Corrosion induced failure mechanisms of prestressing steel

Korrosionsbedingte Versagensmechanismen bei Spannstahl

U. Nürnberger*

Dedicated to Professor Dr. Günter Schmitt on the occasion of his 60th birthday

Rarely 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 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.
- Fracture as a result of fatigue and corrosion influences, distinguishing between corrosion fatigue cracking and fretting corrosion/fretting fatigue.

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.

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.

Rarely occurring fractures of prestressing steel and failures of prestressed concrete structures 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 recommendations 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 steel with a particular emphasis on post-tensioning tendons.

* *U. Nürnberger*
Otto-Graf-Institut, Universität Stuttgart
Pfaffenwaldring 4, 70569 Stuttgart (Germany)

2 Principle of prestressed concrete

If suitably composed and properly manufactured, concrete will show high compressive strength but no sufficiently high tensile strength. In order to increase the loadability of a concrete component, reinforcing steels will be incorporated in reinforced concrete with structural areas under tensile stress (e.g. in the tension zone of a bending girder in the direction of such forces) to take on tensile forces. To enable these steel rods to take on tensile forces, the hardened concrete, however, must crack under load. For optical reasons such cracks in the concrete are undesirable and also have a negative effect on the corrosion protection of the concrete steels.

Prestressed concrete is an advance development of reinforced concrete which means pressurizing the concrete by prestressing steels in such places of a structural element where the concrete normally is exposed to tensile stresses and threatened by cracking and failure. Therefore in prestressed concrete structures the prestressing steel performs essential bearing action. The prestressing steels are arranged as individual tendons or in bundles within (Fig. 1) or outside the structure. In proper structural design (i.e. full pretensioning) prestressed concrete can be brought to a point where concrete as a building material remains free from cracks under tensile stress. This ensures the

0947-5117/02/0808-0591$17.50+.50/0

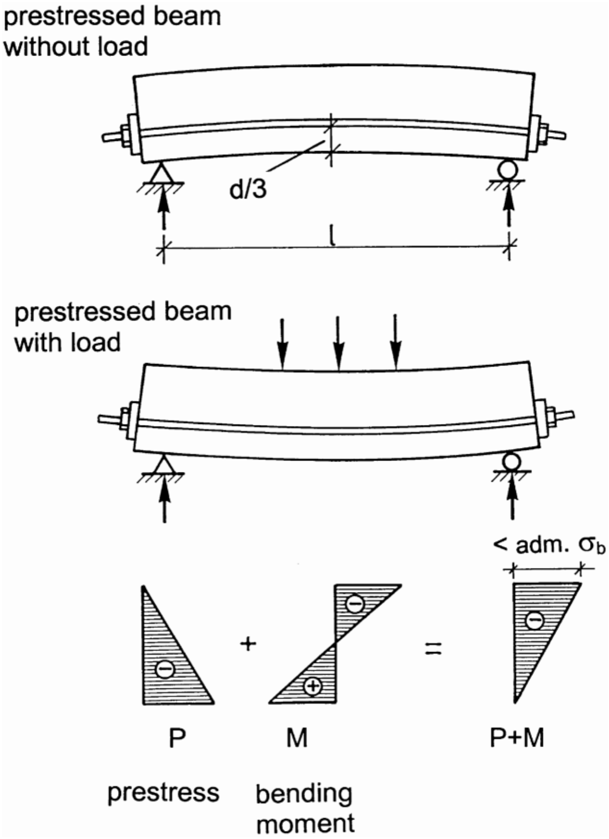

Fig. 1. Principle of prestressed concrete (post-tensioned concrete with internal prestressing)

Abb. 1. Prinzip des Spannbetons (Spannbeton mit nachträglichem Verbund)

corrosion protection of the installed reinforcement. The prestressed concrete type of construction offers application-specific advantages versus the reinforced concrete, however, if poorly executed, it is vulnerable.

In order to obtain a sufficiently high long-term pre-strain the elastic strain of the steel under load must be significantly greater than the later strain of the concrete (contractions of the concrete due to creep and shrinkage). Therefore prestressing steels made from high-strength steel with high proof stress and a wide operational range in the elastic region are to be used. In principle, the time-dependant loss of stress must be kept low and therefore prestressing steels with a low relaxation are to be used. Prestressing steels showing these required serviceability standards are unalloyed and low alloyed steels which react sensitively to corrosion attack and will be used as wires, strands and bars. In general, wires and strands are used as bundled tendons.

Table 1 contains a survey of the different steel types. The application of cold deformed wires and strands dominates worldwide. The yearly production of this steel type is 1 million tons. The strength of commonly used cold deformed prestressing steel increases with a falling diameter of the wire or strand respectively from 1570 up to 2060 N/mm^2. The larger diameter hot rolled bars with a 50 000 tons-a-year production have a considerably lower strength from 1030 to 1230 N/mm^2. The production of quenched and tempered steel wires with at 5000 tons yearly is significantly lower. Their strength corresponds to those of the larger diameter deformed wires.

3 Corrosion protection of prestressing steel

Due to its high strength, prestressing steel reacts more susceptibly to corrosion than other components made of ordinary steel. Therefore, to achieve durable constructions the highly stressed steels or tendons must be protected from external corrosive and aggressive agents such as water, oxygen and salts. This requires that post-tensioning tendons for their entire design life are completely surrounded by a protective barrier of injection mortar or grease and concrete. If right from the beginning this corrosion protection proves to be insufficient or if in the course of time it gets lost due to external influences this might lead to corrosion-caused prestressing steel fractures [1–4], which, as a consequence, might entail a failure of the construction.

3.1 Handling of prestressing steel

During transport and storage as well as at installation until the build-up of the durable corrosion protection the steels must

Table 1. Survey about produced prestressing steel
Tabelle 1. Übersicht der produzierten Spannstähle

type	shape, surface	diameter	anchorage system	strength class European Standard	production (world wide) tons/year
cold deformed	round – smooth	4–12.2 mm		1570–1860[1)] (N/mm^2)	1 000 000 (worldwide)
● wire ● strand	round – profiled round – smooth (7 wires)	5–5.5 mm 9.3–15.3 mm	wedge or button heads	1700–2060[1)] (N/mm^2)	
hot rolled bar	round - smooth round – ribbed	26–36 mm 26.5–36 mm	thread (ends) thread (full length)	1030–1230 (N/mm^2)	50 000 (Germany, UK)
quenched and tempered wire	round - smooth round – ribbed oval – ribbed	6–14 mm 5–14 mm 40–120 mm^2	wedge	1570 (N/mm^2)	5000 (Germany, Japan)

[1)] in Germany max. 1770 N/mm^2

not be exposed in a manner which will impair their usability. Therefore prestressing steel must be stored on site in a dry and clean location.

Once the steel is installed in a post-tensioned structure, it should be stressed and permanently protected by grouting as quickly as possible. Guidance on the maximum period of time between installation and stressing and the final protection of the tendon made of bare prestressing steel may be found in selected standards [5].

If storage and grouting of prestressing steel need to be delayed beyond proposed intervals a particular protection method, e.g. the use of water-soluble oils sprayed onto the steel surface [6], must be provided for post-tensioning tendons.

3.2 Permanent corrosion protection [5, 7]

3.2.1 Post-tensioned concrete

In case of post-tensioning the tendons are placed either in ducts within the body of the concrete section (internal prestressing) or outside the concrete section (external prestressing). Then the ducts, which consist of thin corrugated steel sheet, are filled with a protective material. In case of bonded tendons cement grout free of voids is normally used. It protects the prestressing steel from corrosion by passivation and bonds the tendon to the concrete member throughout the length. Furthermore, a crack free and sufficiently thick and tight concrete cover has to exist.

In prestressed concrete structures with internal unbonded tendons the corrosion protection of prestressing strands is a polyethylene (HDPE) duct filled with grease or wax and the covering concrete. In case of external unbonded tendons strands are protected with a layer of grease and an extruded HDPE-sheathing. All unbonded systems must have waterproof encapsulated tendons without voids, increased sheathing thickness (1.5 mm) and multiple lines of defense against moisture and salt ingress.

3.2.2 Pretensioned concrete

In pretensioned concrete for the manufacture of prefabricated elements the prestressing steels, after the prestressing in a stressing frame, will be surrounded with concrete. The thickness and the density of the concrete cover will then guarantee the corrosion protection.

4 Reasons of damage

In prestressed concrete structures serious corrosion-related damage only seldom occurs. Nevertheless, in connection with certain circumstances prestressing steel may suffer corrosion induced problems. In the following particularly the reasons for corrosion of post-tensioning tendons in internally grouted ducts will be stressed.

Major issues which strongly influence the level of durability actually achieved are [1, 2, 4, 8, 9]:

- insufficient design (poor construction),
- incorrect execution of planned design (poor workmanship),
- unsuitable mineral building materials,
- unsuitable post-tensioning system components, including the prestressing steel.

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 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.

4.1 Insufficient design (poor construction)

Planning errors are bad mistakes during calculating, detailing and constructional design as well as an insufficient assessment of the behaviour of the structure. Here are some examples of faults occurring during the building phase:

- inefficient drainage systems,
- missing or inefficient waterproofing systems,
- poor construction and joints,
- cracking in the concrete.

It is essential that the drainage system of bridges or parking houses should work efficiently to remove water from the road or parking deck surface as well as the water which passes through the surfacing down to the deck water proofing system. The design of the drainage path should be such that if items of the equipment fail, leak or become blocked the water does not find access to the prestressing system.

The use of waterproofing systems, e.g. on concrete bridge decks, will provide a protective barrier against ingress of road salts applied from the bridge road surface. In the past often there were no systems available which provided a complete seal or which could be guaranteed to remain waterproof throughout the whole life of the construction. As a consequence, construction joints underneath membranes leaked. Modern high liquid-applied membranes are likely to be more effective than earlier systems.

Poorly made construction joints may leak. It is advisable to keep anchorages, e. g. in deck slabs of bridges, away from construction joints and prevent any access for the leakage to these sensitive systems. Where the prestressing anchorages are inevitably located at construction joints care should be taken in detailing.

A high proportion of expansion joints leak and their effectiveness and life span are very much dependent on the quality of installation and maintenance. Hence, the risk of contaminants reaching sensitive parts of the structure increases. Appropriate drainage paths for the leakage should be provided to ensure that it is led off and cannot get access to the prestress anchorages or the bearings and that the water cannot pond.

Cracking in concrete can occur for a number of reasons. The cracks could occur mainly in regions with low stresses due to loads and higher to imposed deformations. The relevance of wider cracks is largely related to corrosion. It should be provided that crack widths are limited in accordance with normal design practice. Special care is required to minimise the risk of cracking particularly in the vicinity of anchorages.

4.2 Incorrect execution of planned design

Work errors are serious mistakes in the execution of constructions. They must be attributed to deviating from the original planning or neglecting the regulations existing at the time of construction, but to human insufficiencies of the workforce [2, 10]. So it is not a question of consequences of fundamental deficiencies of this type of construction or of existing directives. Major mistakes in work execution continue to be:

- badly or not at all injected tendons with mortar in case of post-tensioned concrete,
- the manufacture of a not sufficiently protecting concrete cover.

Today we are of the opinion that such fundamental mistakes committed by the construction workforce cannot definitely be excluded in any type of construction and can most effectfully only be avoided by employing better trained personnel.

Poorly executed grouting of post-tensioned members was a predominant reason for damage, for which one important prequisite, however, was that water, polluted by chlorides from de-icing salt agents or a seaside coast location could contact the prestressing steel and initiate some kind of corrosion process. It has already been found that ungrouted tendons in dry structures located in regions with a dry continental climate have not corroded at all.

However, the issue is wider than that, ranging from poor compaction of concrete and high permeability to cases with failures to achieve specified covers:

Experience has shown that neither the steel sheath nor even a well compacted grout can form a sufficiently tight barrier if an aggressive water percolates through a more or less porous concrete or if a too low concrete cover loses its passivating effect by chloride ingress or carbonation. Although defective grouting of the ducts is a primary condition for the development of corrosion, this condition on its own is not enough for generating a damaging corrosion.

4.3 Unsuitable mineral building materials [4, 11]

The systematic use of unsuited building materials has considerably harmed the image of the prestressed concrete construction. For a time, this result in heavy component failures under mostly comparable circumstances. Here, in particular, the high-alumina cement and chloride containing curing accelerators are at stake which, for economic reasons, are used for the manufacture of ceiling cross sections and pretensioned prefabricated girders. In the case of high-alumina cement, damp heat as in stables can lead to increased porosity and ensuing carbonation as well as a strong strength decay of the concrete caused by the reaction of the cement stone. In the event of hydrogen-induced stress corrosion cracking (see section 5.2.2) the sulphide sulphur contained in some German cements also functions as a promotor for the hydrogen uptake of prestessing steels. A mass collapse of ceilings due to corrosion decay (pitting and wide pitting corrosion) and stress-corrosion cracking of the prestressing steels led to the removal of all components in stable ceilings and above other wet rooms that had been manufactured with high-alumina cement and chloride containing curing accelerators. In 1958 and 1962 chloride containing curing accelerators and high-alumina cement were banned from use in reinforced concrete. Nowadays, these problems are solved. Numerous dry room ceilings still contain components made out of high-alumina cement, the dreaded cement stone conversion, however, and steel corrosion cannot occur in the absence of humidity.

Table 2. Analysis of bleeding water
Tabelle 2. Analyse von Blutwasser

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
thiocyanate	0.13 – 0.50	g/l
pH-value	10 – 13	

In the following period get another problem arose when as an active substance thiocyanate in low concentration was added to liquefiers as additives for concrete. With regard to crack initiation in the event of hydrogen induced stress-corrosion cracking the agents act unfavourably similar to sulphide sulphur. In a typical damage assessment for prestressing steel failures with not yet injected post-tensioning tendons Table 2 shows the corrosion prone water-soluble contents of chloride, sulphate and thiocyanate found in the concrete source material and also the contents of these substances found in the aqueous concrete samples. Sulphates and thiocyanates in particular are capable of fortifying themselves in corrosion amplifying concentrations in the bleeding water of the concrete. Dissolved in water, they penetrate the not injected ducts, favouring pitting corrosion (sulphate) or hydrogen adsorption of the prestressing steels (thiocyanate) respectively [12].

4.4 Unsuitable (sensitive) prestressing steels

With regard to the durability of prestressed concrete structures the susceptibility of prestressing steels to corrosion attack is of great significance. Here, all kinds of corrosion (e.g. pitting and wide pitting corrosion, hydrogen embrittlement, stress corrosion cracking, fatigue corrosion, fretting corrosion) must be considered which can occur as a result of the interaction of the type of steel on the one hand and the chemical or mechanical exposure on the other (section 5).

A prestressing steel is for instance considered to be susceptible to hydrogen induced stress-corrosion cracking (section 5.2.2) where minimal hydrogen quantities stemming from corrosion will suffice to cause irreversible damage on prestressing steel. Particularly in connection with the afore-mentioned bad influences of insufficient design (poor construction), incorrect execution of planned design (poor workmanship), unsuited building materials such by now out-lawed types of prestressing steel not sufficiently resistant to stress-corrosion cracking had the most detrimental impact on the durability of prestressed concrete structures [2, 4, 11, 13 – 15]. But even under optimal on-site conditions there were serious problems in the application of certain types, i.e. no serious mistakes could be demonstrated against the planners or those executing the work. The fact that it took years to recognize the insufficient suitability of the steels had to do, among others, with the absence of suitable test prodedures to recognize at an early stage the susceptibility to hydrogen induced stress-corrosion cracking. The most notorious exponents of such steels which are not sufficiently resistant against hydrogen are hot rolled bars with bainitic structure and quenched and tempered wires of an old type (production period till 1965) [8, 13].

Based on damage experiences and on laboratory testing we now know that the susceptibility to hydrogen-induced stress corrosion cracking increases greatly with increasing strength [16]. An assessment of numerous stress corrosion tests conducted in accordance with the FIP-standard showed that increasing the strength of cold deformed steel from 1700 to 2000 N/mm^2 leads to a drop in the service life of a factor of 100. Therefore the upper strength of prestressing steels is limited in Germany to about [17]:

1400 N/mm^2 for hot rolled steel
1700 N/mm^2 for quenched and tempered steel,
1950 N/mm^2 for cold deformed steel.

At this point in time there are no indications that the types of prestressing steels currently in use world-wide are particularly hazardous, which means that normally these steels are sufficiently robust. Nevertheless in connection with special circumstances, discussed in section 4, all types of prestressing steels may suffer corrosion induced problems.

Standardized tests for checking the susceptibility of prestressing steels to hydrogen induced stress-corrosion cracking are available [15]. The development and application of an improved corrosion testing in Germany (DIBt-test) is a consequence of damage caused by using unsuitable prestressing steel. In most cases stress-corrosion tests are carried out according to the so called FIP-standard in a highly concentrated thiocyanate solution. The result of such a testing is a brittle fracture after hydrogen charging and general embrittlement of the whole cross section. The newly used test solution is adopted to practical media over a testing time of 2000 h. The advantage of this testing procedure is that the mechanism of cracking agrees with that observed in practice. It is a pitting induced stress corrosion cracking (section 5.2.2) where the crack initiation is connected with corrosion processes on the steel surface. In Table 3 the conditions of the FIP- and the German long time test are compared. The new test is applied in steel production quality control and also in examining causes of damage. The main observation is that all steels which caused difficulties in practice failed within 2000 h.

In Fig. 2 results of tests with cold deformed wires are shown. The strength of the steels increases from left to right. In the FIP-test the lifetime decreases steadily with increasing strength. In the long time DIBt-test only steel with a high strength failed.

5 Fracture mechanism 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.

5.1 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 permissable prestrain 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).

5.1.1 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 stage due to brittle fracture. The following effects are capable of triggering such attacks in prestressing steel:

Table 3. Parameters and criteria of stress corrosion-test of prestressing steels
Tabelle 3. Parameter und Kriterien des Spannungsrißkorrosionstests von Spannstählen

standard	concentration	temperature	stress	lifetime (request)
FIP	20 mass.-% NH_4SCN	50 °C	0.8 R_m	hot rolled > 30–50 h quench., temp. > 10–15 h cold-deformed > 2–3 h
DIBt	0.5 g/l Cl^- 5 g/l SO_4^{2-} 1 g/l SCN^-	50 °C	0.8 R_m	> 2000 h

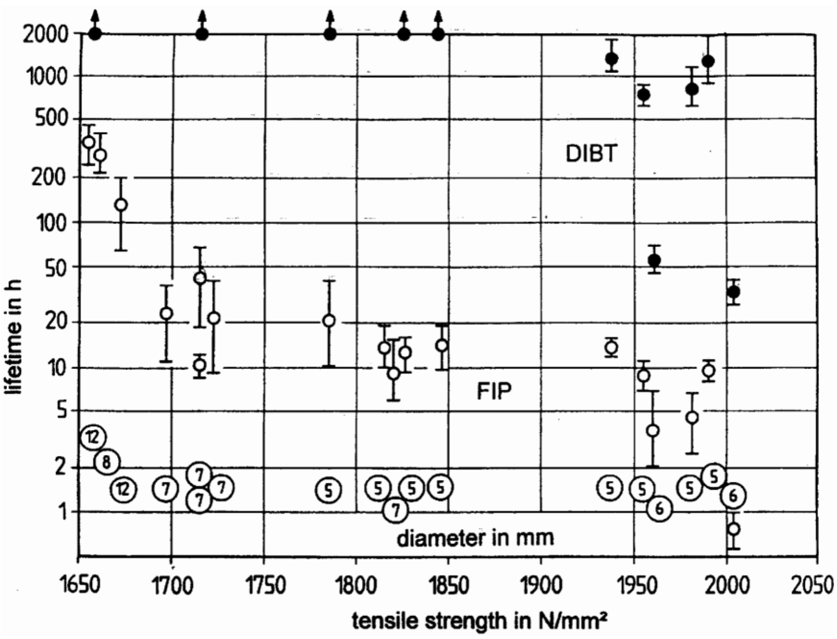

Fig. 2. Results of stress corrosion tests of cold deformed wires after FIP- and (German) DIBt-guidelines [11]

Abb. 2. Ergebnisse von Spannungsrisskorrosionsversuchen an kaltumgeformten Drähten im FIP- und (deutschen) DIBt-Versuch [11]

- 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 2) 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.
- 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 [18] (Fig. 3). Such tests to establish the residual load bearing cpacity 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. 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. 3, 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. 3, 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 h. In this example these life times are underrun at corrosion depths of > 0.2 mm (Fig. 3, stress corrosion test).

5.1.2 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 (section 5.2.2). 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 [19], more so on the deformation properties than on the tensile strength (Fig. 4).

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 damage, indeed, should not occur.

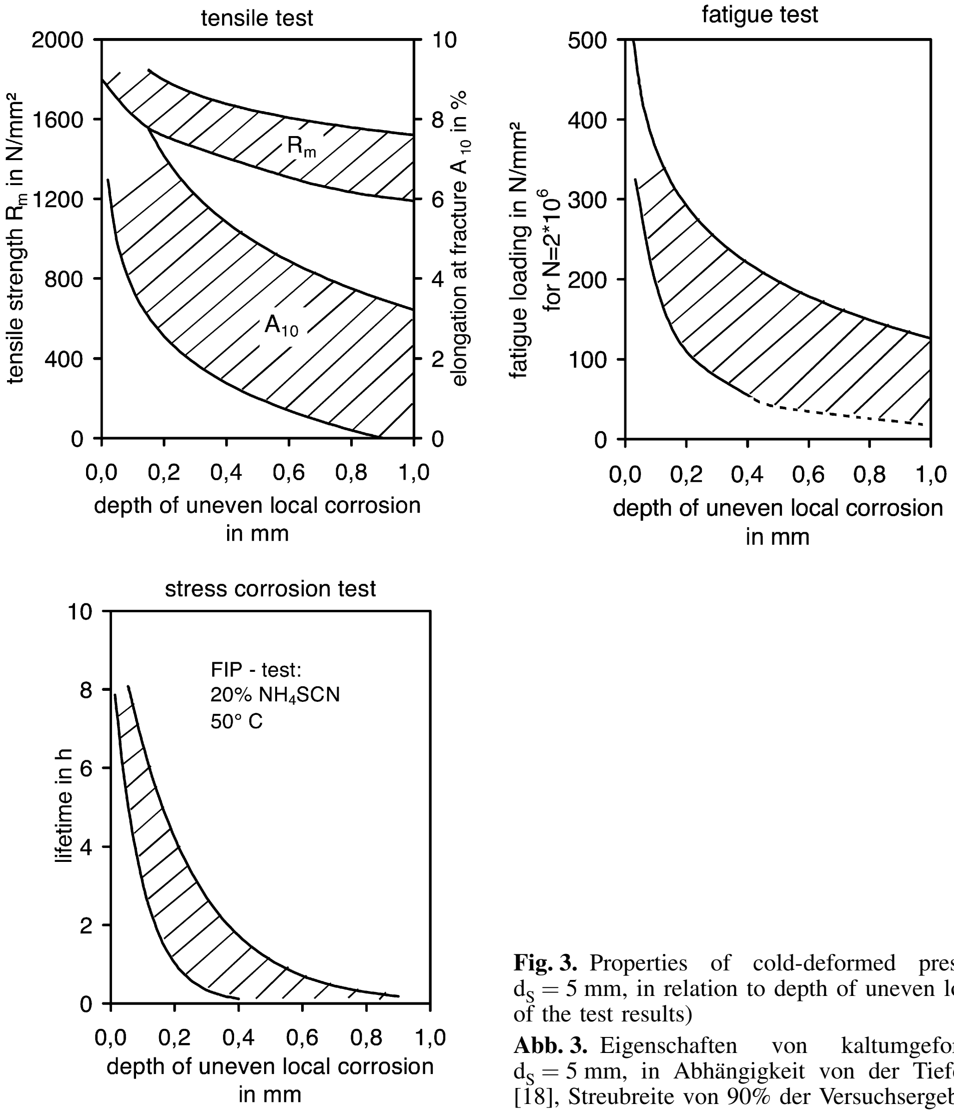

Fig. 3. Properties of cold-deformed prestressing steel wires St 1570/1770, $d_S = 5$ mm, in relation to depth of uneven local corrosion [18] (scattering of 90% of the test results)

Abb. 3. Eigenschaften von kaltumgeformten Stahldrähten St 1570/1770, $d_S = 5$ mm, in Abhängigkeit von der Tiefe eines örtlichen Korrosionsangriffes [18], Streubreite von 90% der Versuchsergebnisse)

5.2 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.

5.2.1 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 [17] 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 [17].

A specific nitrate sensitivity of the steels is always a pre-condition for an anodic stress-corrosion cracking. Low-carbon reinforcing 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 [20].

5.2.2 Hydrogen induced stress corrosion cracking [11, 15, 16, 21, 22]

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.

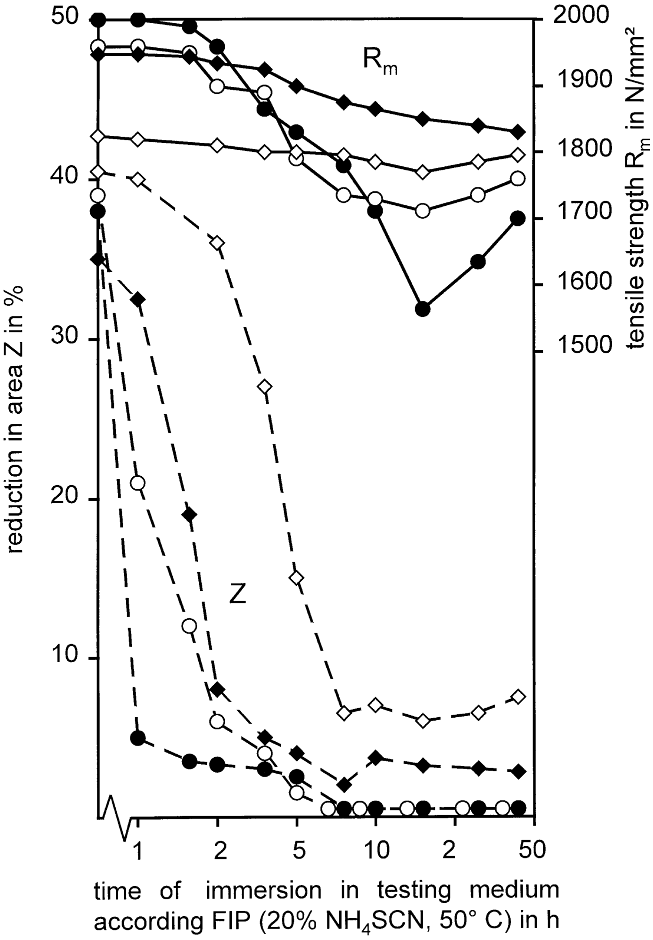

Fig. 4. Tensile strength (R_m) and reduction in area (Z) of cold deformed prestressing steel wires (4 steel melts) after charging with hydrogen [19]

Abb. 4. Zugfestigkeit (R_m) und Brucheinschnürung (Z) von kaltumgeformten Spannstahldrähten (4 Stahlschmelzen) nach Wasserstoffbeladung [19]

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.

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 4). 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).

Table 4. Chemical reactions of corrosion
Tabelle 4. Chemische Reaktionen der Korrosion

anodic iron dissolution
① $Fe \rightarrow Fe^{2+} + 2e^-$

cathodic reactions

if pH > 7
② ${}^1/_2 O_2 + H_2O + 2e^- \rightarrow 2OH^-$

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 $H_{ad} + {}^1/_2 O_2 \rightarrow H_2O$
if oxygen is present

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 damage is 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.

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. 5). 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. Pittings 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, section 5.1.1), 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 damage. 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 pre-conditions 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

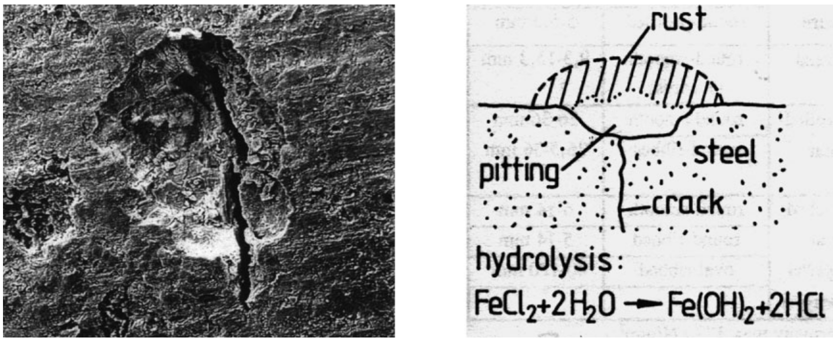

Fig. 5. Pitting induced stress corrosion cracking

Abb. 5. Lochfraßinduzierte Spannungsrisskorrosion

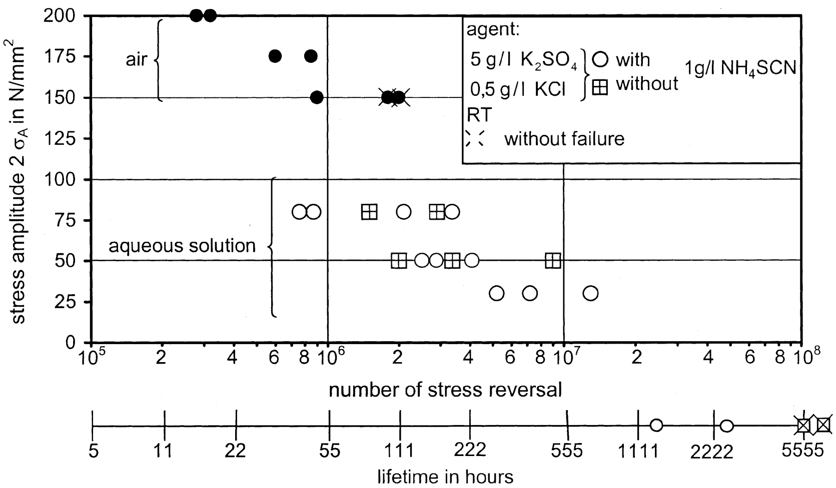

Fig. 6. Stress corrosion-behaviour of prestressing steel St 1420/1570 (German standard), ∅12.2 mm without and with dynamic stress of low amplitude [24]

Abb. 6. Spannungsrisskorrosionsverhalten eines Spannstahls St 1420/1570 (deutscher Standard), ∅12,2 mm ohne und mit Schwingbeanspruchung einer niedrigen Amplitude [24]

it will favour hydrogen induced "non-classical" stress-corrosion cracking [17, 23]. Plastic flow in steel favours an absorption of atomic hydrogen.

Fig. 6 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) [24]. 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 fatigue test. Fig. 6 represents the stress cycle number as a function of the amplitude, in the course of which also the life time, calculated over the frequency ($f = 5\ s^{-1}$), 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 h 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 susceptability of prestressing steels to stress-corrosion cracking.

5.3 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 [25]. 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:

5.3.1 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 [17] 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

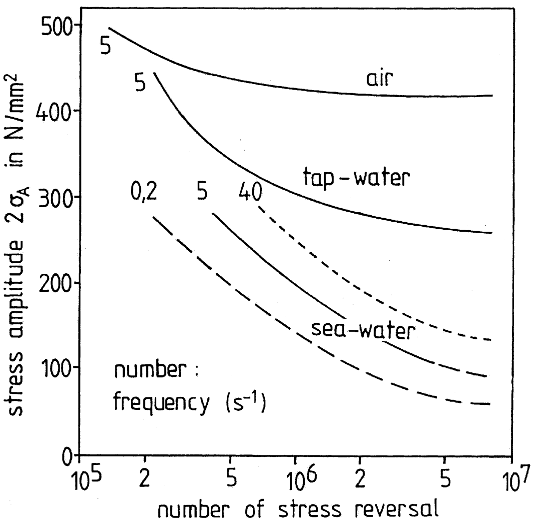

Fig. 7. Fatigue behaviour under pulsating tensile stresses of cold drawn prestressing steel wires ($R_m \approx 1750$ N/mm^2) in air and corrosion-promoting aqueous solutions [17, 23]

Abb. 7. Ermüdungsverhalten unter Zugschwellbeanspruchung von kaltumgeformten Spannstahldrähten ($R_m \approx 1750$ N/mm^2) in Luft und korrosionsfördernden Lösungen [17, 23]

and may even suffer fatigue fractures under dynamic stress [26].

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 of corrosion will increase and the fatigue limit will consequently drop.

For a cold drawn prestressing steel wire Fig. 7 shows a decrease of the corrosion fatigue limit in the sequence air-water-chloride solution. For frequencies of 0.5 s^{-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.

5.3.2 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 [17]. 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 [27]. 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 prepressing steel and duct or injection mortar respectively, tolerable fatigue limits of about 150 N/mm^2 for cycles to fracture of $2 \cdot 10^6$ were found [10, 26].

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 [28]. 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, 10].

6 References

[1] Durability of post-tensioning tendons. Proceedings of workshop held in Gent University on 15–16 November 2001. fib technical report, bulletin 15.

[2] *U. Nürnberger:* Forschung, Straßenbau und Straßenverkehrstechnik *308* (1980) 1–195.

[3] *U. Nürnberger, B. Neubert:* In: Fortschritte im Konstruktiven Ingenieurbau, Verlag Ernst & Sohn, Berlin 1984, pp. 111–124.

[4] *U. Nürnberger:* Influence of material and processing on stress corrosion cracking of prestressing steel (case studies). Publ. of fib commission 9.5, to be published.

[5] *H. R. Ganz:* In: [1], pp 155–171.

[6] *U. Nürnberger:* Schriftenreihe FMPA Baden-Württemberg (Otto-Graf-Institut) *79* (1988) 1–153.

[7] *J.-Ph. Fuzier:* in [1] pp 173–194.

[8] *U. Nürnberger:* In: Vorträge Betontag 1999, Verlag Ernst & Sohn, Berlin 2000, pp. 623–637.

[9] *M. E. Raiss:* In: [1], pp. 203–220.

[10] *G. König, R. Maurer:* Forschung, Straßenbau und Straßenverkehrstechnik (1990) 590.

[11] *U. Nürnberger:* Werkstoffe und Korrosion *48* (1997) 602.

[12] *G. Rehm, U. Nürnberger, R. Frey:* Bauingenieur *56* (1981) 275.

[13] *U. Nürnberger:* In: [1], pp. 89–101.

[14] *J. Mietz, K. Pasewald, B. Isecke:* Abschlußbericht zum DIBt-Forschungvorhaben AZ: IV 1-5-651 (1998), *B. Isecke, J. Mietz*, 33. DafStb-Forschungskolloquim, BAM Berlin, 10. and 11.10.1996, Vortragsbeiträge pp. 135–139.

[15] *B. Isecke:* Kritische Beurteilung neuer Spannstahlentwicklungen. Forschungsbericht im Auftrag des Deutschen Beton-Vereins e.V., Berlin 1998.

[16] *G. Hampejs:* Österreicher Betonverein (1986) 303.

[17] *U. Nürnberger:* Korrosion und Korrosionsschutz im Bauwesen. Bauverlag, Wiesbaden 1995.

[18] *B. Neubert, U. Nürnberger:* Erkennen von Spannverfahrensschädigung – Untersuchung der statischen und dynamischen Kenngrößen in Abhängigkeit von Rostgrad. Bericht II.6-13675 der FMPA Baden-Württemberg, Otto-Graf-Institut, Stuttgart 31.01.1983.
[19] *U. Nürnberger, W. Beul:* Entwicklung einfacher und reproduzierbarer Prüfverfahren für die Empfindlichkeit von Spannstählen gegenüber Spannungsrißkorrosion, Bericht 34-14071 der FMPA Baden-Württemberg, Otto-Graf-Institut, Stuttgart 01.03.1996.
[20] *G. Rehm, U. Nürnberger:* Cement (niederländisch) *XXIV* (1972) 106.
[21] *D. Grimme, B. Isecke, U. Nürnberger, E. M. Riecke, G. Uhlig:* Spannungsrißkorrosion in Spannbetonbauwerken. Verlag Stahleisen mbH, Düsseldorf 1983.
[22] *U. Nürnberger:* Maschinenmarkt *95* (1989) 30, 68 and 128.
[23] *D. Wiume, U. Nürnberger:* Werkstoffe und Korrosion *37* (1986) 485.
[24] *U. Nürnberger, W. Beul:* In Bewehrte Betonbauteile unter Betriebsbedingungen, Wiley-VCH Verlag 2000, pp. 302 – 309.
[25] *U. Nürnberger:* Bauingenieur *56* (1981) 311.
[26] *M. Patzak:* Dissertation, Universität Stuttgart, 1979
[27] *H. Cordes:* Schriftenreihe Deutscher Ausschuß für Stahlbeton *370* (1986).
[28] *G. Rehm, U. Nürnberger, M. Patzak:* Bauingenieur *52* (1977) 287.

(Received: February 28, 2002) W 3623