Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte
Band: 55 (1987)

Artikel: Corrosion protection of prestressing tendons
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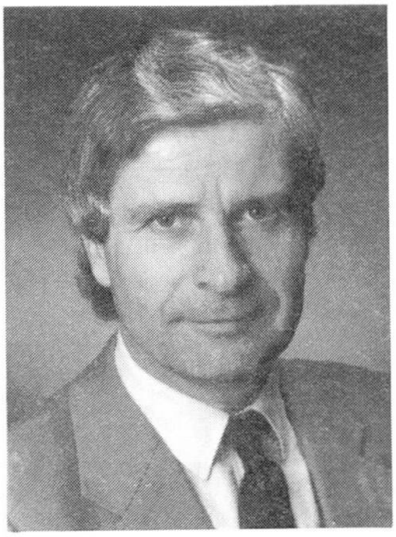
DOI: https://doi.org/10.5169/seals-42709

Corrosion Protection of Prestressing Tendons

Protection contre la corrosion de câbles de précontrainte

Schutz von Spannstahl vor Korrosion



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SUMMARY
Increasing aggressiveness of environmental conditions, new prestressing technologies (partial prestressing, unbonded tendons) and corrosion damage have given rise to a systematic evaluation of measures for the corrosion protection of prestressing steel. This paper analyses well-tried and novel protection measures under consideration of corrosion mechanisms, environmental conditions and prestressing techniques. It is shown that also for extreme cases robust protection measures are available to avoid depassivation of the steel surface during the service life of the prestressed structure.

RÉSUMÉ
L'agressivité croissante de l'environnement, la mise au point de nouveaux procédés de précontrainte du béton (précontrainte partielle par exemple ou précontrainte sans adhérence) et les dommages dûs à la corrosion ont amené à reconsidérer de façon systématique les mesures de protection de l'acier de précontrainte contre la corrosion. L'article expose les procédés de protection contre la corrosion qui ont déjà fait leurs preuves ainsi que les nouveaux procédés, en considérant les mécanismes qui entraînent la corrosion, les conditions de l'environnement et les procédés de précontrainte utilisés. Il existe actuellement des procédés efficaces qui, même dans les cas extrêmes, empêchent de façon sûre la dépassivation de la surface de l'acier de précontrainte.

ZUSAMMENFASSUNG
Zunehmend aggressive Umweltbedingungen, neue Spannbetonarten (wie teilweise Vorspannung oder Vorspannung ohne Verbund), aber auch Korrosionsschäden haben dazu geführt, die Maßnahmen zum Schutz von Spannstahl vor Korrosion einer systematischen Ueberprüfung zu unterziehen. Der folgende Beitrag erläutert erprobte und neue Korrosionsschutzverfahren unter Bezugnahme auf Korrosionsmechanismen, Umwelt – und Bauwerksbedingungen und zeigt, daß auch für extreme Fälle heute robuste Korrosionsschutzverfahren zur Verfügung stehen, die eine Depassivierung der Spannstahloberfläche zuverlässig verhindern.

1. CORROSION PROTECTION STRATEGY

1.1 Corrosion mechanisms

Corrosion of steel in concrete follows an electro-chemical reaction (1) consisting of an anodic reaction at the steel surface and a (driving) cathodic reaction which consumes the dissolved electrons e.g. through a reduction process, or in the presence of dissolved hydrogen through hydrogen evolution which is critical in view of hydrogen embrittlement. These corrosion processes can develop independent on the state of mechanical stresses in the steel. Prestressing steel can show additional corrosion phenomena if stressed to a high instantaneous level. These phenomena are known as stress corrosion cracking. The process of cracking is a combination of the electrochemical corrosion at the steel surface (anodic iron dissolution with cathodic oxygen reduction and/or cathodic hydrogen evolution) and the physical transport and fracture processes inside the steel (hydrogen induced crack initiation and propagation). Electrochemical corrosion is the primary premise for hydrogen uptake. Cathodic hydrogen evolution is only possible if the pH in the environment is below the neutral region. Fretting corrosion initiating fatigue failures will not be considered in the following.

1.2 Corrosion protection objectives

Due to the increasing susceptibility to hydrogen induced stress corrosion cracking (HISCC) with higher steel grades prestressing steels must be protected in a way that during the entire anticipated life time of the structure no anodic reaction can occur on the steel surface, which means that the prestressing steel must remain passivated. The following measures are available to prevent anodic reactions at the steel surface:

a) Active protection through electro-chemical passivation

Steel embedded in alcaline environment (ph $\geq$ 12) is protected against anodic metal dissolution through passivation. This - in an electro-chemical sense - active protection is well experienced. The alcalidity of concrete and injection grout is generally sufficient to avoid anodic metal dissolution at the steel surface. However diffusion processes through the porous structure of concrete and injection grout can cause a loss of alcalinity either through carbonation or through chlorides penetrating to the steel surface. Both cases lead to a deterioration of the passive layer hence destroy the active protection. In the case of chlorides depassivation occurs often locally which leads to small areas of anodic reactions promoted by large cathodic areas.

b) Passive protection through seperation layers (paints, coatings etc.) and non-alcaline injection materials (wax, grease)

Paints and coatings form a barrier protecting the steel from reactions with the environment hence impede also anodic metal dissolutions. Since seperation layers provide no active protection in an electro-chemical sense, corrosion may initiate at voids and holidays. Also non-alcaline injection materials as wax or grease products form a passive protection isolating the steel surface from chemical reactions with its environment.

c) Active protection through impressed current

The use of artificial and inert anodes impressing an external current to the prestressing steel - thus shifting the potential that the steel behaves as a cathode rendering metal dissolutions impossible - will not be considered in the following. Although this protection technology - known as cathodic protection - is well understood to protect structural steel (e.g. pipe lines) and becomes more and more known to protect rebar reinforcement embedded in concrete (2) many open questions, e.g. concerning hydrogen evolution in the concrete forming the electrolyte, still impede its application to prestressed concrete (3).

1.3 Environmental conditions

Environmental Class		Environmental Conditions
1	Modest	Structural elements always dry or under water
2	Moderate	Structural elements under moist conditions
3	Severe	Structural elements under permanent humid conditions and/or under changing wetting and drying conditions
4	Aggressive	Structural elements under aggressive conditions

Table 1: Classification of environmental conditions

Concerning corrosion protection a very rough classification in 4 environmental classes as shown in this table is proposed.

1.4 Type of prestressing steels

The susceptibility against HISCC rises with increasing ultimate strength. Recent corrosion tests (e.g. 6, 7, 8) yield the weighting function $L = c/f_Z^{9.6}\sigma^3$ expressing the influence of the ultimate strength (f_Z) and the instantaneous stress level (σ) on life expectancy (L) or the corrosion sensitivity resp. This relation shows the great influence of strength and stress level. Although the strength of prestressing steels varies (bars: $f_Z \lessapprox 1250$ MPa, wires: $f_Z \lessapprox 1600$ MPa, strands: $f_Z \lessapprox 2000$ MPa) present design recommendations do not specify different protection levels. However it should be noted that the choice of steel of smaller strength and hence greater corrosion resistance may be advisable when exposed to heavy environmental conditions. For very severe exposure conditions the use of stainless prestressing steels has been proposed. However not only the great prize difference between stainless and black steel but also unresolved problems with crevice corrosion and also pitting due to chlorides seem to outrule the use of stainless prestressing steels. The competent design of protection measures for black steel is more reliable and less expensive than the use of stainless steel with still unresolved questions concerning its corrosion behaviour under prestressed concrete conditions.

1.5 Prestressing technology

Concerning corrosion protection a principal difference must be made between bonded (pre- or posttensioned) and unbonded tendons. Bonded tendons are primarily protected through the alcaline environment provided by the cement injection and the surrounding concrete resp. Protection measures therefore aim at correct placing and curing of concrete to assure the required cover, and to achieve a high diffusion barrier against moisture and aggressive ions, and at a limitation of cracks (number and width) in the concrete surrounding the prestressing tendon. For post-tensioned tendons in addition high quality grouting is of utmost importance to assure workability and strength of the grout and to avoid voids along the tendon. Unbonded tendons can also be protected by cement grout when placed outside the concrete cross-section. However in actual practice passive protection by means of paints, coatings or soft plastic injection materials gain more and more in importance. The degree of prestress (full or partial prestressing) is the determining factor for the limitation of cracking in the neighbourhood of prestressing tendons. Under severe environmental conditions it should be required that the concrete around prestressing steel remains precompressed under permanent actions (limit state of decompression) and that cracks developing under rare actions or under actions not taken into account in the design must be controlled by adequate rebar reinforcement.

1.6 Corrosion protection strategy

Effective corrosion protection measures must be considered not only with respect to physical or electro-chemical criteria but also in view of their sensitivity to unsatisfactory workmanship. The required measures must be "robust" against lacking workmanship on site. The following table presents a synthesis of long term corrosion protection measures for structures with bonded prestressing tendons. A synthesis of short term corrosion protection measures is given in (5).

Environmental class (see table 1)	Prestressing steel in tension zone under permanent action combinations		Special protection measures necessary		Allowable desing crack width (mm) under perm. action combinations			Concrete cover (Nominal values (mm))		
					Prestressed concrete		Reinforced concrete	Prestressed concrete		Reinforced concrete
	Post-tens.	Pre-tens.	Post-tens.	Pre-tens.	Post-tens.	Pre-tens.		Post-tens. Sheathing	Pre-tens. Steel	
1	Yes		No		0.2	0.1	0.4	*) 40	35	25
2	Yes		No		0.2	0.1	0.4	*) 50	45	35
3	Yes	Yes No	No	Yes No	0.2	**) 0.1	0.25	50	**) 55	45
4	Yes No		Yes No		**) 0.2 ***)	**) 0.1 ***)	0.25	**) 60	**) 65	55

*) Corrosion protection not relevant for cover of sheathing
**) Not relevant for corrosion protection
***) Under rare action combinations

Table 2: Corrosion protection strategies

The traditional way of protecting bonded tendons through embedding in alcaline conditions is still most reliable if the criteria shown in table 2 are observed. These criteria assume normal concern for and conventional control of workmanship. In the case of bonded tendons partially prestressed structures under aggressive (post-tensioning) or severe and aggresive (pretensioning) conditions need special protection comprising improved sheathing materials and/or coating of steel surfaces. Unbonded tendons outside the cross section must be always protected with a double protection system. For strand tendons a system consisting of single PE-sheathed, greased monostrands installed in a steel or plastic tube which subsequently is injected with cement grout has shown it technical and economical advantage. For bar tendons such a system consists of PE-sheathed, cement grouted single bars installed in a steel or plastic tube. As an alternative wax or grease injected tendons installed in a steel or plastic tube, or bundles of polymere coated prestressing steels installed in metal or plastic tubes are demonstrating adequate performance. Cable stay systems require a higher degree of protection. High quality sheathing made of steel or PE-tubes together with cement grout injection is the actual state-of-the-art. Under aggressive conditions also additional coating of the prestressing steel has been chosen (5).

2. SPECIAL CORROSION PROTECTION MEASURES

2.1 Coating of steel

In the following coating of steel means the application of adhesive seperation layers on the steel surface assuring zero-slip bond transfer from coat to steel. For prestressing steel two principal coating technologies have been developed: Zinc coating and polymere coating. The corrosion resistance of zinc coats depends on the galvanization technology (electrolytic, hot-dip etc.). In most cases only limited protection against chloride attack is assured by zinc coats. Since chlorides belong to the most common aggressive agents, zinc coats must be judged as unsufficient. Furthermore galvanic corrosion between metals of different electrochemical potentials can occur and hydrogen producing galvanic cells can develop between different metals when connected by fresh grout acting as electrolyte (9). Fusion bonded polymere coatings show a more reliable performance. Mechanical and chemical requirements such coats must meet have been discussed elsewhere (10). Of crucial importance are toughness and elongation capacity. Control and acceptance criteria for coated rebars after fabricaction have been specified in (11). However it must be noted that the final protective performance of coats depends not only on the quality as produced in the factory but on the quality as installed, stressed and anchored in the structure. It is therefore important that during handling, installation, stressing and anchoring the coated layer is protected against defects. Particular concern must be given to the anchorage area. Although fusion bonded the reliable transfer of forces from steel to the anchorage requires direct contact between steel and steel hence the coat must be destroyed locally. Special anchorage devices have been developed (5) to overcome this problem. A special problem is related to the coating of strands since in general the central wire is not directly covered. Local corrosion cells may develop within the strand, which requires particular care during all operations until final grouting. Polymere coated prestressing strand has the advantage to be less sensitive against fretting corrosion, hence exhibits when integrated in competently designed tendon systems a remarkably higher fatigue resistance (5). Finally a particular coating technology deserves to be mentioned. A coat layer is applied to the prestressing steel in the steel mill. After installation of the steel into the recess or sheathing tube resp. this coat layer is broken either by heating or through the elongation of the steel during stressing. In the first case - known as thermobond - the applied coat is decomposed after prestressing through heating before it hardens again to form a bond transferring coat layer. In the second case the coat layer consists of microcapsules containing a flowable material which breaks when the steel is stressed thus releasing the soft material which flows around the unbonded steel. To achieve bonded tendons the microcapsules can be filled with a two-component glue which reacts after breaking of the capsules and hardens to a bond transferring coat. In both cases the prestressing steel can move longitudinally (during prestressing) before it is bonded to the structural concrete.

2.2 Plastic injection materials

For unbonded tendons the use of soft plastic injection materials as wax or grease products has been advocated (12, 13). Criteria these products have to meet are discussed in (14). These criteria are related to the compatibility with prestressing steel (chemical purity in respect to corrosive agents as SO_3, SO_4, S, NO_2, NO_3, Cl etc.), the resistance in alcaline environment (saponification behaviour), the ohmic resistance, the resistance against oxydation, and de-oiling, and to the workability (viscosity, temperature-stability etc.). Although high performance materials are available today, their large scale use is still hampered by technological and economical obstacles. A main problem is still related to the development of reliable and cost-effective injection procedures. In general wax or grease products must be heated before the rather large volumes can be filled. The danger of voids due to shrinkage of the cooling material, de-oiling under the injection pressure are some of the problems which still desserve special concern. Also in view of the rather high prize of high quality products (see prize comparison in 14) these problems may be overcome (15) when unbonded strand tendons are composed of individual PE-sheathed greased mono-strands guided in metal or plastic tubes where the volume between the individual strands is filled with cement grout providing a continuous support for the strand bundle and avoiding extreme local pressures at deviator saddles.

2.3 Improved sheathing

Since corrosion processes depend on the transport of oxygen to the steel surrounding concrete a barrier against ion diffusion can halt corrosion. The gas diffusion resistance of metal sheathing can be substantially improved when welded tubes are used instead of corrugated tubes. As an alternative coated tubes or plastic tubes made from PE or PVC have been proposed. In addition to the better long term diffusion characteristics plastic sheathing provides advantages in view of smaller friction losses (also since lòcal corrosion of the inner tube surface prior to grouting is impossible), of reduced fretting fatigue in regions of curved and deviating tendons (16), and of a reduced danger of water penetrating into the sheathing before grouting. The reliable bond transfer from the steel tendon via the plastic corrugated sheathing to the concrete could be proven in numerous tests (17). Still not fully resolved are problems related to the site installation of plastic sheathing, e.g. required stiffness (in particular in view of elevated temperatures), required hardness (abrasion resistance), admissible production tolerances etc. Furthermore the longterm durability of plastic tubes exposed to climatic changes is still difficult to assess. Stress variations due to alternating temperatures, stress concentrations in joints and connectors may lead to early deterioration unless proper detailing has been assured (18).

2.4 Electrically isolated tendons

Finally the possibility of complete electric isolation is mentioned (19). This isolation prevents electric currents needed in corrosion processes. Furthermore the isolating layer forms a barrier against moisture and chloride penetration thus assures also a passive protection. Complete electric isolation requires to encapsulate the total tendon into a non conductive layer, which means that in addition to plastic sheathing all coupling and anchoring devices need to be coated and the joints between these parts must be carefully sealed. Although mainly proposed for unbonded tendons this protection technology can also be applied to bonded tendons if installed in corrugated plastic sheathing. In both cases - bonded and unbonded tendons - electrically isolated systems provide a high degree of protection specially adapted for structures under very aggressive environmental conditions.

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