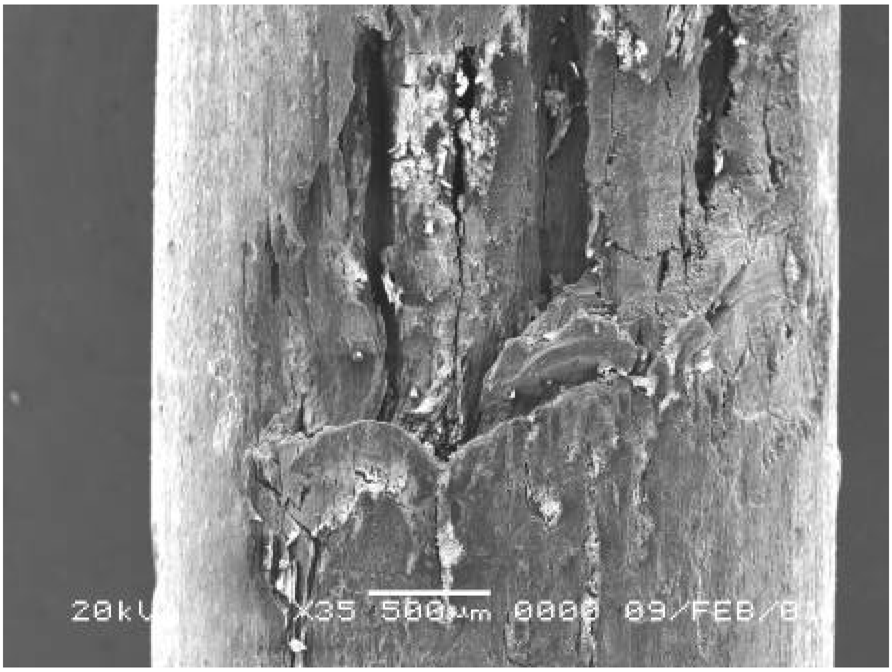

Figure 4. Crevice corrosion attack under Teflon ring.

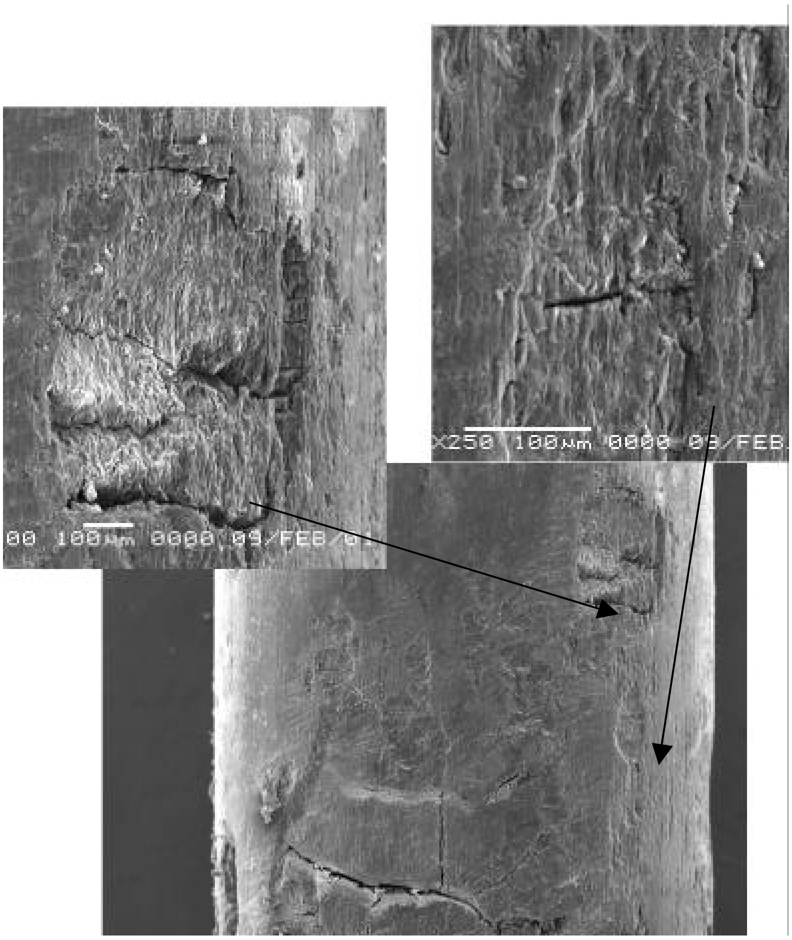

Figure 5. Cracks localized in corroded areas

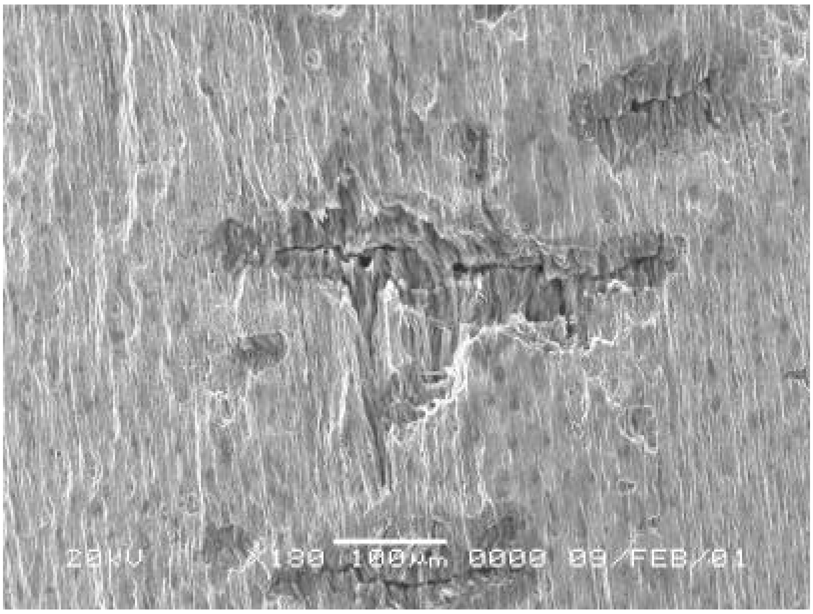

Figure 6. Cracks on steel surface of sample immersed in the solution A

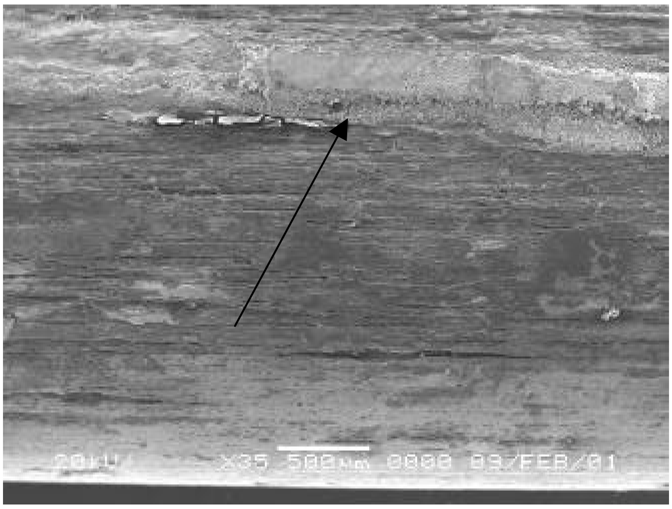

Figure 7. Corrosion attack on the central wire of a seven wire strand after testing for 1100 h in the solution T

4 DISCUSSION

Failure of prestressing steel is generally induced by corrosion. When corrosion attack is generalized (it occurs for examples in carbonated concrete or when steel is exposed directly to the atmosphere) failure occurs when cross section reduction, due to steel consumption, leads to an increase of stress in steel that overpass its UTS. It is well known however that prestressing steel is susceptible to stress corrosion cracking (SCC) (ACI Committee 222 2001; Alonso *et al*. 1993) and to hydrogen embrittlement (HE) (Mietz 1998). In some case brittle fracture is induced by localized corrosion attack, such as pitting (acidification at the pit tip allows hydrogen reduction and, as a consequence, hydrogen embrittlement of the steel). Cracks formation was in fact observed in some case at the bottom of pits (Nurnberger 1992).

Relatively few failures in the literature are attributed to brittle mechanism such as SCC and HE. One possible reason is that the prestressing steels normally used in prestressed concrete construction resist this type of failure quite well if we except special sensitive prestressing steel used during the '50s and the '60s in Germany (Nurnberger 2000). A number of problems have occurred on prestressed concrete structures in recent years that are not reported in literature. This probably because the failures have generated litigation with closure of trial proceedings or nondisclosure agreements between litigant. Another possible reason is that failures may have occurred in conjunction with pitting corrosion. In this case, the investigators may not realize that the failure are due to brittle HE because of the heavy pitting damage that may be present (ACI Committee 222 2001).

Brittle behaviour of steel wires extracted from heavily corroded prestressing cable taken from a prestressed concrete bridge was observed by Vehovar *et al.* (1998). It was supposed that low pH carbonated grouting mixture (pH ranging from 11.3 to 11.6) and the high amount of chloride present (1.1 wt % of concrete) allowed intense pitting corrosion to occur.

Cherry and Price conducted tests with two different strain rate on smooth, cold drown, stress-relieved prestressing wire (1800 MPa UTS) to determine if sodium-chloride solutions of varying pH and anodic polarization would cause SCC (Cherry and

Price 1980). Wire fractured on both tests. Cherry and Price assumed that since failure of the wires were by yield at the point where the cross-section has been reduced by pitting, hydrogen embrittlement does not lead to a synergistic interaction between stress and corrosion so that failure may be ascribed simply to pitting or crevice corrosion caused by the presences of chlorides.

Results reported in this work on the other hand, even if not conclusive, confirmed the evolution of hydrogen induced cracks (HICs) on steel surface in the acid environment of crevice, their growth was presumably strongly influenced by the stress condition which concentrate maximum stress on a limited section of the wire. It has to be stressed however that the major damage of steel wire was caused by the strong acid attack which interested more than the half section of the wire and that, for this type of prestressing steel, could be considered the main cause of the incipient wire failure. Further work on different type of prestressing steel (considering more hydrogen sensitive steel) was therefore planned for the future.

5 CONCLUSIONS

The results shown in the paper suggested that crevice condition, that can easily occur in prestressing steel in concrete construction due to execution faults or construction errors, may lead to severe corrosion attack. Crevice can also occur in chloride contaminated concrete on inner wire surface of wire strands.

Hydrogen induced cracks can develop in such condition on steel wire. On the basis of the results here reported it was however still difficult to evaluate the influence of such cracks on the failure of prestressing steel.

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