CORROSION INDUCED FAILURES OF PRESTRESSING STEEL

KORROSIONSBEDINGTE VERSAGENSMECHANISMEN BEI SPANNSTAHL

RUPTURES D'ARMATURE DE PRECONTRAINTE INDUITES PAR CORROSION

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SUMMARY

Rarely in prestressed concrete structures occurring fractures of prestressing steel in prestressed concrete structure can, as a rule, be attributed to corrosion induced influences. The mechanism of these failures often is not well understood. In this connection it is difficult to establish the necessary recommendation not only for design and execution but also for building materials and prestressing systems in order to avoid future problems. This paper gives a survey about corrosion induced failure mechanisms of prestressing steels with a particular emphasis on post-tensioning tendons.

Depending on the prevailing corrosion situation and the load conditions as well as the prestressing steel properties the following possibilities of fracture must be distinguished:

- Brittle fracture due to exceeding the residual load capacity. Brittle fracture is particularly promoted by local corrosion attack and hydrogen embrittlement.
- Fracture as a result of hydrogen induced stress-corrosion cracking.
- Fracture as a result of fatigue and corrosion influences, distinguishing between corrosion fatigue cracking and fretting corrosion/fretting fatigue.

ZUSAMMENFASSUNG

Die gelegentlich an den im Spannbetonbau verwendeten Spannstählen auftretenden Brüche sind im Regelfall auf korrosionsbedingte Einflüsse zurückzuführen. Die Versagensmechanismen werden häufig nicht ausreichend verstanden. Deshalb ist es schwierig, die notwendigen Empfehlungen nicht nur für Planung und Ausführung sondern auch für die Auswahl der Baustoffe und Vorspannsysteme zu geben, um zukünftige Probleme auszuschließen. Der Beitrag stellt in einem Überblick die korrosionsbedingten Versagensmechanismen von Spannstählen, mit Schwerpunkt der Probleme bei nachträglich vorgespannten Zuggliedern, dar.

In Abhängigkeit sowohl von der vorherrschenden Korrosionssituation und den Belastungsverhältnissen als auch den Spannstahleigenschaften müssen die folgenden Brucharten unterschieden werden:

- Sprödbruch durch Überschreiten der Resttragfähigkeit. Das Auftreten eines Sprödbruches wird unterstützt durch einen lokalen Korrosionsangriff und eine Wasserstoffversprödung.
- Bruch infolge wasserstoffinduzierter Spannungsrisskorrosion.
- Brüche als Folge von Ermüdung und Korrosionseinflüssen. Hierbei ist zu unterscheiden zwischen Schwingungsrisskorrosion und Reibkorrosion/Reibermüdung.

RESUME

Les ruptures occasionnelles des armatures de précontrainte peuvent en général être attribués à l'influence de la corrosion. Le mécanisme de ces ruptures n'est souvent pas bien compris. Il est par conséquent difficile d'émettre des recommandations, non seulement pour la conception et l'exécution, mais également pour le choix des matériaux et des systèmes de précontrainte. Cet article donne un aperçu sur les mécanismes de ruptures induites par corrosion des armatures de précontrainte, en particulier sur les armatures précontraintes par post-tension.

En fonction des conditions corrosives de l'environnement, des conditions de chargement et des propriétés de l'armature précontrainte, on distingue les types de rupture suivants:

- rupture fragile due au dépassement de la capacité résiduelle de charge. La rupture fragile est favorisée par la corrosion locale et la fragilisation par hydrogène.
- rupture par corrosion sous contrainte induite par l'hydrogène.
- rupture en raison des influences combinées de fatigue et corrosion. On distingue la fatigue sous corrosion et la corrosion par friction/fatigue par friction.

KEYWORDS: prestressed concrete, corrosion, failures, steel

1. INTRODUCTION

Most of the prestressed concrete structures built in the last 50 years in accordance with the rules for good design, detailing and practice of execution have demonstrated an excellent durability [1]. Analyses of occasional problems confirm that instances of serious failures are rare considering the volume of prestressing steels that has been in use worldwide.

Major issues which strongly influence the level of durability actually achieved are insufficient design (poor construction), incorrect execution of planned design (poor workmanship), unsuitable mineral building materials, unsuitable post-tensioning system components, including the prestressing steel [1-3]. Insufficient design and incorrect work execution will mean that the necessary corrosion control is not guaranteed from the beginning in all areas or that as a result of natural influences (i. e. carbonation, chloride ingress) it will get lost soon within the time frame of the originally anticipated life time. Unsuitable materials or inappropriate substances in materials will further corrosion and/or stress corrosion cracking. Sensitive prestressing steels cannot withstand even inevitable building-site influences or will fail while in use.

Most corrosion defects are caused by water which seeps through zones of porous concrete and vulnerable areas such as leaking seals, joints, anchorages or cracks, and which flows through the network of ducts which have been grouted to a greater or lesser extent. The major threat is corrosion due to chlorides. The source of chlorides can be either de-icing salts or seawater.

Rarely occurring fractures of prestressing steel and failures of prestressed concrete structure can, as a rule, be attributed to corrosion induced cracking. The mechanism of these failures often is not well understood. In this connection it is difficult to establish the necessary recommendation not only for design and execution but also for building materials and prestressing systems in order to avoid future problems.

This paper gives a survey about corrosion induced failure mechanisms of prestressing steels with a particular emphasis on post-tensioning tendons.

2. FRACTURE MECHANISMS OF PRESTRESSING STEEL

The types of corrosion occurring at times as well as their specific manifestation must be regarded as an essential influencing factor on the behaviour of the prestressing steels under unforeseen or inappropriate service conditions. The exclusive determination that corrosion was involved is not enough for a critical case study and for future damage prevention.

Depending on the prevailing corrosion situation and the load conditions as well as the prestressing steel properties the following possibilities of fracturing must be distinguished:

- Brittle fracture due to exceeding the residual load capacity. Brittle fracture is particularly promoted by:
  - local corrosion attack (pitting and wide pitting corrosion),
  - hydrogen embrittlement.
- Fracture as a result of stress corrosion cracking, where we distinguish between
  - anodic stress corrosion cracking and
  - hydrogen induced stress-corrosion cracking.
- Fracture as a result of fatigue and corrosion influences, distinguishing between
  - corrosion fatigue cracking and
  - fretting corrosion/fretting fatigue.

In the following such events will be described in more detail, also with regard to prestressed concrete construction.

2.1 Brittle fracture

Brittle fracture may occur in high-strength steels after swift tensile stress. This is the case in prestressing steels when there is a fracture under loads until reaching the permissible pre-strain as a result of these influences:

- stress concentration in local notches (e. g. wide corrosion pit),
- high stressing speed and low temperature,
- an embrittlement of the steel structure after hydrogen adsorption (hydrogen embrittlement).

Influence of corrosion

Mainly uniform general corrosion (e. g. after a prolonged weathering on a building site) does not have any major impact on the load bearing capacity. Not until, due to corrosion, an underrun of the required residual cross section has taken place than a prestressing steel fracture may occur after exceeding the residual load bearing capacity. Such events may happen once prestressing steels in ungrouted tendon ducts are exposed over a long period of time to water and oxygen via untight anchorages or construction joints.

If, however, the prestressing steel incurs a local corrosion attack in the form of pitting or wide pitting corrosion, the load bearing capacity may get lost at an early stages due to brittle fracture. The following effects are capable of triggering such attacks in prestressing steel:

The presence of aggressive water in the not yet injected ducts of post tensioning tendons which result from bleeding of the concrete during the erection of the construction. Already in the not grouted and not prestressed condition the steel may suffer from strong pitting or wide pitting corrosion and the load bearing capacity can be reduced considerably.

Bleeding is a separation of fresh concrete, where the solid content sinks down and the displaced water rises or penetrates in the inner hollows. In the bleeding water significantly high contents of sulphates and increased quantities of chlorides may be accumulated (Table 1) by leaching of the construction materials cement, aggregates and water. The high amounts of potassium-sulphates result from the gypsum in the cement. The watery phase of fresh concrete penetrates into the ducts through the anchorages, couplings and defects in the sheet and accumulates at the deepest points. Because of an access of air the alkaline water carbonates quickly. As early as in the non-grouted and non-prestressed condition the steel can suffer from strong pitting. Bleeding water attack may within a few weeks lead to pitting depths of up to 1 mm.

Table 1: Analysis of bleeding water

sulphate	1.90 - 5.20	g/l
chloride	0.13 - 0.18	g/l
calcium	0.06 - 0.09	g/l
sodium	0.18 - 0.37	g/l
potassium	3.60 - 7.30	g/l
pH-value	10 - 13	

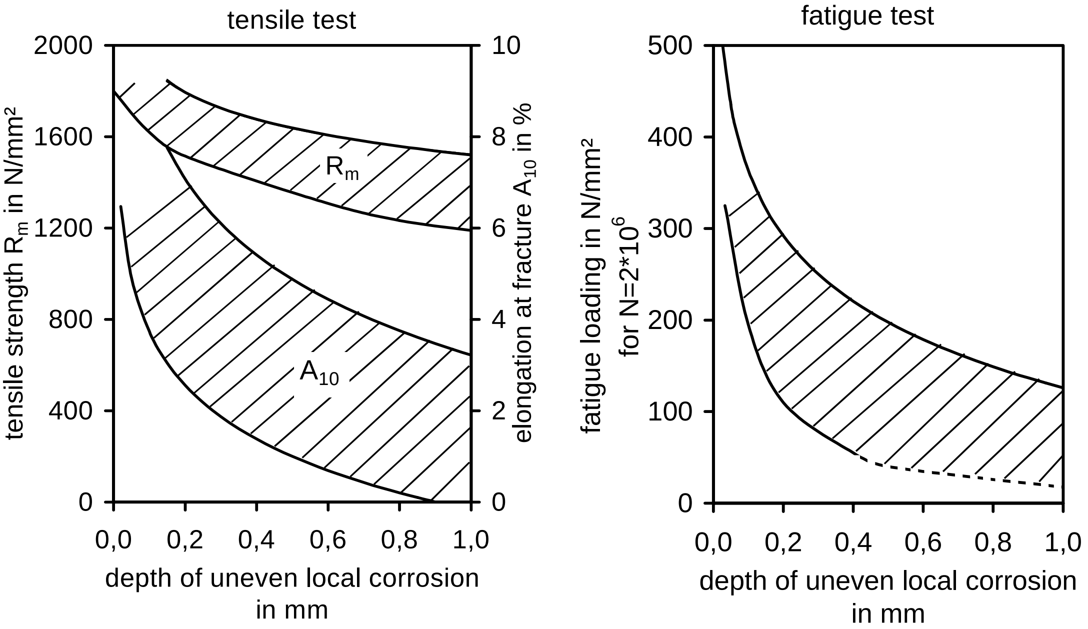
The access of chloride containing waters, e.g. above untight anchorages or joints, in a non-grouted tendon duct may lead to damaging local corrosion attack in prestressing steel during the life time and after years of use. Comparable attacks must be expected once chloride salts penetrate to the tendon through a concrete cover of inferior thickness and impermeability.

The performance characteristics of corroded prestressing steels can be determined in tensile, fatigue and stress corrosion tests (Fig. 1). Such tests to establish the residual load bearing capacity will, for instance, be carried out while inspecting older buildings, after damaged prestressing steel samples had been drawn. This might help to gain the knowledge for necessary repair.

High strength prestressing steels show a far more sensitive reaction to corrosion attack than reinforcing steels, and this increasingly in the sequence tensile test - fatigue test – stress corrosion test [4]. In case of uneven local corrosion a corrosion depth of 0.6 mm may suffice for breaking a cold deformed wire under tension of 70 % of the specified tendon strength of about 1800 N/mm^2 (Fig. 1, tensile test).

At pitting depth of above 0.2 mm cold drawn wires may show fatigue limits (fatigue limits for stress cycles of $N = 2 \cdot 10^6$) of 100 N/mm^2 and less (Fig. 1, fatigue test). Like-new smooth surfaced steels normally show a fatigue limit of more than 400 N/mm^2.

In all the performance characteristics of prestressing steels local corrosion attack has the most detrimental effect on the behaviour to hydrogen induced corrosion cracking. In a test developed by FIP the prestressing steel is immersed under tension into an ammonium thiocyanate solution. A minimum and average time of exposure before failure is specified. For cold drawn wire and strand these values are in the order of 1.5, respectively 5 hours. In this example these life times are underrun at corrosion depths of > 0.2 mm (Fig. 1, stress corrosion test).



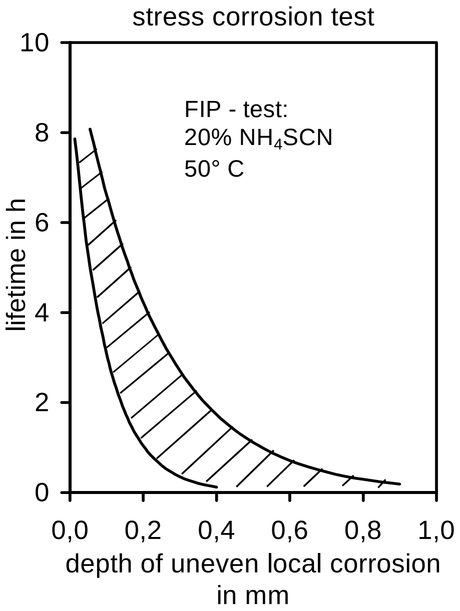


Fig. 1: Properties of cold-deformed prestressing steel wires St 1570/1770, d_S = 5 mm, in relation to depth of uneven local corrosion [Nürnberger] (scattering of 90% of the test results)

Effect of hydrogen (hydrogen embrittlement)

In a specific corrosion situation prestressing steel corrosion may release hydrogen which is then absorbed by the prestressing steel, which, if prestressed at the same time, will allow hydrogen induced stress corrosion cracking with crack initiation and crack propagation (chapter 2.2). Also if the prestressing steel is free of any tensile stresses (not prestressed), hydrogen can be absorbed in the event of corrosion. The steel will not crack, but depending on the quantity of hydrogen absorbed and the specific hydrogen sensitivity the prestressing steel may become brittle. This may have an adverse effect on the mechanical characteristics [5], more so on the deformation properties than on the tensile strength.

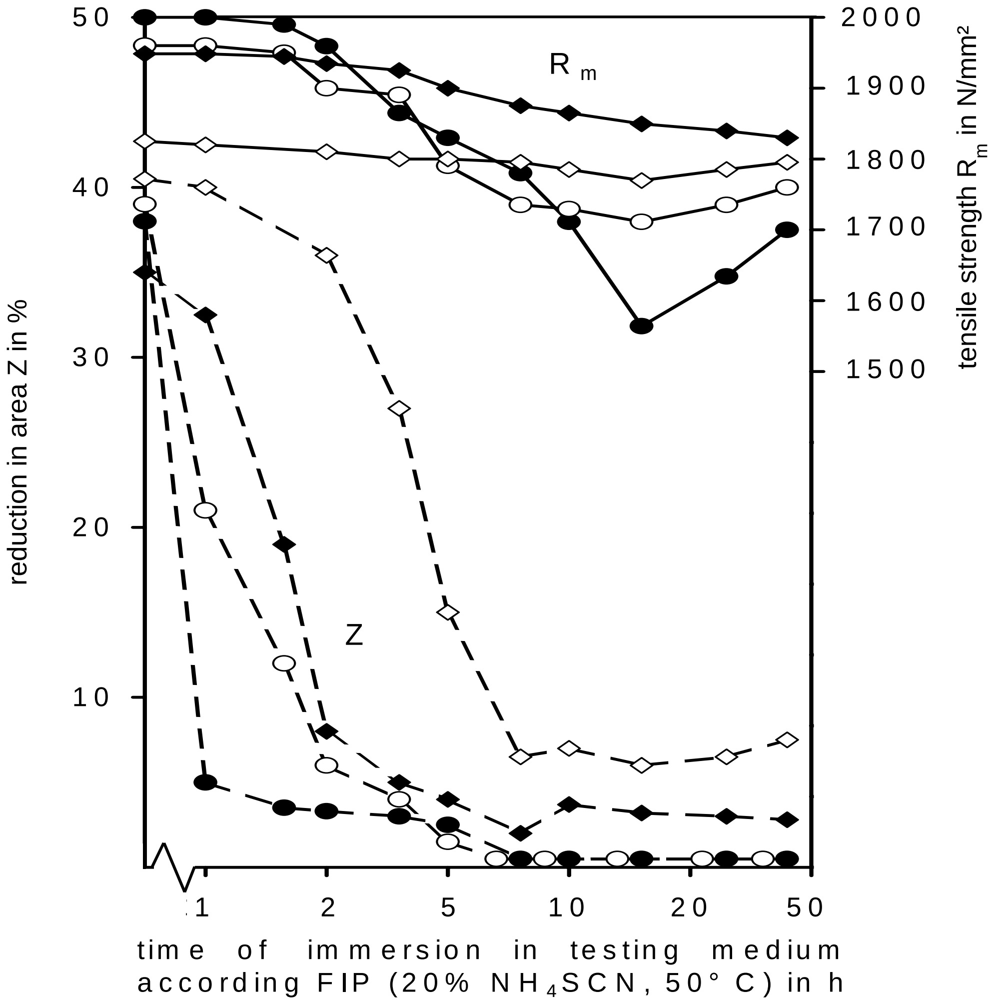


Fig. 2 Tensile strength (R_m) and reduction in area (Z) of cold deformed prestressing steel wires (4 steel melts) after charging with hydrogen [5]

Prestressing steel fractures as a result of corrosion-caused hydrogen embrittlement may occur, for instance, when prestressing to a high stress level or shortly after the prestressing, after the steel had been absorbing high quantities of hydrogen in an enduring unfavourable corrosion situation. If properly and swiftly processed, such damages, indeed, should not occur.

2.2 Fractures because of stress-corrosion cracking

Stress-corrosion cracking is understood to mean crack formation and crack propagation in a material under the effect of mechanical tensile stresses and of an aqueous corrosion medium.

Anodic stress-corrosion cracking

In the presence of nitrate-containing non-alkaline electrolytes (pH-value < 9) unalloyed and low-alloy steels may suffer an anodic stress-corrosion cracking. Crack formation and crack propagation are due to a selective metal dissolution (e. g. along grain boundaries of the steel structure) with a simultaneous effect of high mechanical tensile stresses [6] on condition that there is special tendency of the steels to passivate in nitrate-containing aqueous solutions.

In the prestressed concrete construction the media-related pre-conditions, e.g. in the fertilizer storage and in stable ceilings, can be assumed as a fact. In stables brickwork, salpetre $Ca\,(NO_3)_2$ may be formed by urea. In the presence of moisture the nitrates may diffuse into the concrete and may cause stress-corrosion cracking in the case of pretensioned concrete components affecting the tension wires if the concrete cover is carbonated due to an inferior quality of the concrete [6].

A specific nitrate sensitivity of the steels is always a pre-condition for an anodic stress-corrosion cracking. Low-carbon concrete steels are very susceptible to nitrate induced stress-corrosion cracking. The prestressing steels currently in use, however, are highly resistant to this type of corrosion.

Hydrogen induced stress corrosion cracking [6,7]

Fractures of prestressing steel as a rule can be referred to hydrogen induced stress corrosion cracking (H-SCC). It may happen during the erection of the construction or during later use. The following conditions are necessary:

- a sensitive material or state,
- a sufficient tension load,
- at least a slight corrosion attack.

The risk of fractures due to hydrogen induced stress corrosion cracking therefore results from the joint action of very prestressing steel properties and environmental parameters. What is needed is the presence of hydrogen which comes into being under certain corrosion conditions in neutral and particularly in acid aqueous media through the cathodic partial reaction of the corrosion.

Table 2: Chemical reactions of corrosion

anodic iron dissolution ① $Fe \rightarrow Fe^{2+} + 2e^-$
cathodic reactions if pH > 7 ② $\frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2OH^-$ if pH < 7 ③ $H^+ + e^- \rightarrow H_{ad}$ (hydrogen discharge) if potential is low ④ $H_2O + e^- \rightarrow H_{ad} + OH^-$ (water decomposition)
rivalry reaction with regard to ③ and ④ ⑤ $2\ H_{ad} \rightarrow H_2$ (recombination) is prevented in the presence of promotors ⑥ $2\ H_{ad} + \frac{1}{2} O_2 \rightarrow H_2\ O$ if oxygen is present

During the corrosion process hydrogen atoms have be set free and get absorbed by the steel. In sensitive steels the hydrogen under the effect of mechanical stresses can create precracks in critical structural areas such as grain boundaries. These cracks may grow and result in material fracture.

Special conditions have to exist to activate the formation of adsorbable hydrogen. To understand the correlations between procedure on site and development of damage, the chemical reactions of corrosion should be considered (Table 2). Harmful hydrogen can arise only

- if the steel surface is in an active state or depassivated (this is expressed by reaction 1),
- if the cathodic reaction of corrosion is discharging hydrogen (this is described by reaction 3) or water decomposition (this is described by reaction 4),
- if the adsorbable atomic hydrogen is not changed into the molecular state (see reaction 5).

A reduction of oxygen access may support evolution of adsorbable atomic hydrogen (then reaction 6 is hindered). Therefore at the surface of corroding steel the amount of adsorbable hydrogen atoms rises

- with increasing hydrogen concentration (reaction 3 or 4 is accelerated),
- in the presence of so-called promotors (reactions 5 is hindered),
- in an electrolyte impoverished in oxygen (reaction 6 is hindered).

From the practical point of view one can say that hydrogen assisted damages are only possible

- in acid media or if the steel surface is polarized to low potentials (e. g. if the prestressing steel has contact with zinc or galvanized steel),
- in the presence of promotors such as sulphides, thiocyanate or compounds of arsenic or selenium,
- and under crevice conditions, because the electrolyte in the crevice is poor in oxygen.

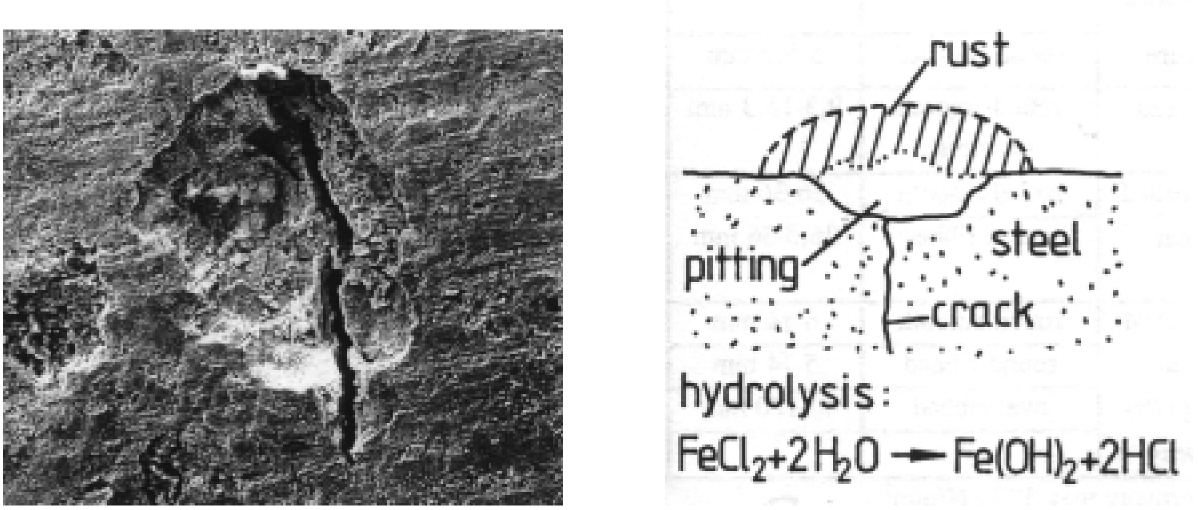


Fig. 3: Pitting induced stress corrosion cracking

In concrete structures the attacking medium is mostly alkaline and acid media are limited to exceptions. Nevertheless, in natural environments the pitting induced H-SCC can take place (Fig. 3). Pitting induced H-SCC means crack initiation within a corrosion pit. In the corrosion pits the pH-value falls down because of hydrolysis of the Fe^{2+}-ions. Pitting or spots of local corrosion can be explained by differential aeration or concentration cells. Especially effective is the attack of condensation water or salt enriched aqueous solution (bleed water, chapter 2.1), when erecting the constructions.

In prestressed construction chloride contamination supports a local corrosion attack. In the case of sensitive prestressing steel all but minimal contents of hydrogen can lead to irreversible damages. Then a minimal local corrosion attack without visible corrosion products on the steel surface may lead to steel fracture.

In prestressed concrete structures all types of uneven local corrosion should be prevented to exclude failures because of hydrogen assisted cracking.

The preconditions for "classical" stress-corrosion cracking are most readily to be found in prestressed concrete construction, i. e. crack formation and propagation under purely static stress. By prestressing the stress amplitudes of the structure caused e. g. by wind and traffic are kept low. Nevertheless, the occurrence of pulsating loads or service-related strain changes of the steels will raise the crack corrosion risk since it will favour hydrogen induced "non-classical" stress-corrosion cracking [6]. Plastic flow in steel favours an absorption of atomic hydrogen.

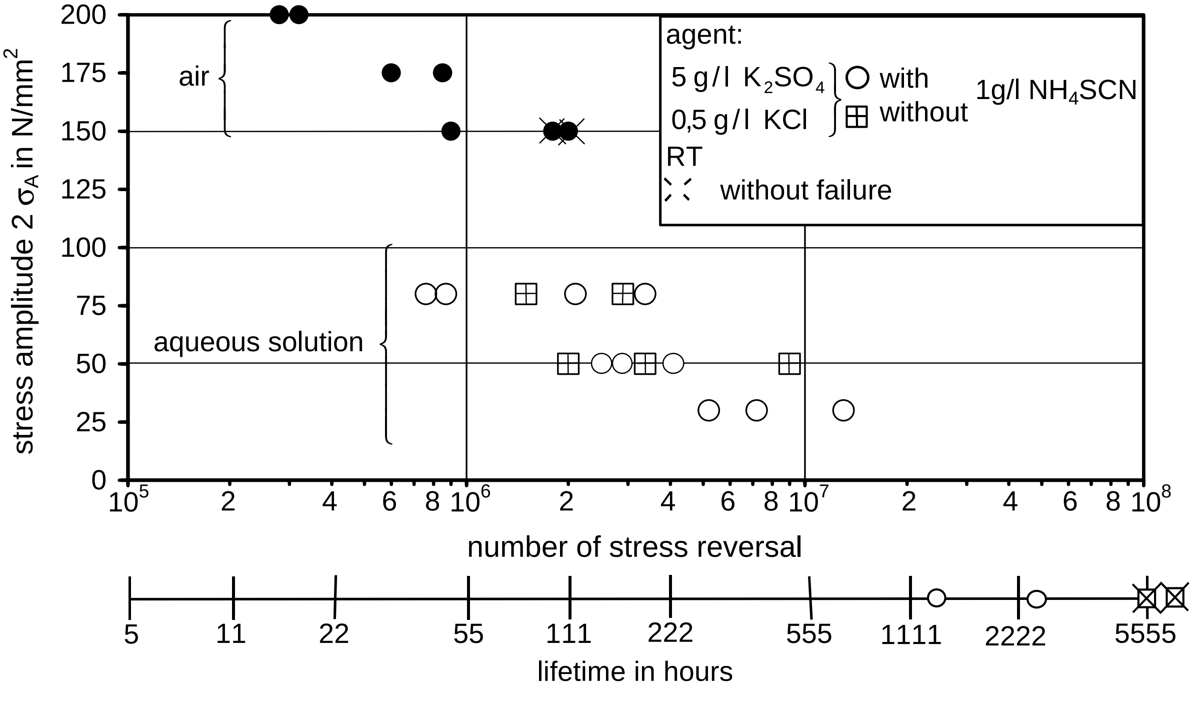


Fig. 4: SCC-behaviour of prestressing steel St 1420/1570 (German standard) ∅12.2 mm without and with dynamic stress of low amplitude

Fig. 4 [8] compares the behaviour of a quenched and tempered prestressing steel (from a case of damage) sensitive to hydrogen in a stress-corrosion cracking test with and without superimposed fatigue loading of low amplitude (30 – 80 N/mm^2). The aqueous test solution contains 5 g/l SO_4^{2-},0.5 g/l Cl^- without and alternatively with 1 g/l SCN^- as a promotor for a hydrogen absorption. The stress-corrosion cracking test under static stress was realized at 80 % of the tensile strength. This stress corresponds to the constant maximum stress in the tensile fatigues test. Fig 4 represents the stress cycle number as a function of the amplitude, in the course of which also the life time, calculated over the frequency ($f = 5s^{-1}$), is applied. The stress corrosion test results without superimposed fatigue loading are applied at a range of stress of 0 N/mm^2. The hydrogen insensitive steel failed in the "static" test within a test period of 5000 hours in the promotor-containing solution but did not fail in the promotor-free solution. If a fatigue test of low amplitude is superimposed, the lifetime in the promotor-containing solution will more and more decrease with rising amplitude. In the wave stress it is striking that fractures also occur on steels in the promotor-free solution.

It was found that in cold deformed prestressing steels the influence of a superimposed fatigue loading on the hydrogen induced stress-corrosion cracking is revealing itself weaker. These tests lead to the conclusion that already fatigue loadings of low amplitude or elongations caused by changes in utilization tend to significantly jeopardize the susceptibility of prestressing steels to stress-corrosion cracking.

2.3 Fractures because of fatigue and corrosion

Prestressing steels can only be subject to a noticeable steel stress in dynamically strained reinforced concrete structures if there is concrete in a cracked state. The stress amplitudes of prestressing steel due to acting high dynamic loads (e. g. a high traffic load of a bridge) may then amount to > 200 N/mm^2 in the crack region. In the uncracked state the steels will show ranges of stress of clearly less than 100 N/mm^2.

Cracks in concrete may occur in partially prestressed structures. Since such cracks tend to open and to close in a superimposed fatigue stress the following facts must be considered:

Corrosion fatigue cracking

If corrosion promoting aqueous media penetrate through the concrete crack to the dynamically stressed tendon, corrosion fatigue cracking is possible although this type of corrosion has not been observed in prestressing steel construction so far. Corrosion fatigue cracking [6] manifests itself in that a metallic material under dynamic stress in a reactive corrosion medium (water, salt solution) will show a much more unfavourable fatigue behaviour than under fatigue loading in air. This can be explained by characteristic interactions of metal physical and corrosive processes which favour initial precrack formation and propagation. As opposed to the stress-corrosion cracking the corrosion fatigue cracking does not require a specifically acting corrosion medium.

In case of post-tensioning tendons the duct made of thin steel sheets does not offer a lasting corrosion protection and may even suffer fatigue fractures under dynamic stress [9].

A decrease of the fatigue limit by corrosion is the more distinct the higher the strength of the steel and the more aggressive an attacking medium are. Hence the high strength prestressing steels, when e. g. simultaneously attacked by an aqueous chloride-containing medium, may show a very unfavourable fatigue behaviour.

In traffic carrying bridge structures only the low-frequent stresses lead to high stress amplitudes. This results in additional unfavourable conditions with regard to corrosion fatigue cracking: with a falling frequency the influence corrosion will increase and the fatigue limit will consequently drop.

For a cold drawn prestressing steel wire Fig. 5 shows a decrease of the corrosion fatigue limit in the sequence air-water-chloride solution. For frequencies of $0.5s^{-1}$ the fatigue limit for stress cycles of 10^7 is below 100 N/mm^2.

The problem of corrosion fatigue cracking of cracked components can be remedied by sufficient concrete cover and limiting the crack width. This is the way of keeping pollutants away from the prestressing steel surface.

Fretting corrosion / fretting fatigue

In the vicinity of concrete cracks due to fatigue loading displacements between the tendon and the injection mortar or the steel duct respectively will occur in a cracked component. In bended tendons a high radial pressure acts at the same time on the fretting prestressing steel surface. If air or oxygen advance to the fretting location through the concrete crack a fretting corrosion is favoured [6,10]. Fretting corrosion is described as damaging a metal surface similar to wear as a result of oscillating friction under radial pressure with a partner. In the presence of oxygen oxidation of the reactive surface will take place.

In fatigue loaded steels and under fretting corrosion stress at the same time the fatigue behaviour is under a very unfavourable influence due to fretting fatigue [10]. This is attributable to structural disintegration and the occurrence of additional tensile strengths in the fretting area. In concrete embedded tendons, subjected to a relative movement and a radial pressure in the concrete crack between prestressing steel and duct or injection mortar respectively, tolerable fatigue limits of about 150 N/mm^2 for cycles to fracture of 2×10^6 were found [9,11].

In prestressed concrete constructions also the anchorages of the tendons, due to fretting corrosion influences, show a fatigue limit which is reduced compared with the free length [12]. Under dynamic stress of the anchored tendon the fatigue limit, depending on the type of anchorage, is reduced to values between 80 and 150 N/mm^2. For this reason, anchorages will always be positioned in areas of least stress changes. In the fatigue experiment the prestressing steels always fracture in the force transmitting area, i. e. at the beginning of the anchorage. Here, the fatigue limit is reduced due to the presence of shifting between the prestressing steel and the anchor body and the high radial pressures at the same time.

In prestressed concrete bridges, however, particularly the coupling joints proved to be problematic. If such joints crack as a result of imposed stresses (e.g. due to non uniform sun heating and low amount of reinforcement which crosses the coupling joint) the tendon couplings will suffer major stress fatigue cycles from the traffic load which also led to prestressing steel fractures owing to the stress-sensitive couplings [2,11].

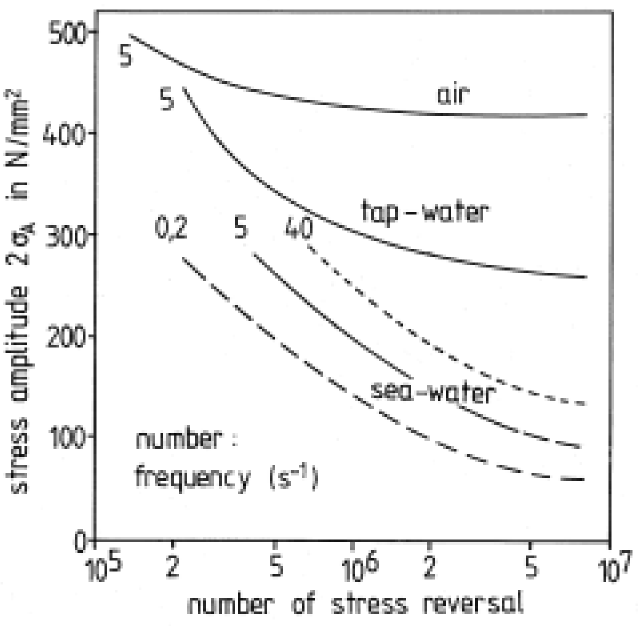


Fig. 5: Fatigue behaviour under pulsating tensile stresses of cold drawn prestressing steel wires (Rm ≈ 1750 N/mm^2) in air and corrosion- promoting aqueous solutions (Nürnberger)

3. CONCLUSION

Depending on the prevailing corrosion situation and the load conditions as well as the prestressing steel properties the following possibilities of fracturing must be distinguished:

- Brittle fracture due to exceeding the residual load capacity. Brittle fracture is particularly promoted by local corrosion attack and hydrogen embrittlement.
- Fracture as a result of hydrogen induced stress-corrosion cracking.
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