Factory applied corrosion protection of prestressing steel
Factory applied corrosion protection of prestressing steel

State-of-art report prepared by
Task Group 9.1

January 2001
Subject to priorities defined by the Steering Committee and the Praesidium, the results of fib's work in Commissions and Task Groups are published in a continuously numbered series of technical publications called 'Bulletins'. The following categories are used:

<table>
<thead>
<tr>
<th>Category</th>
<th>Minimum approval procedure required prior to publication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Report</td>
<td>approved by a Task Group and the Chairpersons of the Commission</td>
</tr>
<tr>
<td>State-of-Art Report</td>
<td>approved by a Commission</td>
</tr>
<tr>
<td>Manual or Guide (to good practice)</td>
<td>approved by the Steering Committee of fib or its Publication Board</td>
</tr>
<tr>
<td>Recommendation</td>
<td>approved by the Council of fib</td>
</tr>
<tr>
<td>Model Code</td>
<td>approved by the General Assembly of fib</td>
</tr>
</tbody>
</table>

Any publication not having met the above requirements will be clearly identified as preliminary draft.

This Bulletin N° 11 has been approved as a fib State-of-art report in September 2000 by fib Commission 9 Reinforcing and Prestressing Materials and Systems.

The report was drafted by fib Task Group 9.1 Factory applied corrosion protection systems for prestressing materials:

Günter Hampejs* (Convenor, Austria), Frederick F. Hunt* (Deputy-Convenor, USA)
Members: Pierre Boitel* (France), André Demonté* (Belgium), Dieter Jungwirth* (Germany), Paul B. Mockford* (United Kingdom), Vittorio Valentini (Italy), Niklaus Winkler (Switzerland)
Corresponding Members: Hans Rudolf Ganz (Switzerland), Ulf Nürnberg (Germany), P. Y. Manjure (India), Yasuharu Mikami (Japan), Shingo Taniyama (Japan), Tom W. Twardzik (USA), Tsutomu Zaiki (Japan)

* Main contributors to this publication

Full affiliation details of Task Groups members may be found in the fib Directory.

Cover picture:
Monostrand - prestressing strand with corrosion protection by grease or wax and HDPE sheathing.

© fédération internationale du béton (fib), 2001

Although the International Federation for Structural Concrete fib - fédération internationale du béton - created from CEB and FIP, does its best to ensure that any information given is accurate, no liability or responsibility of any kind (including liability for negligence) is accepted in this respect by the organisation, its members, servants or agents.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without prior written permission.

First published 2001 by the International Federation for Structural Concrete (fib)
Post address: Case Postale 88, CH-1015 Lausanne, Switzerland
Street address: Federal Institute of Technology Lausanne - EPFL, Département Génie Civil
Tel (+41.21) 693 2747, Fax (+41.21) 693 5884, E-mail fib@epfl.ch, web http://fib.epfl.ch

ISSN 1562-3610
ISBN 2-88394-051-7
Printed by Sprint-Druck Stuttgart
1 Scope

Approximately 100 years ago the first patent applications in the area of prestressed concrete were filed. Since then this construction method has been more successful than any other. Most bridge constructions have used this method. Prestressing steel is also widespread used in ground anchors.

In prestressed concrete, prestressing steel serves to put the concrete under compression and to resist the resulting tensile stresses. Steel is an excellent material for this purpose. It has good ductile properties and provides tensile strength at an attractively low price. Prestressing steel has only one disadvantage, as any iron product: It is not durably resistant against corrosive influences. The consequence of this fact is that:

All steel needs adequate corrosion protection. Fortunately, concrete, the partner of steel in prestressed concrete structures, provides very good corrosion protection to steel, because of its high pH value. There is no doubt, active corrosion protection of prestressing steels through cement grout is the most economic and durable corrosion protection, if properly executed. [1]

Insufficient corrosion protection may result in delayed fractures. It is necessary to take into account and to take precautions, protecting the steel from harmful influences. The knowledge to avoid such damage exists and can be read in the literature [1 to 4]. Besides this, numerous corrosion protection systems which fulfill requirements such as controllability and exchangeability, are available. Examples are shown in figure 1.

![Components of corrosion protection systems](image)

Fig. 1 - Components of corrosion protection systems: 4 x 7 x 13 possible combinations

A comprehensive document of FIP: "Corrosion protection of prestressing steels" [1] has already been dedicated to this topic.

Thus the general aspects of corrosion protection need not be discussed in this report, but it will concentrate on factory applied corrosion protection and the products manufactured in this way. Factory applied corrosion protection can be produced in controlled processes and thus is obviously easier to control and assure better quality than corrosion protection applied later at the site.
This report shall inform the designer and installer (executing persons) about the different possibilities for industrially applied corrosion protection and provide the necessary knowledge for application. Corrosion protection systems may be influenced by surrounding conditions, for example alkalinity or ultraviolet radiation. More detailed information is given in the appropriate clauses of this report.

2 Special properties of prestressing steel

Prestressing steel is a material which has not only a high tensile strength but also good ductility. The stress-strain curve shows a high limit of elasticity with good elastic and plastic elongation. Thus, the losses from creep and shrinkage of concrete may be compensated for without considerable loss of prestressing force.

The favorable price-performance ratio, makes the application of steel for the prestressing of concrete attractive from an economical point of view. Besides the tensile characteristics, low relaxation, good fatigue properties, robustness and insensitivity against corrosion are required too. These properties are attainable if the relevant technical regulations are adhered to [5].

2.1 Tensile strength

The achievable tensile strength is closely related to the diameter of the prestressing steel. The thicker the prestressing steel is, the lower is its achievable tensile strength. The relation between diameter and achievable tensile strength may be approximately described according to the following law:

\[ R_{m \text{ achievable,}d} = R_{m1} \cdot d^{-1/n} \]

In this formula, \( R_{m1} \) is a reference strength for diameter 1 mm, which is approximately 2600 MPa. The exponent \( n \) is approximately 5. The validity of this relation is shown in figure 2. Even other high tensile products such as steel cord, with diameters in the range of 0.2 mm, or very thick bars of up to diameter 100 mm, follow this formula for the estimation of the achievable maximum strength quite closely.

2.2 Relaxation

Nearly all prestressing steel products available on the market have a so-called very low relaxation. In wire and strand this property is achieved through simultaneous stretching and stress relieving treatment. This makes it possible to stress these steels up to 70 % - 75 % of their tensile strength and the steel keeps its original stressing force nearly without changes.
even after long periods under this loading. The relaxation losses after 1000 hours, basing on 70 \% of tensile strength $R_{m\text{eff}}$ are less than 2.5 \% for wire and strand less than 4 \% for bar.

2.3 Corrosion sensitivity

It is no secret - each steel is sensitive to corrosion, even stainless steel has his risks in special environment, but there are good possibilities to protect steel against corrosion. In this paper are listed up several ways of save corrosion protection. Corrosion sensitivity of a given steel is depending on the level of its tensile stress. Moreover steels with higher tensile strength show an increased sensitivity to corrosion. According to a formula given by Stolte [1] for the lifetime of prestressing steel in the FIP· test with NH$_4$SCN, the following can be derived:

- For a given steel, the lifetime in the test is related to the imposed tensile stresses with power of up to minus three.
- For a given manufacturing type of steel, the lifetime in the test is related to it's tensile strength with power of up to minus nine.
- For an imposed tensile stress of $\sigma = 0.8 \times R_m$ and a a given manufacturing type of steel, the lifetime in the test is related to power of up to minus twelve:

$$\text{Lifetime } L = C \times \sigma^{-3} \times R_m^{-9} \text{ and with } \sigma = 0.8 \times R_m \rightarrow L = C_1 \times R_m^{-12}$$

$C, C_1$ are constant
$\sigma =$ tensile stress in the test
$R_m =$ ultimate tensile strength

The reported value of power -12 [1] has been proved later on with a larger number of test results to be too high, but it gives a good indication of the actual very high dependence. In fig. 3 is shown a set of about 1000 individual test results from cold drawn wire and strand. The individual results of each corrosion test have a large spread. Therefore it is difficult to find out a more precise dependence.

The best way to describe the sensitivity of prestressing steels would be to look for the constant $C_1$ (C), which indicates the position in the field of log(lifetime) over log(tensile strength) in the NH$_4$SCN test. When $R_m$ is expressed in MPa and $L$ in hours, then $C_1$ comes out at a value of about 10 power 39 to power 41. Higher figures indicate less sensitivity against corrosion under the test conditions. This comparison of relations however, is only valid for steels produced by the same manufacturing method. Different production methods result in different constants, C or $C_1$, of the formula given above.

Fig. 3 - Results of NH$_4$SCN-corrosion tests on cold drawn wire and strand
Different types of prestressing steels show different corrosion behavior [1] depending on the external environment and duration. The mainly used types are:

- Cold drawn wire, or cold drawn and stranded wire, stress relieved at final size,
- hot rolled and stretched, or hot rolled, stretched and stress relieved bar,
- quenched and tempered rod.

Basically, prestressing steels are more sensitive than mild reinforcing steel, which makes corrosion protection of special importance.

The NH4SCN-test was developed for cold drawn wire and strand. Now it is standardized in ISO 15630-3 [12]. Results for steels from other means of production need to be treated with caution. Generally, like every corrosion test, it shows quite a large spread of individual test results. Therefore it is necessary to have a sufficient number of results for statistical evaluation. Nevertheless, the test is a possible means for basic evaluation of the sensitivity of different steels to corrosion under tensile stress. Depending on diameter and nominal tensile strength (which is also related to the diameter) of the different products there are different specifications in the product standards of prestressing steel. Figures for the required lifetimes are given, for instance, in the European standard prEN 10138 [5]. This figures may be used as product-specific characteristic values.

In practice corrosion is dependant on the following parameters:

- humidity
- access of oxygen
- time
- difference of potentials
- aggressive components, promoters, pH-value
- steel stresses / strength
- steel sensitivity

A very extensive statistical investigation by Nürnberger [6] and an investigation conducted in the Netherlands [7] show, that in case of corrosion damage the probability of an early occurrence is greater than in a later period. Accumulated frequency over the time to damage in a logarithmic scale shows nearly linear dependency.

From this result it may be concluded that in most cases poor corrosion protection will cause damage relatively soon, while good corrosion protection remains effective over long time.

In most cases, but not always, corrosion of steel causes rust formation. While the mechanical properties are hardly influenced by superficial rust, it has a high effect on the fatigue behavior. The fatigue strength of rusty steels may be reduced down to 50 % of the original value, compared to the results of non corroded steel.

Rust may also be produced on the steel due to friction during fatigue loading (solicitation), so called fretting corrosion (friction rust). This effect reduces the fatigue properties. Through the application of zinc layers, grease or wax, the access of oxygen is prevented during friction, friction is reduced and steel protected in this way displays better fatigue properties than "dry" steels.
This paper deals with types of corrosion protection applied in the factory only. This way assures, as already said, corrosion protection of best quality in highest performance.

The basic possibilities for good corrosion protection are detailed described in the FIP-report "Corrosion Protection of Prestressing Steel" [1].

- One of the best types of corrosion protection is adjustment of a pH-value of about 12 to 13 in the vicinity of the prestressing steel, which can be achieved through concrete and cement grout.
- Even if this requirement is not fulfilled, it is possible to protect the steel by preventing access of harmful corrosive media, especially humidity and oxygen, by application of:
  - reactive cover coatings, e.g. zinc
  - non-reactive coatings, e.g. epoxy coating, grease or wax
  - several protective layers, e.g. sheathing, HDPE-sheathing or similar.

3 Requirements for corrosion protection

3.1 Environment

The type of environment may range from a normal interior climate to aggressive acid environments. Suitable environment classifications are given e.g. in EN 206. The individual corrosion protection systems have to withstand the related corrosion attack.

Moreover, mechanical influences such as impact, fire or ultraviolet light exist. Wind-induced vibrations may damage the protection through banging against other tendons or in the anchorage region. This has to be avoided by design measures. Robustness is required.

3.2 Duration

A distinction is made between

- temporary corrosion protection up to 2 years
- semi-permanent corrosion protection between 2 and 10 years and
- permanent corrosion protection up to approximately 100 years.

3.3 Price/performance ratio

The proper selection of corrosion protection will be influenced by the price/performance ratio \( \text{P}_{\text{pr}} \). This is the price, which is paid for ONE kN tensile force and ONE m length of the tendon. This not only includes the price \( \text{P}_{\text{mat}} \) (in price/t) of the material of the tendon but also the expense of corrosion protection \( \text{P}_{\text{corr}} \) (in price/t) and the anchorage \( \text{P}_{\text{anch}} \) (in price per anchorage) are included in the calculation.

The relationship may be expressed in the following equation:

\[
\text{P}_{\text{pr}} \text{ in price} / (\text{kN} \cdot \text{m}) = \left[ n \cdot \text{P}_{\text{anch}} + L \cdot (\text{P}_{\text{mat}} + \text{P}_{\text{corr}}) \right] / \left[ L \cdot \text{(tensile force)} \cdot \text{mass} \right]
\]

Simplified, the price for the free length of a tendon without the anchorage can be calculated:

\[
\text{P}'_{\text{pr}} \text{ [in price} / (\text{kN} \cdot \text{m})] = (\text{P}_{\text{mat}} + \text{P}_{\text{corr}}) \times 0,00785 / \text{f}_0.1
\]

\( L \) = Length of the tendon in m
\( \text{f}_0.1 \) = Limit of elasticity in MPa
\( n \) = Number of anchorages per tendon
The price $P'_{pr}$ of different protected materials in relationship to the price of a bare strand, which is set to 100%, is shown in table 1.

**Table 1 - Price of different protected materials in relationship to the price of a bare strand**

<table>
<thead>
<tr>
<th>Clause</th>
<th>PRODUCT</th>
<th>$P'_{pr}$ in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.1</td>
<td>Galvanized strand without sheath</td>
<td>140</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Zn+Al coated strand without sheath</td>
<td>150</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Zn coated strand + wax or grease + HDPE sheath</td>
<td>160</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Zn+Al coated strand + wax or grease + HDPE sheath</td>
<td>170</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Monostrand – bare strand + wax or grease + HDPE sheath</td>
<td>140</td>
</tr>
<tr>
<td>4.2.5</td>
<td>Double sheathed strands</td>
<td>250</td>
</tr>
<tr>
<td>4.2.7</td>
<td>Epoxy coated strand (epoxy also between the wires)</td>
<td>180</td>
</tr>
<tr>
<td>4.2.7</td>
<td>Epoxy coated strand (epoxy also between the wires) + sand for better bond</td>
<td>200</td>
</tr>
</tbody>
</table>

### 3.4 Design requirements

In most cases corrosion protection in the free length is easier to achieve than in the anchoring or coupling zone, or in the area of deflection saddles. It is necessary to provide the possibility for tensioning and re-tensioning and in many cases also accessibility and exchangeability. This is valid in most cases of so-called external tendons.

Fire and vandalism protection may also be important. Embedding in concrete may help.

Frequently, tests are carried out in service conditions to evaluate the influence of temperature and stress changes on the behavior of corrosion protection systems, e.g. approval tests for external tendons in the saddle and anchorage zone.

### 3.5 Advantages and disadvantages

Numerous influences can be presented clearly in a matrix, which, depending on the product, permits a grading of classes. See table 3 in chapter 4.3.

### 4 Proposed solutions

Below, a selection of standard corrosion protection systems which are applied in the factory are presented. The most important properties of the individual solutions are described.

#### 4.1 Temporary corrosion protection

Depending on the manufacturing process, the surface of the steel is covered with intentionally applied or production-dependant remainders, which already provide some temporary corrosion protection.

- Cold drawn wires receive a preparatory layer consisting of phosphate, lime, borax or similar as a lubricant base before the drawing process. During drawing this is further covered with a thin layer of lubricant which consists mainly of stearate or drawing soap. Under normal, non-aggressive environmental conditions this layer can protect the steel from corrosion for several days up to some months.
Fig. 5 - Double sheathed strand - possible combinations

Fig. 6 - "After bond" - Delayed curing corrosion protection of prestressing strand
Fig. 7 - Anchorage of external tendon with epoxy coated strand for severe corrosive conditions—multiple barriers

Fig. 8 - Anchorage of external tendon with individually changeable monostrand
Fig. 9 - Anchorage of stay cable with galvanized wires

Fig. 10 - Stay cable with galvanized strand, waxed and tightly extruded HDPE. Each strand is individually exchangeable
Fig. 11 - Classical anchorage of monostrand for flat slab and containment

Fig. 12 a) Free length of the anchor

Fig. 12 b) Fixed anchor length

Fig. 12 - Permanent ground anchor with greased and HDPE extruded strand in the free length and bare strand in the anchorage zone
In addition a soluble oil may be sprayed on. The effectiveness of such oils is very restricted. Such a layer can prevent real corrosion attacks for only a short time. The shelf life under normal environmental conditions can be considerably increased and a rust film is avoided. Tendons in non injected sheathings can be protected for at least six months, if there is no circulation of humid air. It is sensible to place so-called spies. These spies are reference steels which help to monitor the situation in the environment of the prestressing steels.

- Oil remainders reduce the coefficient of friction by approximately 30%.
- If oils or greases are used, it has to be considered that they also impair the bond properties in concrete. Tests show that the bond effect of freshly sprayed smooth steels is only 1/3, and, if the steels have been stored longer, 2/3 of the non oiled steel. No difference can be determined for ribbed steels.
- After injection, the outer layer behaves alkaline. The cement paste virtually absorbs the remaining oil like a sponge. Flushing out with water causes pollution and creates new problems with formation of rust on the tendon. Water is left partly in the duct and filling with grout is hindered. The reduced bond of oiled steels is still sufficient for post tensioning [11].
- In the case of pretensioning, oiling of the steel is prohibited.
- In closed ducts (sheathing), dry, clean protective gases like nitrogen may be used for temporary corrosion protection.

### 4.2 Permanent corrosion protection

#### 4.2.1 Zinc

Zinc provides active corrosion protection. It is sacrificed to corrosion for as long as there is still metal available on the steel surface. It is even effective at a distance of some μm up to 1 mm from the damaged area. Thus corrosion protection by zinc primarily depends on the consumption rate and the remaining thickness of the zinc layer. Good zinc coating moreover reduces the danger of fretting corrosion in case of fatigue loads. Bad and cracked zinc layers may reduce fatigue strength.

Galvanized prestressing steels have already been standardized in a draft of ISO 14658 and a EN draft standard based on the French standard NF A 35035 is also available [9]. This standard contains also tolerances for the thickness of the zinc coating. Usually pure zinc is used for galvanization. The standard ASTM A 475-95 "Standard Specification for Zinc-Coated Steel Wire Strand" [8] is not written for prestressing steel, but may be used for comparison.

If the prestressing steel is anchored with wedges, care has to be taken that the zinc layer is not so thick that the teeth of the wedges are completely filled with zinc.

Prestressing steels may be galvanized by a number of processes. The steel may be damaged by hydrogen in the form of H⁺ in status nascendi, at the surface of the steel due to chemical reactions. The best (safest) way to avoid the danger of hydrogen is to apply the hot dip galvanization process. A FIP-report in FIP-notes 4/1991/4 has been dedicated to this topic [4].

Zinc is not only dissolved by acids, but also reacts with solutions of high pH-value. Zinc is partly dissolved by fresh cement mortar, but this fact can be neglected in practice.

#### 4.2.2 Zinc + aluminum

Coatings of zinc containing approximately 5% aluminum appeared in the 1980's. The composition corresponds to the eutectic in the zinc aluminum phase diagram. It has a very
file

Microstructure, which gives good ductility and allows it to be cold drawn after coating wire.

The corrosion resistance in the salt spray test of the zinc aluminum coating is estimated to be two to three times higher than the pure zinc coating.

Under corroding conditions, the zinc in the coating reacts sacrificial and generates cathodic protection. It is dissolved first and thus the amount of aluminum in the layer gets higher. Oxidation of the aluminum then occurs and aluminum oxides, which are formed, provide a good barrier against further corrosion. From this process the coating gets a black surface typical of layers of zinc + aluminum.

Production

The process is similar to that of hot dip galvanizing with zinc. In the case of the zinc aluminum alloy, there are two possible means of production. In the case of wire dipped in a molten bath of Zn + 5% Al, there is a need for very careful surface preparation.

An easier method is where the wire is hot dipped twice. In the first step the wire passes through a classic hot dip zinc bath. In the second step the wire passes through a zinc bath with controlled aluminum content. This forms an intermediary layer with aluminum contents of 15% up to 25% due to special thermal diffusion. Areas of higher aluminum content have relatively high hardness (Vickers) and may influence the anchorage behavior in the wedges.

Under highly alkaline conditions zinc + aluminum is dissolved. This action continues after curing of the cement mortar in the presence of water. Therefore direct contact of zinc + aluminum coated steel with cement mortar is not recommended.

4.2.3 Zinc (zinc + aluminum) + wax + high density polyethylene (HDPE)

Corrosion protection systems with several barriers are usually considered to be safer than systems with only one corrosion barrier even if this is a good one. Zinc (Zn+Al) + wax + HDPE is a triple system.

Even if the wax is removed locally, the corrosion protection is still guaranteed through the zinc layer.

Zn + wax + HDPE provide an excellent solution for external tendons and stay cables. In the case of external tendons the plastic sheathing is tightly extruded onto the steel and wax so that movement of the steel inside the HDPE-coating is not possible. For this reason this product can not be used within the concrete cross section for post-tensioning.

For all multiple corrosion protection systems it is important that the individual layers are effective independently of each other. For this purpose it is important that:

- they are of suitable thickness and density,
- they cover the steel permanently and durably,
- they prevent penetration of corrosion in case of damage. This condition requires good bond between the layer and the steel, either through effective adhesion to the surface, as in the case of galvanization or even galvanization and epoxy-coating, or through soft permanent contact, as in the case of wax.
- For external tendons the temperature during use has to be considered. Even wax, which is quite stiff at room temperature, in comparison to grease, liquefies at relatively low temperatures of approximately 70°C, at the so called congealing point. The information in the data sheets has to be considered. The drop point of grease is at about 65 °C, for wax about 150 °C.
4.2.4 Wax/grease + HDPE sheathing

This product is usually used for unbonded tendons. It is generally known as Monostrand and delivered under a lot of different names. The product is also delivered combined in units of two or four parallel strands. When this product is placed within the concrete cross-section, the requirements for corrosion protection and behavior under the possible existing temperatures need not be at the same high level as for external tendons.

While wax is highly recommended in case 4.2.3, so called permanently elastic grease may be used for post-tensioning without bond in the concrete cross-section.

If greases are used, account must be taken of the fact that they always have a certain tendency for separation of oil. The oil may flow out and the remainder of the grease may become hard and thus no longer provide 100 % safety against corrosion in the form of a dense cover. Suitable greases are supplied by nearly all petroleum refineries under different brand names. These products are subject to numerous regulations, the most important of which are listed in the FIP State of the art report "Corrosion Protection of Prestressing Steel" [1] and in the FIP State of the art report "Thick walled plastic sheath" [13]. The environmental compatibility may have to be considered.

Besides HDPE, polypropylene (PP) may also be used as plastic sheathing. PP is harder, stiffer, has better temperature resistance, but it has the disadvantage that it is more difficult to process, to handle in production and most importantly it is considerably more expensive. PP is normally used only for ducts. More detailed information about the material may be found in [13].

Monostrand type strands have the following advantages:

• Easy placing in the sheathing
• Good corrosion protection in the free tendon length
• If the HDPE is damaged the wax prevents penetration of corrosive media at the defect
• Epoxy coated strands may be used.
• If the interstices between the wires of the strand are filled with grease and if a HDPE-sheathing with a diameter larger than that of the prestressing wire, or strand, is extruded on, the prestressing steels can easily be moved within the HDPE-sheathing.
• In case of suitable design and accessibility of the anchorages, it is even possible to exchange the tendons.
• The grease also reduces friction in case of intended or unintended deflections.
• Fretting corrosion is avoided through reduced friction in the greased plastic sheathing and the fatigue strength of the steel is considerably increased. It may be increased by up to 2 times in comparison to that of the bare strand.
• The greasing process may be interrupted during production of the corrosion protection, where bond is required be provided, for instance in the anchorage area.

The following factors have to be taken into account:

• Grease or wax melts over about 60 °C.
• With increasing temperature the HDPE softens.
• Over about 230 °C organic substances start to separate cracked fractions.
• When organic products are used in free air, ultraviolet radiation should be taken into account.

4.2.5 Double sheathed strand

Besides single Monostrand, single sheathed strand in form of individual tendons, Monostrand in compact bands of two or four parallel strands connected together during the extrusion of the HDPE sheathing have been developed.
In a further development a second layer of HDPE with a rectangular shape is applied by extrusion or similar process in the factory. This double sheathed strand is shown in fig. 5 with its possible combinations (see colour part in the middle of this bulletin).

**Advantages of double sheathed strand are:**
- Full factory applied corrosion protection of the tendon
- The second HDPE layer protects from mechanical damages and corrosion influences as well
- Grouping of tendons creates the possibility of very high pre-stressing forces
- Possibility of simple and effective deviation saddles
- High fatigue load resistance
- The individual tendons may be changed easily

It is necessary to take into account the influences of temperature and ultraviolet radiation - see clause 4.2.4.

### 4.2.6 Polyurethane

This type of plastic is very seldom used for the production of factory applied corrosion protection of prestressing steel. Its main characteristics are given in table 2. Because of the reaction with water, the use of polyurethane is not recommended in applications where permanent contact with water may occur.

<table>
<thead>
<tr>
<th></th>
<th>TPE-U</th>
<th>ATPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>kg/dm</td>
<td>1.15 to 1.25</td>
</tr>
<tr>
<td>Shore hardness A</td>
<td></td>
<td>82 to 98</td>
</tr>
<tr>
<td>Shore hardness D</td>
<td></td>
<td>32 to 73</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>MPa</td>
<td>15 to 650</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>MPa</td>
<td>30 to 50</td>
</tr>
<tr>
<td>Elongation</td>
<td>%</td>
<td>250 to 500</td>
</tr>
<tr>
<td>Temperature for injection moulding</td>
<td>°C</td>
<td>180 to 245</td>
</tr>
<tr>
<td>Maximum temperature for use</td>
<td>°C</td>
<td>80 to 120</td>
</tr>
</tbody>
</table>

*Table 2 - Main characteristics of polyurethane-elastomers [14]*

### 4.2.7 Epoxy coating

Following the example of epoxy-coating reinforcing steels, bars and strands have been coated, however, to a much higher quality. The layer thickness is approximately 0.7 mm (0.4 mm up to 1 mm). Various standardized tests are carried out on the powder, resin and coated steel. Examples of applicable codes are: ASTM A 882M-91 and ISO 14655-99.

Preparation of the steel surface (shot blasting) is of importance. The application of a primer to improve bond between steel and resin layer is recommended. During manufacture of the epoxy powder efforts are made to find compositions yielding a resin cover which is as tight and ductile as possible.

Formerly, only the surfaces of strands were coated. It showed that humidity entered the interstices around the core wires, the wires corroded and the bond with the coating was reduced. Today the strand is opened during coating and closed again thereafter so that there are no voids, even in the core region.
Sand is applied to the still soft epoxy surface to increase bond. Such products are available in the USA and Japan.

Special wedges with wide and deep teeth are necessary for the anchorage of strands with thick epoxy coating. The teeth have to penetrate through the cover to prevent slipping through. Epoxy-coated strands have high fatigue strength even in the anchorage region as friction corrosion is avoided. Fatigue strength is about 1.5 times higher as that of uncoated strands.

Duplex-systems with 200 μm epoxy layer and 800 μm PE-layer represents an inexpensive alternative.

Epoxy coating withstands to relatively high temperatures up to about 200 °C. At higher temperatures it starts to decompose.

4.2.8 Plastics with delayed curing

A Japanese patent on the basis of a two-component resin called After-Bond permits stressing of the PT-steel in a sheathing under low friction conditions and, because of delayed curing of the epoxy, later a system of post-tensioning with bond is achieved. The outside of the duct provides bond with the concrete. Figure 6 shows an example of 7-wire and 19-wire strand with delayed curing protection (see colour part in the middle of this bulletin).

The epoxy does not only provide bond but furthermore serves as a good corrosion protection in the non-cured as well as in the cured state.

The advantages of this system are as follows:
- Simple placing and positioning of the tendon
- Easy anchorage after tensioning
- Same low friction coefficient as with unbonded tendons
- The resin hardens after stressing and bond is produced over the sheath
- Excellent corrosion protection by epoxy over the whole length of the tendon plus HDPE sheathing
- Outer diameter of the tendon is smaller than the metal sheath of a grouted tendon

Disadvantages of the system are:
- Restricted processing period, danger of curing before end of the stressing works.
- Quite high amounts of epoxy are necessary, thus the costs are relatively high.

An exact description of the system can be found in [10].

4.2.9 Tar-epoxy resin and paints

The curing period can be estimated depending on the environment temperature and ranges from some hours at 100°C to more than 100 days at 20°C.

Conventional corrosion protection paints, e.g. according to DIN 55928 are available, or paints with tar epoxy. If the parts are not dipped unprotected longitudinal stripes may remain at round cross sections. A lot of effort is necessary to get a tight coating. In the anchorage zone special treatment is needed.

In some cases, for instance for the corrosion protection of steel ropes, paint is used on the basis of epoxy ester or chlorinated rubber mixed with zinc dust.

4.3 Evaluation

Table 3 is intended to give a rough evaluation of the systems mentioned.
### Table 3 - Evaluation of the individual solutions

<table>
<thead>
<tr>
<th>Solution</th>
<th>Handling and special influences</th>
<th>Expected lifetime depending on surrounding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clause</td>
<td>Type of protection</td>
<td>Handling on site</td>
</tr>
<tr>
<td>4.1</td>
<td>Oil emulsion for temporary protection</td>
<td>easy</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Zinc</td>
<td>easy</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Zinc + aluminum</td>
<td>easy</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Zinc (+aluminum) + wax + HDPE</td>
<td>easy</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Monostrand</td>
<td>easy</td>
</tr>
<tr>
<td>4.2.5</td>
<td>Double sheathed strand</td>
<td>easy</td>
</tr>
<tr>
<td>4.2.6</td>
<td>Polyurethane</td>
<td></td>
</tr>
<tr>
<td>4.2.7</td>
<td>Epoxy coating</td>
<td>careful</td>
</tr>
<tr>
<td>4.2.8</td>
<td>Plastics with delayed curing</td>
<td></td>
</tr>
<tr>
<td>4.2.9</td>
<td>Tar-epoxy resin paints</td>
<td>complicated</td>
</tr>
</tbody>
</table>

#### Symbol Signification

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Signification</th>
</tr>
</thead>
<tbody>
<tr>
<td>/</td>
<td>Inefficient</td>
</tr>
<tr>
<td>T</td>
<td>Temporary, &lt; 2 years</td>
</tr>
<tr>
<td>M</td>
<td>Mid-term, 2 to 10 years</td>
</tr>
<tr>
<td>D</td>
<td>Durable, &gt; 10 years</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Signification</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>Good behavior</td>
</tr>
<tr>
<td>0</td>
<td>neutral</td>
</tr>
<tr>
<td>-</td>
<td>Problems possible</td>
</tr>
<tr>
<td>NR</td>
<td>NOT recommended</td>
</tr>
</tbody>
</table>

### 5 Practical examples

Typical practical examples of factory applied corrosion protection for prestressing steel in a neutral design are shown in form of pictures as the figure 7 to figure 12. (See color part in the middle part of this bulletin.) More detailed information is available by the producer of the products shown (producer of prestressing steel).

### 6 Future development - outlook

A single epoxy-coating is improved through duplex systems and making it less sensitive to local damage. Zinc under the epoxy would be desirable. Presently there are still some problems in the interface between zinc and epoxy, which have been solved technically but not yet economically.

Stainless steel is resistant against different corrosive attacks, e.g. chlorides, depending on the kind of alloy. The composition of these steels is under development. In individual cases tendons are also plated with stainless steel. In soil, unpredictable corrosive influences have to be expected. Thus there will always be a certain risk for the application of tendons in soil.
price for stainless steel is several times higher than that of standard prestressing steel. Thus, its use is limited to special applications.

Finally, there are the non-metallic materials, in the form of glass-, plastic-, and carbon fibers, which are relatively brittle and display no plastic deformation before failure. Anchoring is one of the most important difficulties in application of these products. Moreover, the price/performance ratio is still high, especially that of carbon fibers. Furthermore, glass is sensitive to alkaline environments and thus has to be isolated from concrete.

References

[7] Netherlands Committee for Concrete Research (CUR) "Cases of damage due to corrosion of prestressing steel - Fig. 4, Page 67
[12] ISO 15630-3 Steel for the reinforcement and prestressing of concrete - Test methods - Part 3: Prestressing steels
CONTENTS

1 Scope 1

2 Special properties of prestressing steel 2
   2.1 Tensile strength 2
   2.2 Relaxation 2
   2.3 Corrosion sensitivity 3

3 Requirements for corrosion protection 5
   3.1 Environment 5
   3.2 Duration 5
   3.3 Price / performance ration 5
   3.4 Design requirements 6
   3.5 Advantages and disadvantages 6

4 Proposed solutions 6
   4.1 Temporary corrosion protection 6
   4.2 Permanent corrosion protection 7
      4.2.1 Zinc 7
      4.2.2 Zinc + aluminum 7
      4.2.3 Zinc (zinc + aluminum) + wax + high density polyethylene (HDPE) 8
      4.2.4 Wax / grease + HDPE sheathing 9
      4.2.5 Double sheathed strand 9
      4.2.6 Polyurethane 10
      4.2.7 Epoxy coating 10
      4.2.8 Plastics with delayed curing 11
      4.2.9 Tar-epoxy resin and paints 11
   4.3 Evaluation 11

5 Practical examples 12

6 Future development - outlook 12

References 13
Factory applied corrosion protection of prestressing steel

Contents

1 Scope
2 Special properties of prestressing steel
3 Requirements for corrosion protection
4 Proposed solutions
5 Practical examples
6 Future development, outlook
   References