CORROSION INDUCED FAILURES IN PRESTRESSED CONCRETE STRUCTURES AND PREVENTATIVE MEASURES

KORROSIONSBEDINGTE SCHÄDEN IN SPANNBETONKONSTRUKTIONEN UND HIERAUS ABGELEITETE PRÄVENTIVMASSNAHMEN

DOMMAGES EN CONSEQUENCE DE CORROSION DANS DES CONSTRUCTIONS EN BETON PRECONTRAINT ET DES MESURES PREVENTIVES

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SUMMARY

During the past 40 years in Germany some serious damages in post- and pre-tensioned components have been occurred because of stress corrosion cracking of prestressing steel. Especially those problems caused a great stir, where the attendant circumstances of design, execution and building materials were not unusual. But the prestressing steel was unsuited to resist the inevitable conditions on construction site and inside the construction.

Therefore some important measures and corrections were introduced to reduce number of damages related to stress corrosion cracking. They include improved standards and recommendations for planning and executions of new constructions and for strengthening of older ones. Research was done to de-velop non-destructive measuring techniques to investigate older prestressed constructions. With regard to building materials such materials which not guarantee durable protection of the embedded steel had been forbidden and a steady control prevents that unwelcome materials can come on the market. As well as hot rolled bars, the quenched and tempered wires and the cold deformed wires and strands had been improved in the last 40 years.

ZUSAMMENFASSUNG

Innerhalb der letzten 40 Jahre kam es in Deutschland zu einigen schwerwiegenden Schäden in Spannbetonbauteilen mit sofortigem und nachträglichem Verbund, die auf Spannungsrißkorrosion der Spannstähle zurückgeführt werden konnten. Besonders jene Fälle erregten die Aufmerksamkeit, bei welchen die näheren Begleitumstände hinsichtlich der Planung, Ausführung und verwendeten Baumaterialien nicht ungewöhnlich waren. Jedoch war der Spannstahl ungeeignet, den unvermeidbaren Bedingungen auf der Baustelle und innerhalb der Konstruktion zu widerstehen.

Deshalb wurden einige wesentliche Maßnahmen und Neuerungen eingeführt, um die Zahl der korrosionsbedingten Schädigungen herabzusetzen. Diese beinhalten verbesserte Normen und Empfehlungen für die Planung und Ausführung neuer Konstruktionen sowie die Instandsetzung älterer. Forschung wurde durchgeführt, um zerstörungsfreie Meßmethoden zu entwickeln, die es erlauben ältere vorgespannte Konstruktionen zu untersuchen. Baumaterialien, die einen dauerhaften Schutz des eingebetteten Stahls nicht garantieren, wurden verboten und ständige Kontrollen stellen sicher, daß ungeeignete neue Materialien auf den Markt kommen. Bei den Spannstählen wurden sowohl die warmgewalzten als auch vergüteten und kaltumgeformten Drähte und Litzen innerhalb der letzten 40 Jahre ständig verbessert.

RESUME

Pendant les derniers 40 ans, il y avait en Allemagne quelques dommages assez graves dans des éléments de construction en béton précontraint avec adhésion immédiate ou ultérieure (post-tendu), qui pouvaient être ramenés à une corrosion fissurante. L'attention attiraient en particulier ces cas, où les conditions concernant la planification, la réalisation et les matériaux de construction n'étaient pas extraordinaires. Toutefois, l'acier ne pouvait pas résister aux influences inévitables du chantier en général et dans la construction en particulier.

Pour diminuer les dommages à cause de la corrosion, quelques mesures et innovations essentielles étaient introduites. Celles-ci comprennent des normes et des recommandations perfectionnées pour la planification et la réalisation de nouvelles constructions et la mise en état des constructions plus âgées. On a exécuté des recherches pour développer des méthodes de mesure non-destructives, qui permettent l'examination des constructions précontraintes plus âgées. Les matériaux de construction, qui n'etaient pas capables de protéger l'acier à une longue vue, sont interdits; des contrôles permanents empêchent la distribution des matériaux inconvenables. En ce qui concerne l'armature de pré-contrainte, il faut constater, que pas seulement les fils et les torons cylindrés à chaud ou écrouissés, mais aussi les fils et torons traités par trempe et revenu, étaient améliorés continuellement pendant les derniers 40 ans.

KEYWORDS: prestressed concrete, prestressing steel, stress corrosion crack-ing, failures, durability, corrosion protection

1. INTRODUCTION

In prestressed concrete the purpose of prestressing lays in exerting pressure on the low tensile strength concrete in that areas, where the concrete normally is exposed to tensile stresses and threated by cracking and failure. Therefore in prestressed concrete structures the high strength prestressing steel performs essential bearing action.

In posttensioned concrete members high strength steel wires, strands or bars are arranged in ducts. After casting and hardening of concrete the prestressing reinforcement is tensioned and compressive stresses are generated in concrete. After that ducts are grouted with cement mortar, in order to protect the steel against corrosion and to guarantee a permanent load capacity.

During the past 40 years in Germany some serious damages in post-tensioned and pre-tensioned components have been occurred because of stress corrosion cracking of the prestressing steel [1-3]. These failures happened due to onsite conditions and were favoured of the sensitiveness of the used prestressing steel.

Stress corrosion cracking and the subsequent failure of steel and construction may occur

- if the protection is not guaranteed from the beginning as a result of poor workmanship,

- or it is lost because of deterioration of the construction in the course of the time,
- or the prestressing reinforcement is predamaged during handling.

Also an application of unsuitable materials for prestressing steel, injection mortar or concrete can alone or in combination with other factors favour SCC.

2. THE BASIS OF STRESS CORROSION CRACKING

Fractures of prestressing steel as a rule can be refered to hydrogen induced stress corrosion cracking (H-SCC) [4,5]: It may happen during erection of the construction or during the later use. The following conditions are necessary for H-SCC:

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

During the corrosion process hydrogen atoms have to 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 atoms. To understand the correlations between procedure on site and development of damage, the chemical reactions of corrosion should be considered (table 1).

Table 1: *Chemical reactions of corrosion*

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

cathodic reactions
⑤ $\frac{1}{2} 0_2 + H_2O + 2e^- \rightarrow 2\ OH^-$

if pH < 7 ⑤:
⑤ $H^+ + e^- \rightarrow H_{ad}$ **(hydrogen discharge)**

rivalry reaction with regard to ⑤
⑤ $2H_{ad} \rightarrow H_2$ **(recombination)**
is prevented in the presence of promotors

⑤ $2H_{ad} + \frac{1}{2} O_2 \rightarrow H_2O$
if oxygen is present or air access

Harmful hydrogen can arise only

- if the steel surface is in the 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),
- if the adsorbable atomic hydrogen is not changed into the molecular state (see reaction 4).

Therefore at the surface of corroding steel amount of adsorbable hydrogen atoms rises

- with increasing hydrogen concentration (reaction 3 is accelerated),
- in the presence of so-called promotors (reaction 4 is hindered).

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

- in acid mediums
- or in the presence of promotors such as sulphides, thiocyanates and compounds of arsenic or selenium.

In concrete structures the attacking medium is mostly alkaline and acid solutions are limited to exceptions. Nevertheless, in natural environments the pitting induced H-SCC can take place (Fig 1). 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 corrosions can be explained by differential aeration or concentration cells. Especially effective is the attack of condensation water or salt enriched watery solutions when erecting the constructions. In prestressed construction carbonation of concrete and mortar as well as chloride contamination are responsible of local corrosion attack.

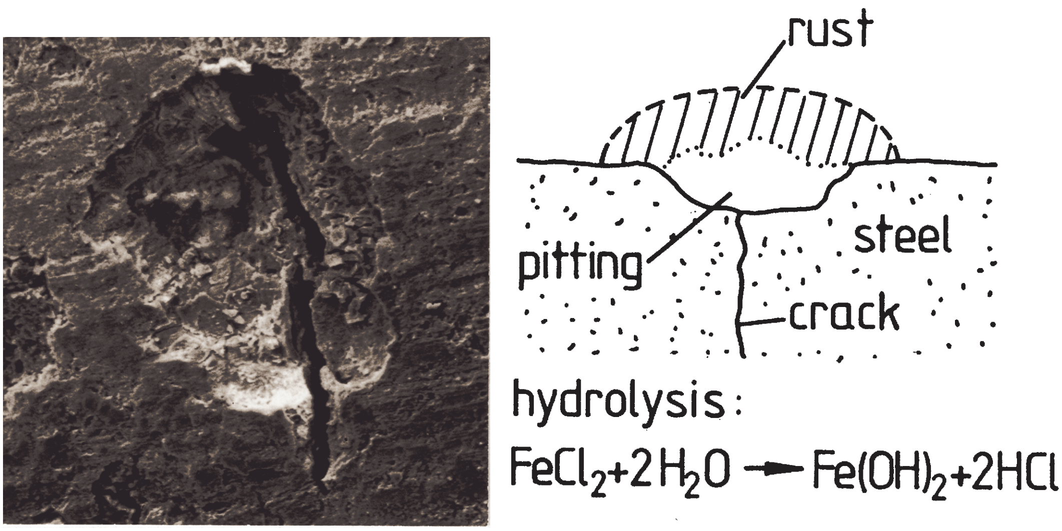

Fig. 1: *Pitting induced stress corrosion cracking*

3. PRESTRESSING STEEL

In case of sensitive prestressing steel already minimal contents of hydrogen can lead to irreversible damages. Therefore the steel quality and the susceptibility to hydrogen of the applied steel melt is of enormous importance [6,7]. In Table 2 one can find a survey of the different steel types. World wide dominates the application of cold deformed wires and strands. They yearly production of cold deformed material is 1 million tons. The strength of commonly used cold deformed prestressing material amounts with falling diameter of the wire from 1570 up to 2060 N/mm^2. In the case of strands the upper strength limit is higher.

Table 2: *Survey about produced prestressing steel*

type	shape, surface	diameter	anchorage system	strength class European Standard	production (world wide) tons/year
cold deformed •wire	round -smooth	4-12,2 mm	wedge or button heads	1570-1860[1)] (N/mm^2)	1.000.000 (world wide)
	round-profiled	5-5,5 mm			
•strand	round-smooth (7 wires)	9,3-15,3 mm		1700-2060[1)] (N/mm^2)	
hot rolled •bar	round-smooth	26-36 mm	thread (ends)	1030-1230 (N/mm^2)	50.000 (Germany, UK)
	round-ribbes	26,5-36 mm	thread (full length)		
quenched and tempered •wire	round-smooth	6-14 mm	wedge	1570 (N/mm^2)	5.000 (Germany, Japan)
	round-ribbed	5-14 mm			
	oval-ribbed	40-120 mm^2			

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

The larger diameter hot rolled bars with 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 is with yearly 5.000 tons significantly lower. Their strength corresponds with those of the larger diameter deformed wires. Hot rolled and quenched and tempered steel are produced only in few countries.

Table 3 summarises the advantages and application of the different steel types. Cold deformed steel may be applied for all types of prestressing and in all types of members. This material is economical to produce and relatively high strength can be reached. The strand has an advantage of easy transport and storage, flexibility, easy installation and good bond behaviour. Nowadays the hot rolled bars and quenched and tempered steel have their special areas of application. Bars, which are tension members with high load-bearing capacity and easy handling, are given the preference if transverse prestressing and earth anchors are required. Ribbed quenched and tempered wire with oval cross section and very good bond behaviour are needed for prefabricated elements and sleeper for the railway.

Table 3: *Advantages and application of prestressing steel*

type	especial advantage	application
cold deformed •wire •strand	• economically to produce • high strength • low coil diameter, high coil weight (strand) • flexible tension members (strand) • easy to install (strand) • good bond behaviour (strand)	for all types of prestressing and all types of elements
hot rolled •bar	• tension members with high load • simple to anchor • easy handling • effective bond of ribs	transverse prestressing, earth anchors
quenched and tempered •wire	• very good bond behaviour	prefabricated elements, sleeper (railway)

4. REASON OF DAMAGES

In connection with special circumstances all types of prestressing steels may suffer SCC. Making a diagnosis of defective building can help to find solutions to avoid future problems. Reasons of damages of prestressed concrete structures can be classified as [3]:

- insufficient design,
- incorrect handling of building materials,
- incorrect execution of planned design,
- unsuitable mineral building materials,
- unsuitable (sensitive) prestressing steel.

The reason 1 to 4 are responsible for lack or time dependent loss of passivation and a promotion of SCC.

Damages as the consequence of these influences should not be the main topic of this contribution. However, especially those problems caused a great stir throughout the world of prestressed concrete, where the attendant circumstances of design, execution and building materials were not unusual. But the prestressing steel was unsuit to resist the inevitable conditions on construction site and inside the construction. During the last 10 years in Germany some serious damages in pre-tensioned and post-tensioned components have been occurred, which were strongly favoured by the sensitivity of the used prestressing steel. In the following two cases will be discussed and we will end up with conclusions respectively consequences.

Some cases steel fractures in the yet ungrouted ducts of post tensioned structures as well as serious collapses of building components can be attributed to the presence of aggressive water in the ducts which results from bleeding [6,8]. Bleeding is a separation of fresh concrete, where the solid content sink down and the displaced water rises or penetrates in inner hollows. In the bleeding water significantly high contents of sulphates and increased quantities of chlorides may be accumulated (Table 4) by leaching of the construction materials cement, aggregates and water. The high amounts of potassium-sulphate result from the gypsum in the cement. The watery phase of fresh concrete penetrates into the ducts through anchorages, couplings and defects in the sheet and accumulates at the deepest points. Already in the not grouted and not pre-stressed condition the steel may suffer from strong pitting. If the steel is sensitive to hydrogen pitting induced stress corrosion cracking takes place (Fig 2).

Table 4: *Analysis of bleeding water*

sulphate	1,90 - 5,20	mg/l
chloride	0,13 - 0,18	mg/l
calcium	0,06 - 0,09	mg/l
sodium	0,18 - 0,37	mg/l
potassium	3,60 - 7,30	mg/l
pH-value	10 - 13	

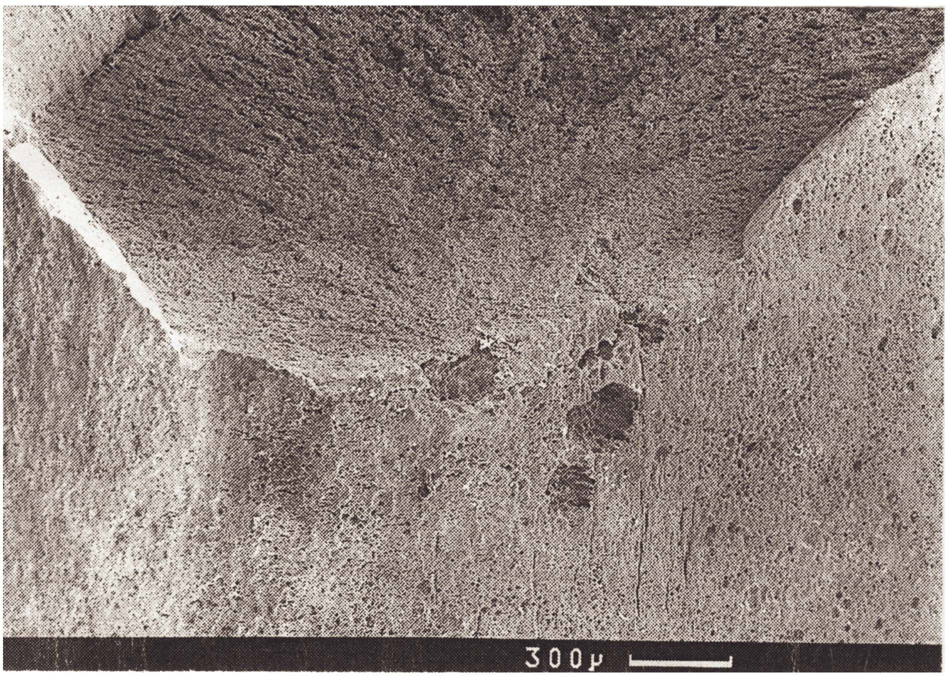

Fig. 2: *Fracture starting at a corrosion pit*

In some cases construction elements of buildings failed after more than 25 years as a consequence of SCC [2,3,5,6,8]. For example the beams of the roof of a laboratory had been affected causing the roof collapse (Fig 3). In an other case the beams over a factory building were affected. It was found, that in both cases the used quenched and tempered steel was very sensitive to hydrogen induced cracking. Investigations showed, that in the time of erecting the building the steel had suffered precorrosion and precracking probably owing to contact with normal influences such as condensing water and bleeding water. A conformation of this hypothesis gives this X-ray pattern photograph with many cracks in the steel (Fig 4). And it was concluded from the research, that the pre-cracks, initiated in a very early stage of the building, could grow discontinuously in the grouted state over a very long period of time.

Fig. 3: *Broken beam as a result of stress corrosion cracking*

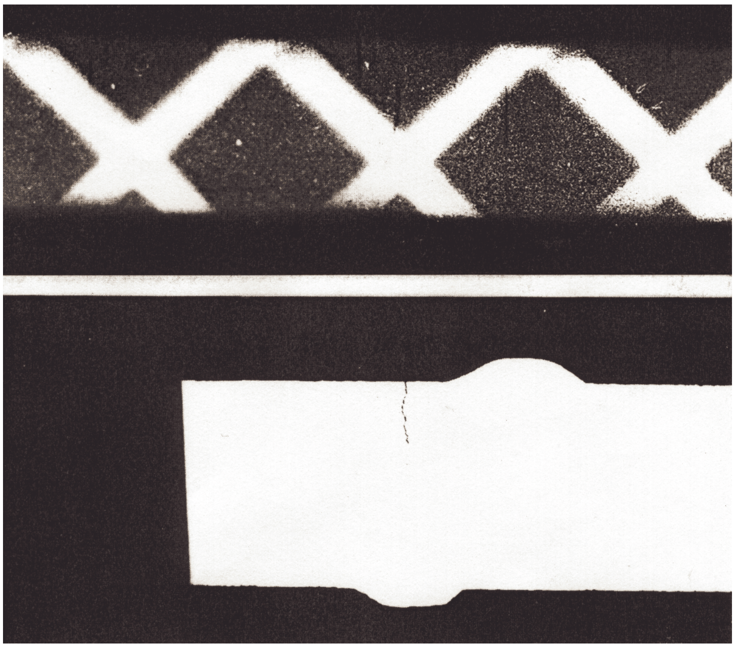

Fig. 4: *X-ray pattern photograph of a precracked steel, below: cut of the wire*

Fig 5 illustrates the typical intercrystalline fracture of the steel wires with crack propagation pattern on the grain faces. Such a mechanism evidently can occur only on the condition, that the prestressing steel has a very high sensitivity to SCC, that means it react to very small amounts of hydrogen.

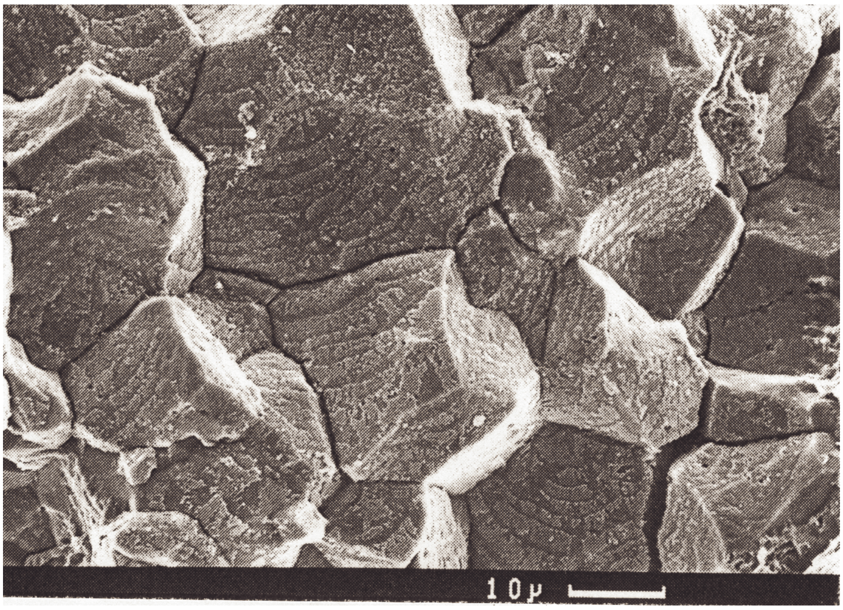

Fig. 5: *Intercrystalline fracture with crack propagation pattern on the grain faces*

The wires of the bundle were broken in one section. The ducts were grouted completely and fractures have occurred within an alkaline and chloride free mortar.

The problem of very high sensitivity of prestressing steel is not restricted to special steel types. A cold deformed wire was involved in another case. Numerous circularly wrapped and prestressed concrete pressure water pipes in the ground exploded after some years in service (Fig 6). As a consequence an extensive expanse has been flooded. During service life concrete cover had suffered loss of bond and microcracking by sulphate action. Responsible for this effect was the production technology of the pipes, namely the accelerated hydration by heat curing [5]. As a consequence the concrete around the steel, that means the concrete in the contact zone steel / concrete, was carbonated.

Fig. 6: *Stress corrosion cracking of a circularly wrapped pipe*

In this case the prestressing steel proved to be extremely sensitive to hydrogen influence. The strength of the steel was higher than 2000 N/mm^2 and as a result of radial shear stresses firstly longitudinal and later also transverse cracking took place (Fig 7).

Fig. 7: *Cracking of the cold deformed wires*

5. CONSEQUENCES

Table 5 summarises the most important measures introduced in Germany after some periods with increased number of damages related to SCC.

Table 5: *Reasons of damages of prestressed concrete structures and consequences*

reason of damage	consequences
insufficient design	• strengthening of construction • improved standards and recommendations for planning and execution of work • inspection of other constructions of the same kind • demolition of elements or construction
incorrect execution of planned design and incorrect handling of building materials	• see above • training and careful education of personnel • supplementary reinforcement to avoid unannounced failure
unsuitable mineral building materials	• limitation of chlorides in water, cement and aggregates • prohibition of cements, additives and accelerators which favour corrosion and hydrogen evolution
unsuitable (sensitive) prestressing steel	• prohibition of qualities, which suffer SCC under on-site conditions • development of steel types which are more resistant to hydrogen • limitation of maximum strength • long-time SCC-test (2000 h) under practical conditions

Corrections as a result of insufficient design are the concern of design engineer and of constructional experts. They include improved standards and recommendations for planning and execution of new constructions and for strengthening of older ones. Focus of the last years were measures during erection the building related to

- investigation of concrete technologies, which favour bleeding of fresh concrete.
- In this connection it was found, that addition of additives to fresh concrete such as retarder and liquefier may increase bleeding [6].

- In other cases it was recommended to flush out the salt rich bleeding water after concreting [4].
- A far reaching decision was the limitation of time between prestressing of steel and injection of ducts in German standard DIN 4227.

All measures had the aim to hinder corrosion and cracking before protecting reinforcement with injection mortar.

Much research was done to develop nondestructive measuring techniques to investigate older prestressed constructions. There exist numerous buildings where formerly produced prestressing steel was used. Nowadays we know because of other damages, that some of the older steel types are very sensitive to H-SCC. Therefore a magnetic methods was developed to assess cracks and fractures before a possible catastrophic collapse [9,10]. The prestressing steel is magnetised straight through the concrete cover by a strong magnet. Deep cracks and fractures are to detect by an alteration of the flow of the magnetic lines (Fig 8). To examine the magnetic flow, characteristically changed by cracks and fractures, a very sensitive Hall-analyser is used. It is carried on the concrete surface along the tension members. If a multitude of broken steel wires are detected and the further bearing capacity is not sure a demolition of the construction may be recommended.

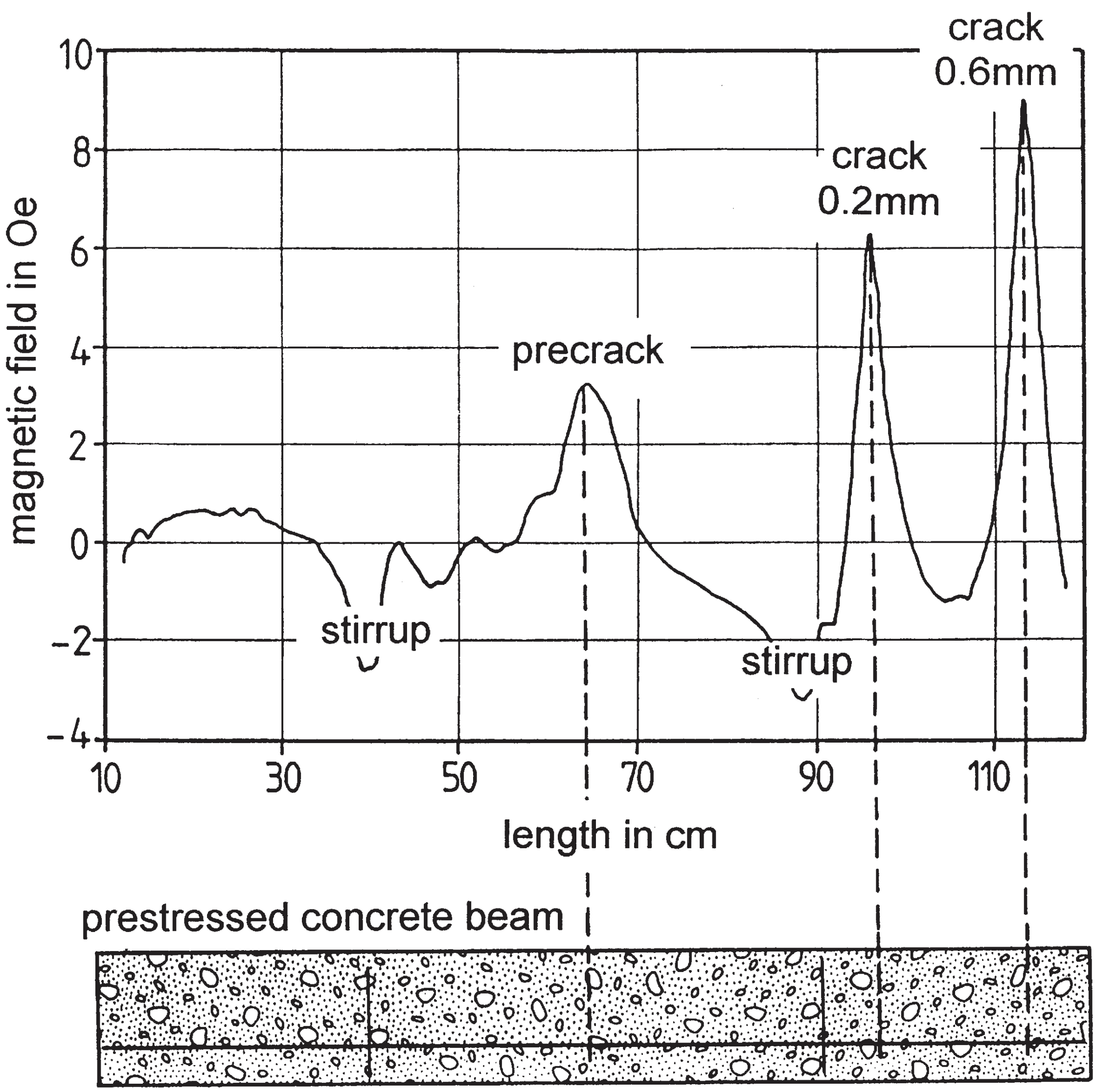

Fig. 8: *Magnetic field of a cracked wire embedded in concrete (Sawade)*

Further incorrect execution of the planned design and incorrect handling of the building materials may be found. For instance the concrete cover is too low and of no adequate quality or the ducts are not injected well. In such case the improper dealing with the prestressed concrete is responsible for problems.

In Germany the application of a supplementary reinforcement is under discussion [3]. In the case of loss of capacity a failure without warning should be avoided. This measure is very controversial discussed because it represents a turning away from the principle of prestressed concrete and induces economic disadvantage for the German construction industry.

With regard to building materials in the past strict instructions led to an essential reduction of failures [11]. Already 30 years ago the content of chlorides in water, cement and aggregates was limited to a very low level. Cements which not guarantee durable protection of the embedded steel had been forbidden, and a steady control prevents, that unwelcome materials can come on the market. That concerns all types of cements and additives, which are continuously investigated electrochemically with regard to corrosion and hydrogen evolution.

But the most radical change took place on the field of prestressing steel. In Germany a great variety of steel types is in use (section 3). New types find their way into the prestressing technique, other types are excluded because they not proved to be reliable. That means they suffered SCC under onsite conditions [1 - 3]. As well as hot rolled bars, the quenched and tempered and the cold deformed steel had been improved in the last 40 years.

Concerning the failures with quenched and tempered steel a so called old type of steel was involved [12]. In the beginning these material was carbon-silicon-manganese alloyed (Table 6). Because of a non sufficient stress corrosion cracking behaviour, already an attack of condensating water resulted in hydrogen induced problems, the chemical composition was changed in 1965 [13]. The carbon content was lowered and chromium was alloyed. Because of this precaution the full quenching and subsequent tempering was improved and the retained martensite and detrimental residual stresses were reduced. Further the manganese content was decreased and silicon content was increased. As a consequence absorption, solubility and diffusivity of hydrogen was considerably diminished [14].

Table 6: Analysis of quenched an tempered prestressing steel

	old type	new type
carbon	0.65	0.48
silicon	1.19	1.80
manganese	0.88	0.62
phosphorus	0.014	0.012
sulphur	0.020	0.014
chromium	0.04	0.46

As mentioned at the beginning the old type quenched and tempered steel was involved in numerous and serious damages. But nearly no failures happened after application of the new steel type.

In a similar action the sensitive hot rolled bar with bainitic structure 1985 was replaced by a new type pearlitic steel [5].

Based on experiences with damages and on laboratory testing we know, that the susceptibility to H-SCC increases greatly with increasing strength [5,6]. An interpretation of numerous SCC-tests conducted according to the FIP-standard showed, that with an increase of the strength of cold deformed steel from 1700 to 2000 N/mm^2 the service life drops by a factor of 100. Therefore the upper strength is limited in Germany to about

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

and there is no tendency to release this requirement. In the European standard EN 10138 an upward extension of the strength of cold deformed wire and strand is planned. In the case of strands the strength range is to be extended up to 2060 N/mm^2 which complies essentially with the wish of prestressing steel makers in France. Essential German objections to this European standard [15] are related to the extension of the strength limit for cold deformed material because a such high strength steel seems not to be sufficiently safe under practical conditions.

At long last also the development and application of an improved corrosion testing in Germany is a consequence of damages caused by using unsuitable prestressing steel [4,16,17]. In most cases SCC-tests are carried out according to the so called FIP-standard [18] in a highly concentrated thiocyanate solution. The result of the FIP-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 mediums over a testing time up to 2000 hours. The advantage of this standard testing procedure is, that the mechanism of cracking agrees with that observed in the practice. I is a pitting induced SCC where the crack initiation is connected with corrosion processes on the steel surface. In Table 7 the conditions of the FIP- and of the German long time test are compared. Besides a mixture of neutral salts the new solution contains also 0,5 g/l thiocyanate as a promotor in order to provide hydrogen in a amount which can occur in defective concrete constructions. The new test is applied in steel production quality control and also in examining causes of damages. The main observation is all steels or steel melts that caused difficulties on practice failed in standard test within 2000 hours. This observation is valid for cold deformed material, quenched and tempered wire and hot rolled bars.

Table 7: *Parameters and criteria of SCC-test of prestressing steels*

standard	concen-tration	tempe-ratur	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	>2000h

In Fig 9 the results of tests with cold deformed wires in comparison with those of the FIP-test are shown. The strength of the steel increases from left to right. In the FIP-test lifetime decreases steadily with increasing strength. In the long time test only steel with a very high strength failed. We may have stress corrosion fractures within 2000 hours, if the strength exceeds about 2000 N/mm^2. Similar results on quenched and tempered steels are published in [7].

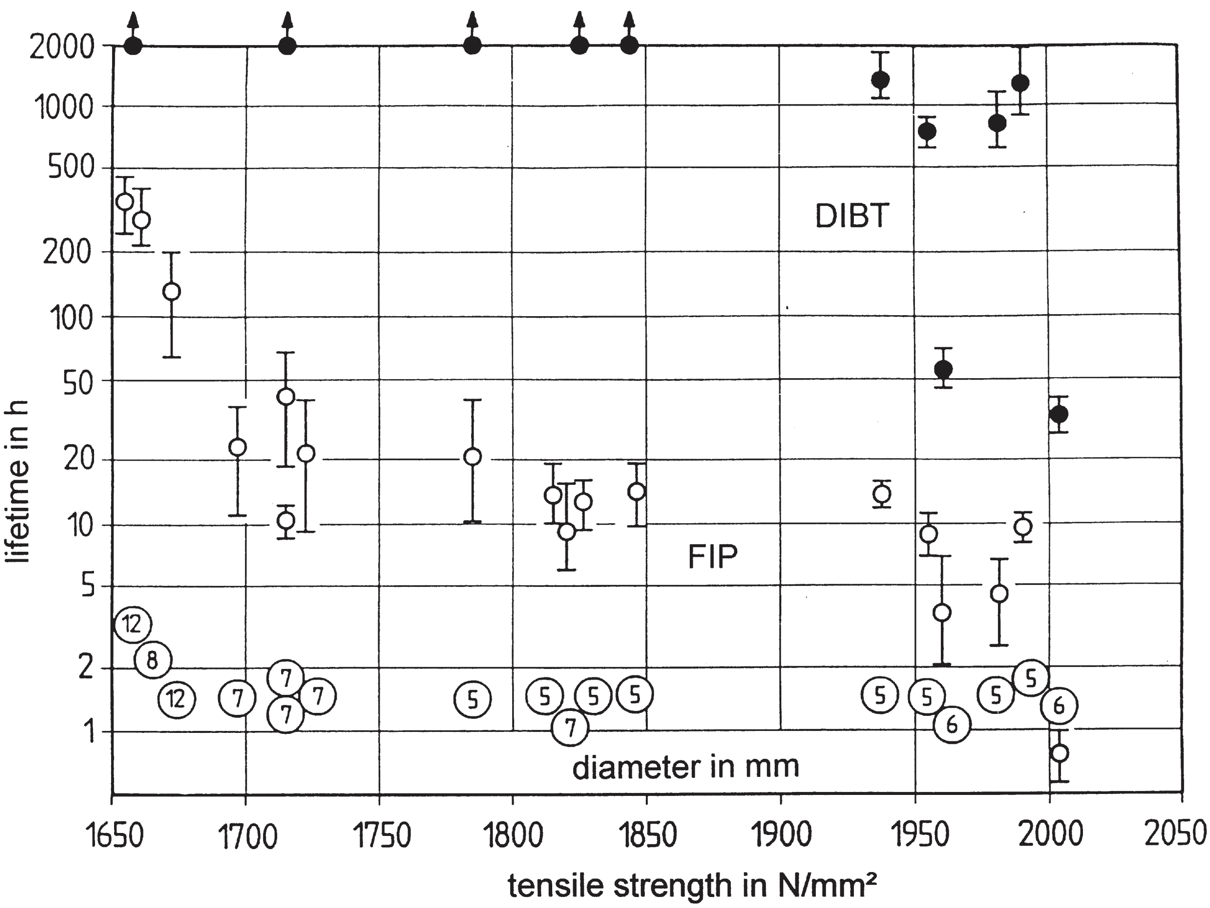

Fig. 9: *Results of stress corrosion tests of cold deformed wires after FIP- and (German) DIBT-guidelines*

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⑤ $2H_{ad} \rightarrow H_2$ **(recombination)**
is prevented in the presence of promotors

⑤ $2H_{ad} + \frac{1}{2} O_2 \rightarrow H_2O$
if oxygen is present or air access

Table 2: *Survey about produced prestressing steel*

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 (world wide)
•wire	round-profiled	5-5,5 mm	wedge or		
•strand	round-smooth (7 wires)	9,3-15,3 mm	button heads	1700-2060[1)] (N/mm^2)	
hot rolled	round-smooth	26-36 mm	thread (ends)	1030-1230 (N/mm^2)	50.000 (Germany, UK)
•bar	round-ribbes	26,5-36 mm	thread (full length)		
quenched and tempered •wire	round-smooth	6-14 mm	wedge	1570 (N/mm^2)	5.000 (Germany, Japan)
	round-ribbed	5-14 mm			
	oval-ribbed	40-120 mm^2			

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

Table 3: *Advantages and application of prestressing steel*

Table 4: *Analysis of bleeding water*

sulphate	1,90 - 5,20	mg/l
chloride	0,13 - 0,18	mg/l
calcium	0,06 - 0,09	mg/l
sodium	0,18 - 0,37	mg/l
potassium	3,60 - 7,30	mg/l
pH-value	10 - 13	

Table 5: *Reasons of damages of prestressed concrete structures and consequences*

Table 6: Analysis of quenched an tempered prestressing steel

	old type	new type
carbon	0.65	0.48
silicon	1.19	1.80
manganese	0.88	0.62
phosphorus	0.014	0.012
sulphur	0.020	0.014
chromium	0.04	0.46

Table 7: *Parameters and criteria of SCC-test of prestressing steels*

standard	concen-tration	tempe-ratur	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	>2000h

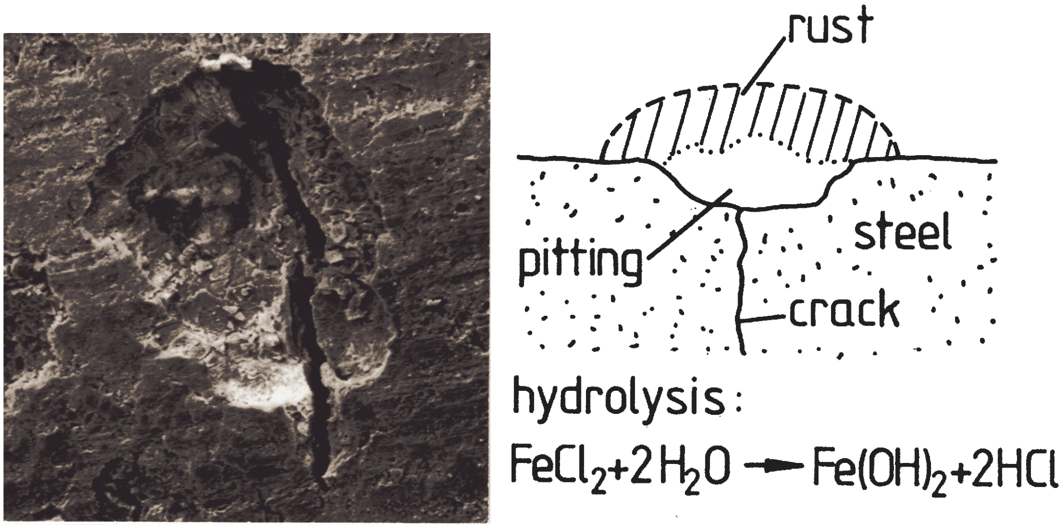

Fig. 1: *Pitting induced stress corrosion cracking*

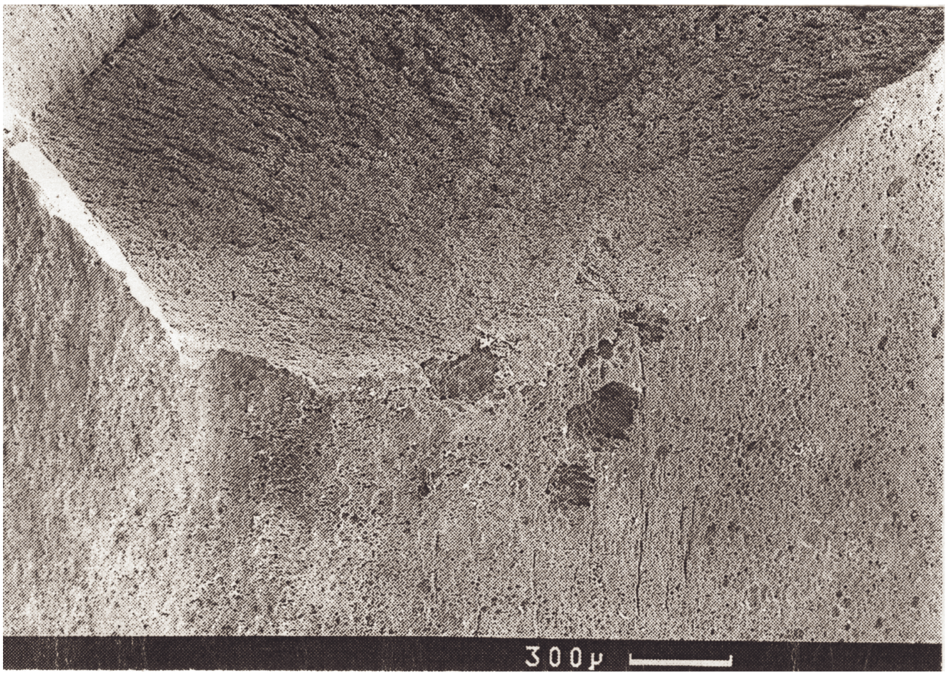

Fig. 2: *Fracture starting at a corrosion pit*

Fig. 3: *Broken beam as a result of stress corrosion cracking*

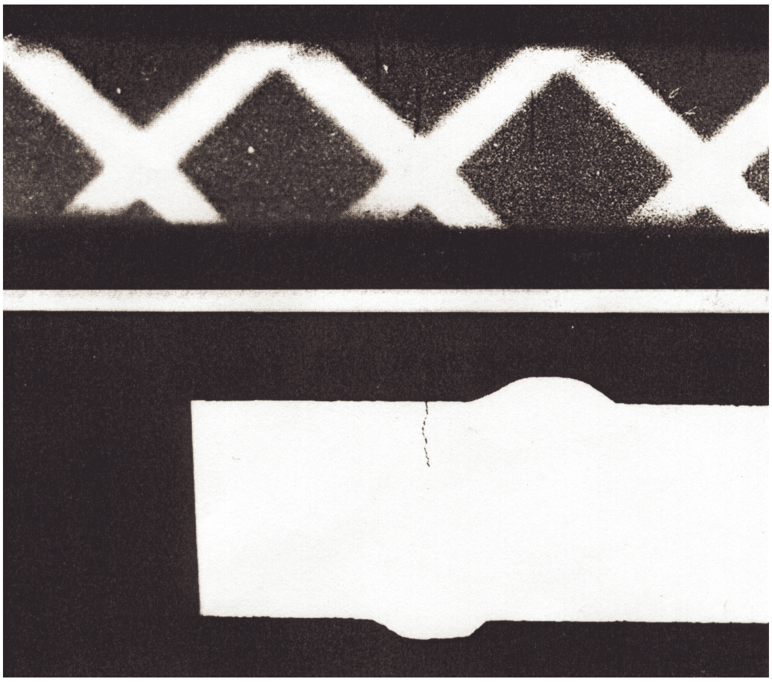

Fig. 4: *X-ray pattern photograph of a precracked steel, below: cut of the wire*

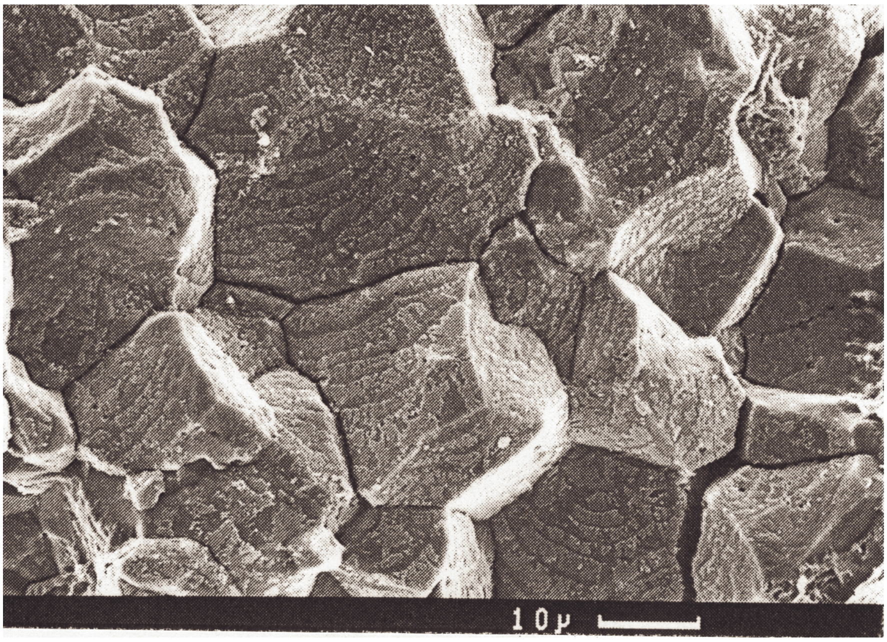

Fig. 5: *Intercrystalline fracture with crack propagation pattern on the grain faces*

Fig. 6: *Stress corrosion cracking of a circularly wrapped pipe*

Fig. 7: *Cracking of the cold deformed wires*

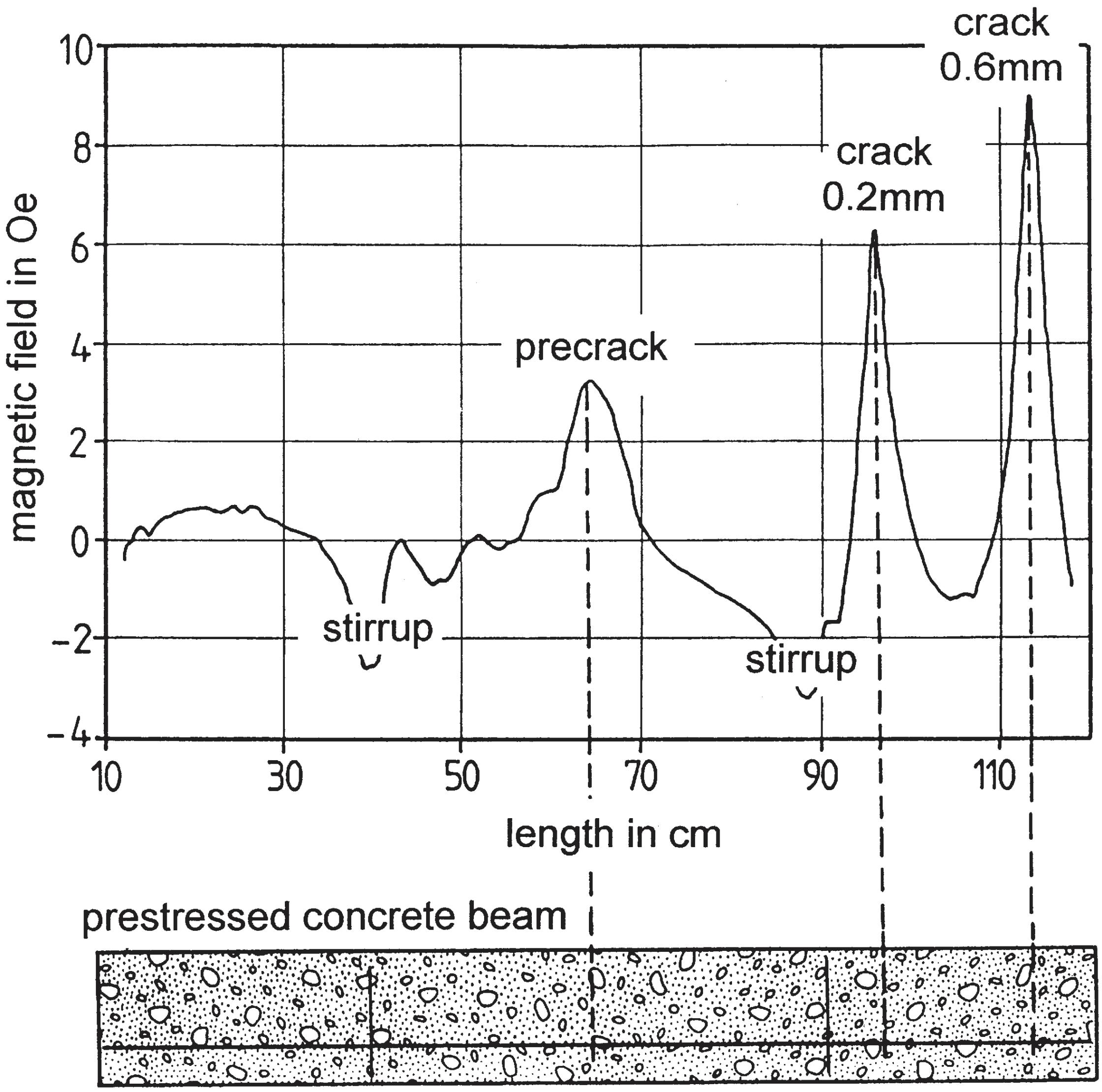

Fig. 8: *Magnetic field of a cracked wire embedded in concrete (Sawade)*

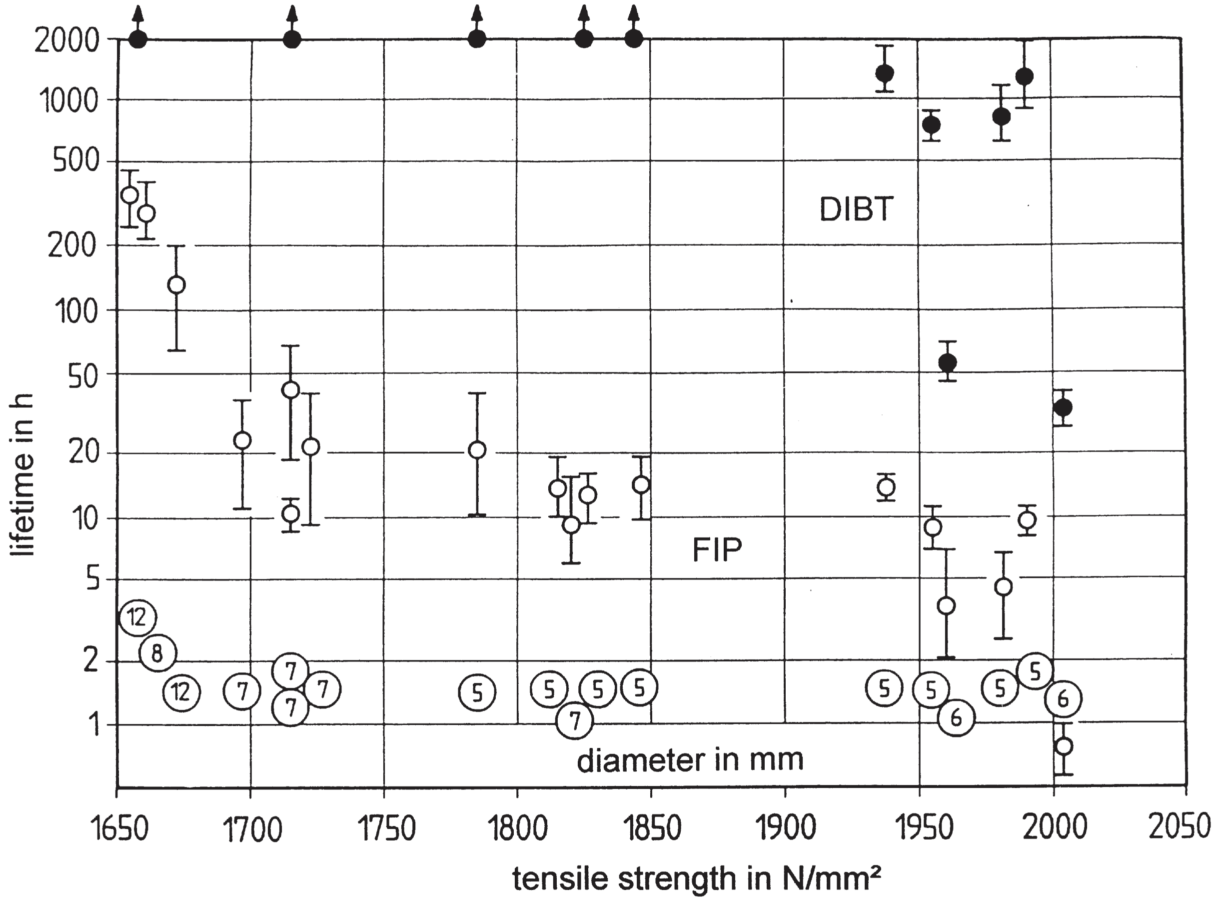

Fig. 9: *Results of stress corrosion tests of cold deformed wires after FIP- and (German) DIBT-guidelines*