Corrosion of Prestressing Steels and Its Mitigation

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In the last decade, there has evolved an increasing awareness and understanding of environmental effects and their potential for long-term degradation of the structures we build. Today, there is a better understanding of such phenomena as carbonation of concrete and the ingress of chloride ions even in crack-free concrete. As a result of these factors and recent evidence of severe corrosion damage, in many countries an increasing concern has arisen among engineers regarding possible corrosion damage to prestressing tendons and long-term service life. This paper discusses the magnitude of the problem, the corrosion mechanism and various types of corrosion. It also presents examples of corrosion damage and identifies those methodologies that have either been used or could potentially be used to provide increased corrosion protection of prestressing steels.

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Nothing lasts forever — man as well as the structures he builds — from the moment of birth and throughout their life spans, they undergo a process of deterioration that culminates in their ultimate demise. Even The Parthenon on the Acropolis in Athens, some 2400 years old, had to undergo reconstructive surgery to save it from the ravages of modern urban pollution.

From the time of the development of reinforced concrete in the 19th century and prestressed concrete in the 20th century, we have been engaged in a struggle with a particular form of deterioration. The corrosion of reinforcing and/or prestressing steel used to enhance the load carrying capacity of the concrete structures we build is a serious problem. Corrosion has been described as "the scourge of the century."

For many years, the corrosion resistance of conventionally reinforced and prestressed concrete structures had been assumed to be adequate by virtue of its embedment in concrete and the demonstrated corrosion-inhibiting properties of portland cement. Prestressed concrete gave a new dimension to the applicability of concrete structures.

Prestressed concrete, in comparison to conventionally reinforced concrete, was considered to be even more resistant to corrosion because it was perceived to be crack-free as a result of prestressing. Indeed, there was a wide belief that one only needed to ensure the quality of materials and workmanship to preclude corrosion in concrete structures.

The corrosion of tendons in prestressed concrete structures can be much more serious than in conventionally reinforced concrete structures, since the prestressing tendons have a relatively small cross-sectional area under very high stress. The higher strength steel is inherently more susceptible to the possibility of brittle fracture due to stress corrosion or hydrogen embrittlement. Corrosion related fracture of prestressing steel can lead to collapse of a bridge structure without warning.[1]

In the last several decades the technology of prestressed concrete has progressed from relatively short span members, used primarily in buildings and bridges, to major structures such as cable stayed bridges, offshore sea structures, nuclear reactor vessels, large commercial and industrial buildings, parking garages and other special purpose structures. An increasing awareness and understanding has also evolved of environmental effects and their potential for long-term degradation of the structures we build.

It must be emphasized that instances of serious corrosion in prestressed concrete structures are rare. However, the consequences of corrosion of prestressing steel in structures under severe exposure conditions in terms of structural failure, safety and economic impact are so potentially severe that prevention measures beyond current common practice are being sought, considered and utilized.

This does not imply that prestressed concrete is in any way an inferior construction material. However, it is only relatively recently that there has been a recognition of the effect of exposure to particularly harsh environments, and even more recently to the need to provide more direct measures of corrosion protection to the prestressing steel.

The objective of this paper is to identify those methodologies that have either been used or could be used to provide increased corrosion protection of structures utilizing prestressing steel and thus enhance their service life.

MAGNITUDE OF THE PROBLEM

A number of surveys have been conducted and reported in the literature in the last two decades in an effort to quantify the magnitude of the corrosion problem of prestressing steels.[2-10] A 1978 survey,[5] covering a time interval from 1950 to 1977, cited 28 structures worldwide with known corrosion incidents. This represents an average of one failure per year. This report cited only those cases where corrosion had occurred in completed structures.

The study was specifically oriented to post-tensioned tendons composed of stress relieved wires, strands or high strength bars. Those cases where corrosion occurred during shipment, storage or the construction interval were not reported. It was estimated that, of the approximately 30 million tons (27 million Mt) of prestressing steel used in the Western world (at that time), only 200 tendons were affected by corrosion. The authors concluded that this incidence rate of 0.0007 percent was negligible because the cause of corrosion was known and avoidable.

Four years later, in a 1982 report[6] covering the time interval from 1978 to 1982, 50 structures in the United States alone were found in which tendon corrosion had occurred, an average of 10 per year. Of the 50 incidences reported, 10 cases of probable brittle fracture were related to stress corrosion or hydrogen embrittlement. It was estimated in 1988 that, in the United States and Canada, the number of reported corrosion incidents was in the hundreds.

Nurnberger[9,11] evaluated 242 incidences of corrosion damage of prestressing steel that were reported in the literature or by various governmental agencies worldwide during the interval from 1951 to 1979. Of interest in this report are the statistical evaluations of corrosion damage. A graphical depiction of the distribution of corrosion damage to prestressing steel as related to its application is presented in Fig. 1. Of the total 242 incidences, buildings, pipes, storage structures and bridges represent 27, 24, 19 and 13 percent, respectively.

Fig. 2 represents the distribution of corrosion damage related to type of prestressing, that is, circular wound prestressing (pipe and storage tanks), post-tensioned, pretensioned and unbonded (post-tensioned). An indication of the distribution related to the type of prestressing steel failure is given in Fig. 3.

Distribution by structure type, where total failure or an important part of it is related to corrosion of the prestressing steel, is given in Fig. 4. The failure of "parts of buildings" refers to failure of prefabricated pretensioned members. "Storage structures" refers to those prestressed by circular post-tensioning. "Miscellaneous failures" refers to post-tensioned members and members primarily under axial tension (as differentiated from flexural members). Distribution of damage to the prestressing steel element or structure failure relative to age is presented in Fig. 5.

In Fig. 6, the distribution of the various causes leading to corrosion is presented. "Corrosion protection" in Fig. 6 refers to inadequate and/or inappropriate corrosion protection, the term "Steel manuf." refers to steel types susceptible to corrosion, "Steel handling" is with reference to damage as a result of inappropriate and/or inadequate tensioning techniques or abrupt deviations at the anchorages, and "aggressive medium" is partly the result of the environment and partly from aggressive materials stored in pre-

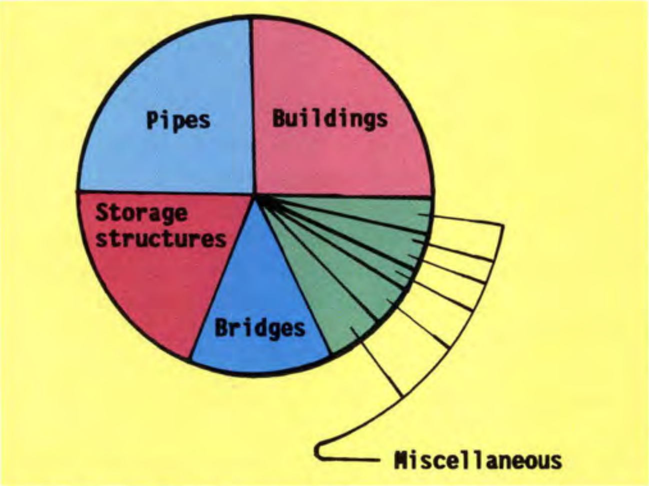


Fig. 1. Distribution of corrosion damage related to application (from Ref. 9).

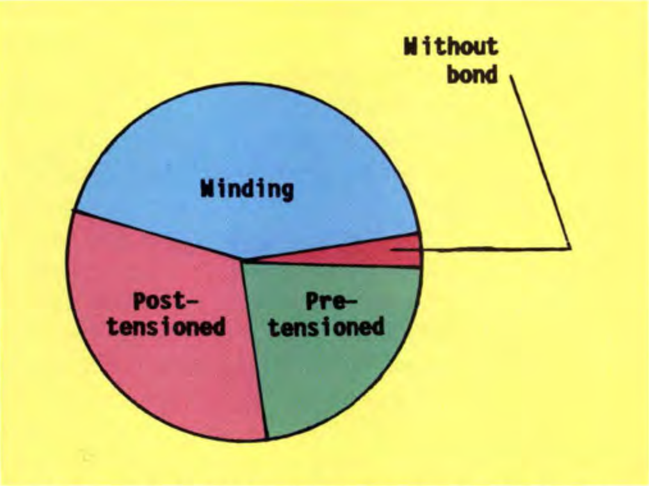


Fig. 2. Distribution of corrosion damage related to prestress method (from Ref. 9).

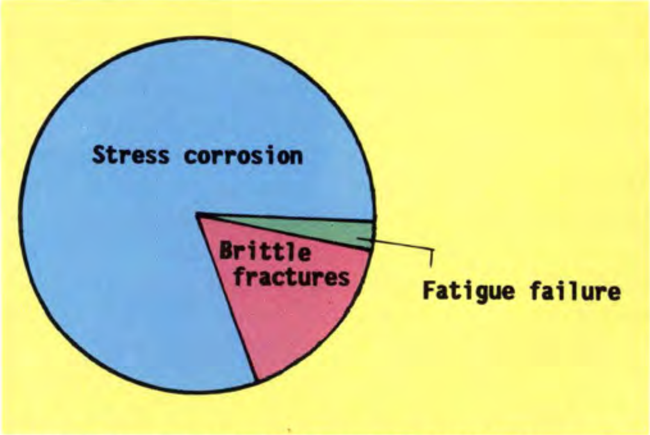


Fig. 3. Distribution of corrosion damage related to type of tendon failure (from Ref. 9).

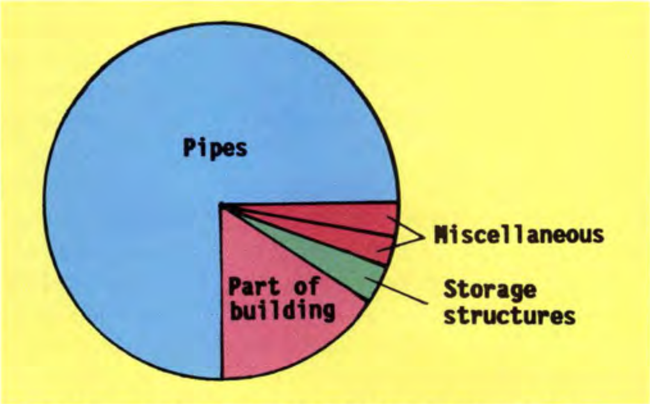


Fig. 4. Distribution of total or partial failure resulting from corrosion damage to prestressing steel as related to structure type (from Ref. 9).

Fig. 5. Distribution of corrosion damage related to age (from Ref. 9).

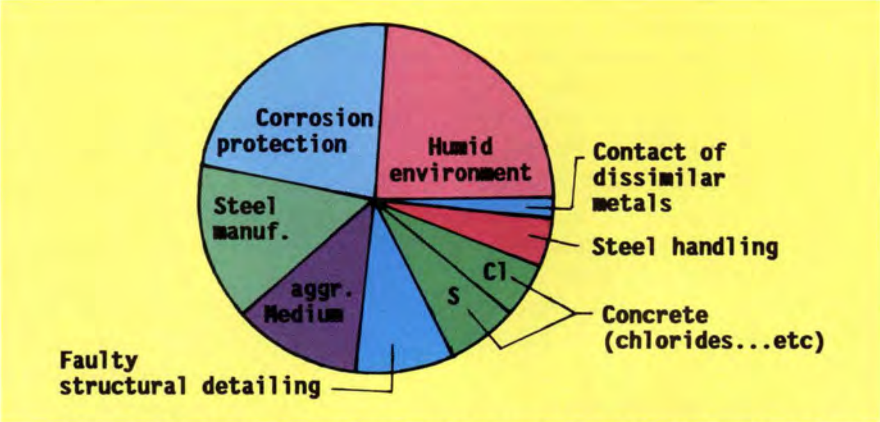


Fig. 6. Distribution of corrosion damage related to cause of corrosion (from Ref. 9).

stressed storage tanks and vessels.

There is a danger that the favorable conclusions of some of the early reports and surveys that dismiss the failure incidences as negligible and the result of obvious design defects, materials and workmanship may lead to complacency. There is a discernible trend to an increasing number of corrosion reported incidents with time. This may be partially explained by the following realities:

- The age of the prestressed concrete population is increasing.
- Many of the earlier surveys did not reflect the effects of the substantial increase in the use of deicing salts that began in the 1960s.
- Structures are currently being constructed in harsh environments, constructed in or in close proximity to marine environments, urban environments subject to carbonation, and possibly to acid rain which has yet to be evaluated.

In evaluating reports and surveys attempting to define the magnitude of the problem of corrosion of prestressing steels, the date of the report and what was known or understood about the phenomenon when the report was written has to be considered. It should be remembered, in addition to the three points previously mentioned, that many of the ills of earlier prestressed concrete structures have since been corrected. For example, limits have been placed on the chloride content of the concrete, the use of sensitive prestressing steels susceptible to corrosion has been reduced or eliminated, some prestressing systems have been modified, guidelines for shipping and storage have been developed, and other improvements have been made.

Conversely, we have only relatively recently begun to understand the role that a structure's environment plays. Although not well understood in some forms, we are gaining insight into the mechanism of corrosion and its different forms. We are becoming aware of the influence of corrosion on the properties of prestressing steels, for example, that uniform corrosion can reduce fatigue resistance by as much as a factor of two. It should also be remembered, especially when evaluating worldwide surveys, that heat-treated prestressing steel is not used in the United States because of its vulnerability to stress corrosion.

It is apparent that an exact determination (or even an approximation) of the magnitude of the corrosion problem of prestressing steel with respect to the existing inventory of prestressed concrete structures is at best elusive.

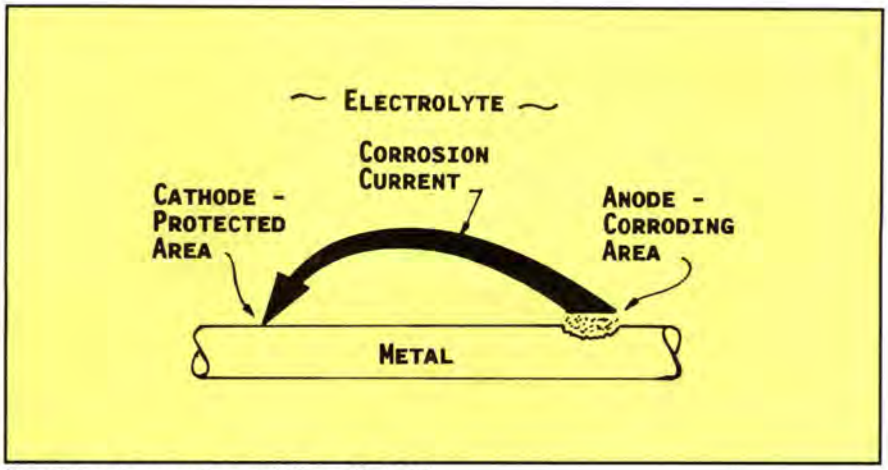


Fig. 7. Basic corrosion cell (from Ref. 14).

CORROSION MECHANISM

Corrosion is the term used to designate the deterioration of a metal by chemical or electrochemical reaction with its environment.[12] Most commonly used metals are produced by extraction from their oxides. Therefore, the refined metal is in a thermodynamically less stable state than that of its natural oxide form and under appropriate conditions will revert to oxides, i.e., it corrodes.

The process by which corrosion occurs is generally recognized to be an electrochemical reaction, that is, a galvanic cell is developed. In this cell, the metal releases electrons which are absorbed by the corroding agent, usually oxygen. Galvanic corrosion, in a classical sense, is caused by the difference in electrical potential that develops when two dissimilar metals are coupled (a battery effect). However, the term galvanic corrosion is used in a broader sense to denote corrosion occurring from dissimilar surface conditions of a metal, differences in oxygen concentrations or differences in environmental conditions (such as the moisture content of concrete).[2,13]

Three basic elements are required to establish an electrolytic cell: an anode, a cathode and an electrolyte. For corrosion to occur, the anode and the cathode must be connected by the electrolyte in such a manner as to allow electrical current to flow (see Fig. 7).[14] The term anode is used to denote the location at which the metal corrodes. At this location, the metal atom gives up electrons in a reaction with the corroding medium and becomes an ion. The free electrons are consumed at the cathode by oxygen reduction.

TYPES OF CORROSION

Types of corrosion may be categorized in several ways; for example, by the environment causing corrosion or the manner in which steel is affected. Categorization by the manner in which the steel is affected is discussed in the subsections that follow. The most common types of corrosion that affect prestressing steels are uniform corrosion, localized or pitting corrosion and stress corrosion.[13]

Hydrogen embrittlement had for some time been considered as a separate type. However, now it is being considered as a variation of stress corrosion. Brittle fracture of prestressing steel by either stress corrosion or hydrogen embrittlement is especially dangerous and of grave concern to engineers and designers. Fretting corrosion is another type that is becoming of increasing concern. Other types of corrosion are crevice corrosion and stray current corrosion.

Uniform Corrosion

This type of corrosion is one in which there is an approximately uniform surface attack of the steel, which implies that discrete anodic and cathodic sites are not present. This then requires that the anodic and cathodic areas are equal, polarization of both areas are equal and both processes equally control the corrosion rate.[10] This type of corrosion can be categorized as a chemical attack (as distinguished from an electrochemical cell). It occurs when unprotected steel is exposed to the environment, perhaps during shipping or storage, or prior to grouting. In this type of corrosion, it is possible for corrosion products to form a continuous film and thus retard further corrosion.[10,13,15]

Localized Corrosion and Pitting Corrosion

Because of a lack of homogeneity of the metal surface or the environment, separate electrochemical cells may be developed and localized corrosion can occur. This action is in contrast to the designation "chemical," as applied to general corrosion. The corrosion becomes more localized as the ratio of anodic area to cathodic area decreases, and a locally high corrosion rate occurs. This may lead to a sudden brittle failure after a negligible loss of material. At those locations where metal surface passivation has been destroyed or damaged, localized corrosion will generally occur.

In the presence of aggressive ions, such as chlorides, a pitting mechanism may occur. Pitting produces points of stress concentration, which concentrate strain in a small volume of metal. High strength steels of low ductility do not redistribute stresses readily, increasing considerably the magnitude of stresses in the area affected by pitting. Although total weight loss resulting from pitting may be very small, the consequences can be very severe. Since the rate of pitting corrosion is usually relatively high, time from construction to failure of the structure may be short.[15]

Stress Corrosion Cracking

Stress corrosion cracking (SCC) is a type of highly localized corrosion that produces cracking as a result of the simultaneous presence of corrosion and tensile stress.[16] This phenomenon is of importance because it can occur at stresses within the range of design stresses. Although many mechanisms have been postulated, none completely explain the phenomenon of stress corrosion cracking. The process of corrosion produces a discontinuity on the surface of the metal (a pit), thus providing a stress raiser.

Stress corrosion cracks have often been observed to originate at the base of a pit. Once a crack has started, there is a large stress concentration at the tip of the crack, with subsequent crack propagation. Cracks propagate either along grain boundaries (intergranular) or on slip planes within the crystal lattice (transgranular).[10] Eventually, these cracks can cause sufficient reduction in cross section to precipitate a brittle failure.

Hydrogen Embrittlement

Hydrogen embrittlement cracking of steel under stress occurs when atomic hydrogen penetrates into the metal structure, where it recombines to hydrogen molecules, producing an internal pressure in the metal. Absorption of atomic hydrogen by the prestressing steel usually occurs by cathodic charging, which happens in a corrosive environment when the steel is electrically coupled to a more anodic metal, for example, zinc coating.

The atomic hydrogen may be formed by the corrosion process itself or as a result of some manufacturing operation, such as pickling. Cracking of the metal may be initiated as a result of the internal pressure developed by the hydrogen molecules causing tensile stress, or in combination with a critical external tensile stress. Atomic hydrogen may enter the metal over an extended period of time. Rupture due to hydrogen embrittlement has occurred several years after installation.

Fretting Corrosion

Fretting corrosion results from surface wear arising from two surfaces in contact, under load, and subjected to vibration and slip. Requirements for occurrence of fretting action are interface pressure and presence of vibration or cyclic relative motion that is of sufficient magnitude to produce slip or deformation of the mating surfaces. Relative motion required to produce fretting corrosion is extremely small, less than 0.4 micro-in. (10^{-5} mm). Fretting corrosion is a form of fretting in which the chemical reaction predominates. The mechanism of fretting that eventually results in localized cracks is not known with certainty.[10]

Crevice Corrosion

Crevice corrosion is an intensive localized reaction that occurs within crevices or other shielded areas on the surface of the metal. Crevices can originate at the contact of the prestressing steel to another impervious body. The electrolyte trapped in the crevice produces an imbalance of electrolyte concentrations within the crevice and the outside surfaces. A brittle failure of steel may occur without warning.

Stray Current Corrosion

Stray direct current may be present in the ground as a result of electrical leaks, or failure to provide positive and permanent electrical insulation. Stray currents cause corrosion at locations where current leaves the structure and enters the ground or water electrolyte. All too frequently, designers are unaware of or overlook the fact that stray electrical currents may pass through the prestressing steel, producing a potential difference between the concrete and steel and leading to corrosion of the steel by the creation of electrochemical corrosion cells.[17]

Structures particularly vulnerable to this type of attack are those associated with electrified rail or tramway systems; those that may be fully or partially embedded in the ground such as bridge pier footings and piles; power generating or transmission plants; chemical plants or other manufacturing facilities where large amounts of electrically conducting liquids are handled; structures in which there is a very large amount of welding such as nuclear vessels; and sea structures in which concrete and steel act compositely, with the sea water acting as the electrolyte. Examples of the latter are offshore platforms, bulkheads, docks and floating bridges.

High tensile prestressing steel is more sensitive to stray currents than normal steel. It requires certain precautions in those structures that are exposed to the potential of this type of corrosion. Appropriate measures to electrically insulate the structure should be considered in design. Schrier[18] provides a general introduction to stray current corrosion and an FIP report[19] discusses the influence of stray electrical currents on the durability of prestressed concrete structures.

Alternating current electricity is much less likely to cause severe corrosion, unless it is of low frequency (approximately 17 Hz).

Corrosion Fatigue

Corrosion fatigue, although not a form of corrosion per se, is the reduction in fatigue resistance resulting from the presence of a corrosive medium. Fatigue stress, when accompanied by corrosion, will normally cause a more rapid failure than static stress of the same magnitude. This type of failure is not related to any special combinations of aggressive ion and metal, and it occurs in most aqueous media. The mechanism appears to be related to the exposure of oxide-free, cold-worked metal that becomes anodic and corrodes, transgranular cracks gradually developing under the cyclic stressing.[10]

EXAMPLES OF CORROSION DAMAGE

An example of corrosion damage of prestressing steel in pretensioned I-girders of a bridge is shown in Fig. 8. A failure of a parking garage as a result of corrosion of post-tensioning tendons in the floor slab is illustrated in Fig. 9. Both failures occurred in the United States.

The Azergues River Bridge in France was constructed in 1962. It consisted of post-tensioned concrete girders.[20] During an inspection of the bridge conducted in 1972, considerable cracking of the girders was discovered, the number of which increased with time. A detailed investi-

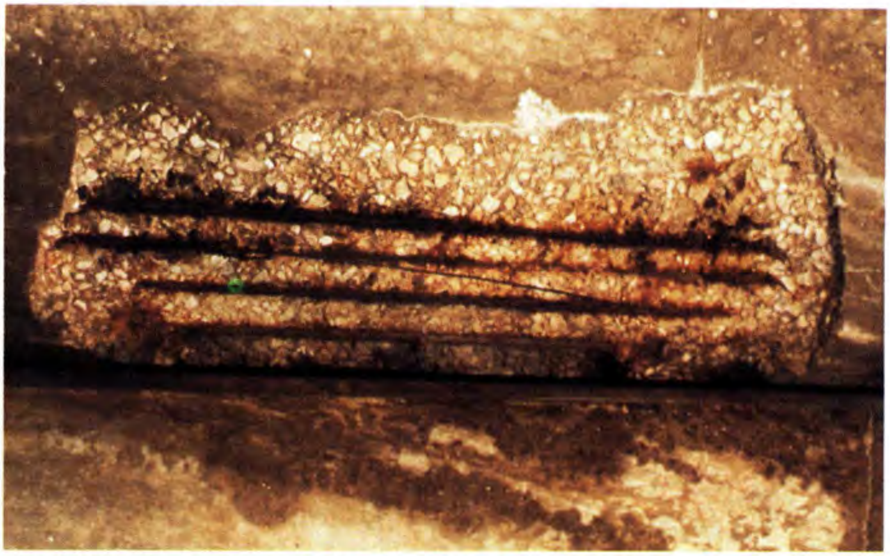


Fig. 8. Corroding pretensioned I-girders.

Fig. 9. Parking garage failure resulting from corroded tendons (Courtesy of Florida Wire and Cable Company).

Fig. 10. Collapsed Ynys-y-Gwas Bridge (from Ref. 1).

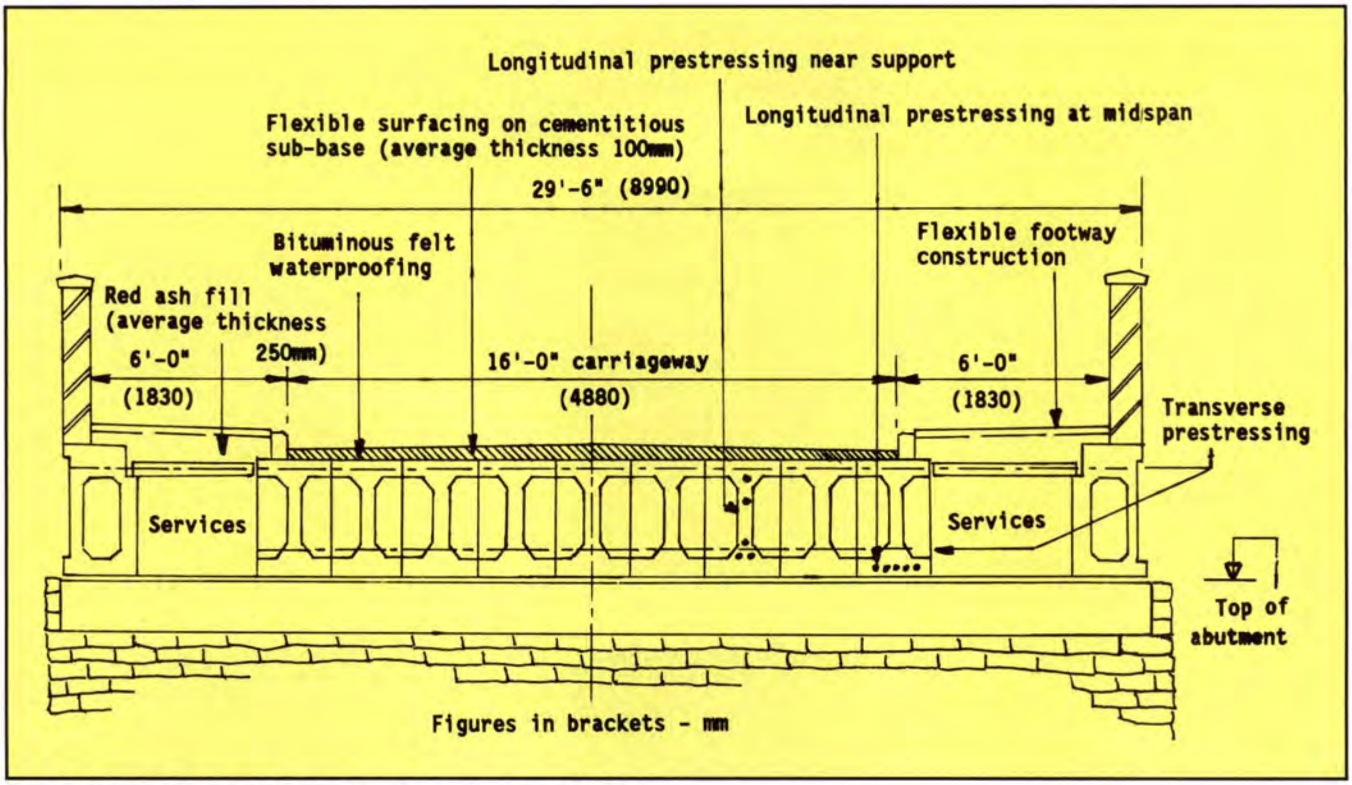


Fig. 11. Cross section of Ynys-y-Gwas Bridge (from Ref. 1).

gation of 144 tendons indicated 16 fully grouted tendons, 38 partially grouted tendons, 80 ungrouted tendons and 10 tendons that were neither stressed nor grouted. This obviously indicates that good workmanship is not always attainable. It was, therefore, of no great surprise that considerable corrosion — including prestressing steel failure — was observed, primarily resulting from chloride penetration. The superstructure was replaced.

On December 4, 1985, the Ynys-y-Gwas Bridge in Great Britain collapsed without warning (Fig. 10).[1] This was a 60 ft (18.3 m) simply supported segmental bridge constructed in 1953. As shown in cross section in Fig. 11, the bridge consisted of nine internal I-girders, each consisting of eight precast segmental sections, with a transverse diaphragm at one end of each segment. The box-section fascia girders were of similar segmental construction. The bridge was post-tensioned longitudinally and transversely. All joints of this precast segmental bridge were 1 in. (25 mm) cement mortar joints. Over the years, chlorides penetrated through the mortar and reached the tendons. The bridge had been inspected 10 times, with the last inspection in June 1985. None of these inspections revealed any warning signs of distress.

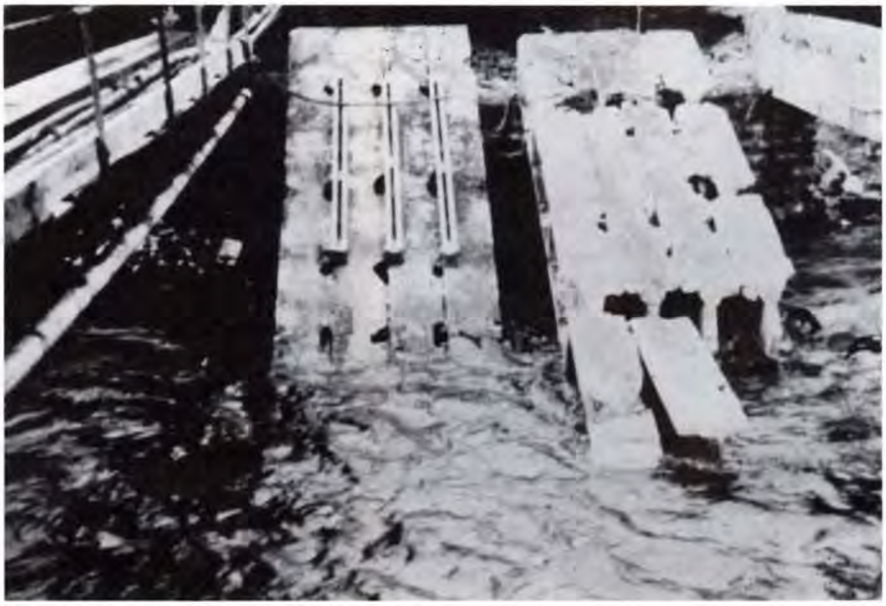


Fig. 12. Collapsed Ynys-y-Gwas Bridge.

No traffic was on the bridge at the time of collapse. All nine internal girders collapsed, but the box girder fascia beams remained in place (Fig. 12). Corroded lengths of wire from poorly grouted transverse tendons are illustrated in Fig. 13. Fig. 14 shows a transverse tendon crossing a longitudinal joint, with corrosion localized at the joint.

When the structure was inspected six months prior to collapse, no external evidence of corrosion was found. The collapse of this bridge suggests that monitoring structural deformations during inspections may detect tendon failures at an early stage prior to sudden collapse.[21]

Other examples are a corrosion failure of a ground anchorage (see Fig. 15) and a strand from a cable stay fatigue specimen (see Fig. 16). In the latter case, premature failure occurred in fatigue acceptance testing. The source of corrosion was attributed to an additive in the grout. The shiny spot to the right of the break in Fig. 16 is evidence of fretting, where the helical spacer strand was in contact with the longitudinal strand. In Fig. 17, corrosion of a cable stay is occurring prior to encapsulation by grout. The temporary anti-corrosion system (prior to grouting) had been depleted as a result of extensive delays in construction.

CORROSION PROTECTION SYSTEMS

A number of techniques and materials are now in use or are being considered for corrosion mitigation of pretensioned and post-tensioned steel (bonded and unbonded), ducts, anchorage hardware and cable stays for bridges. Generally, techniques for improved corrosion mitigation may be divided into two broad categories: those that enhance concrete durability and/or improve its properties, and those that provide direct corrosion protection to the steel.

In the first category, the trend had been toward increasing concrete cover, decreasing the water-cement ratio and limiting chlorides in admixtures. Techniques used to improve the properties of the concrete or grout are the inclusion of corrosion inhibitors (such as calcium nitrite), permeability reducers (such as silica fume) and organic sealers or membranes.

Included in the second category are such techniques as epoxy-coated steel ducts and polyethylene ducts, epoxy-coated prestressing strand and post-tensioned anchorage hardware, heat-shrink tubing for duct joint seals and an electrically isolated mono-strand system.[8] The sections that follow discuss those methods and techniques being used or considered for the direct protection of the prestressing steel and associated hardware.

Fig. 13. Corroded wire from poorly grouted transverse duct (from Ref. 1).

Fig. 14. Transverse tendon crossing a longitudinal joint (from Ref. 1).

Fig. 15. Corrosion failure of a ground anchorage (Courtesy of Peter Matt).

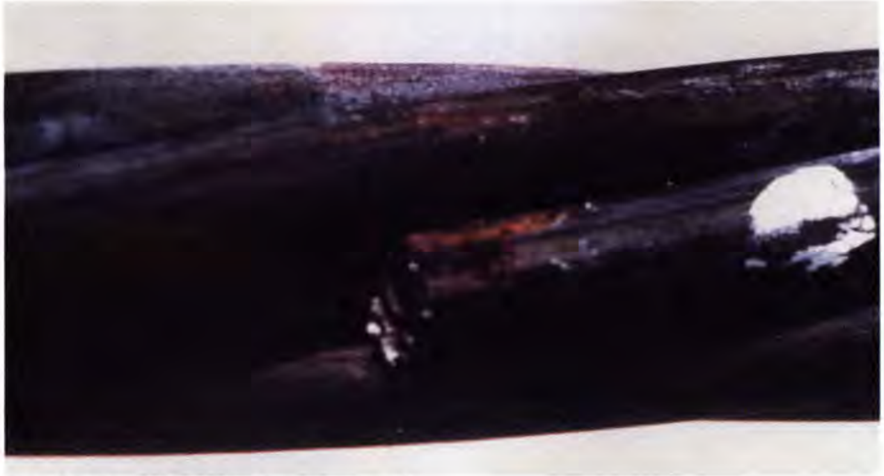


Fig. 16. Corrosion of cable stay strand.

Fig. 17. Corrosion of a cable stay prior to encapsulation by grout.

DUCTS

In bonded post-tensioned systems, the duct performs the function of forming a void in the concrete for the insertion of the prestressing steel, which is subsequently stressed. To serve this purpose, the duct should have the following characteristics:[8]

- Impervious to the intrusion of mortar during placement of the concrete.
- Sufficient strength to prevent crushing, puncture or other damage during installation of the duct or placement of the concrete.
- Sufficient abrasion resistance and stiffness to prevent the prestressing steel from cutting or crushing the duct wall during tensioning.
- Adequate chemical stability to avoid destructive reactions with the cement, grout or prestressing steel.
- Ability to transfer bond between the grout and the surrounding concrete.

Current practice for bonded post-tensioned tendons typically utilize corrugated ferrous-metal ducts to provide corrosion protection. Generally, the metal duct is also required, at least in the United States, to be galvanized to enhance corrosion resistance. Galvanized strip-steel ducts are applied in some countries while in others they are not permitted. The concern is that corrosion of the zinc coating during hardening of the cementitious grout could polarize the bare prestressing steel cathodically. Hydrogen could then develop and jeopardize prestressing steels that are susceptible to hydrogen embrittlement.

In recent years, attempts have been made to increase the corrosion protection afforded to post-tensioning steel in harsh environments or critical areas on monolithic segments of segmental bridges. This has led to an additional requirement of corrosion resistance of the duct itself. If the ducts are, in themselves, non-corrosive and impervious to chloride ions and water, then this is an effective way of protecting the prestressing steel.

Epoxy-coated metal ducts, spirally corrugated and hoop-corrugated polyethylene ducts have relatively recently been introduced in an effort to provide additional corrosion protection. Recent research[8] evaluating the corrosion protection effectiveness of duct specimens compared the following variables: bare steel duct, galvanized steel duct, fusion-bonded epoxy-coated steel duct and polyethylene duct; normal cementitious grout, cementitious grout modified with a calcium nitrite corrosion inhibiting additive and cementitious grout modified with a condensed silica fume additive; and duct joints sealed with either normal duct tape or heat-shrink plastic tubing.

Test specimens consisted of bare, unstressed strand grouted in 2 in. (51 mm) diameter ducts of 10 ft (3 m) length with a duct joint at midlength. Testing consisted of submerging the 5 ft (1.5 m) central portion of the duct specimens in a 15 percent (by weight) solution of sodium chloride in water for 3½ days, then air drying at 100 +/–10°F (37.8 +/–3.8°C) for 3½ days. The test procedure was followed for 304 days.

This represents an extraordinarily severe corrosion test, as the duct specimens were not encased in a concrete cover. At the conclusion of the tests, grout samples were obtained from the joint regions and near the edge of the test regions for chloride ion content determination. The results are presented in Table 1.[8]

These results indicate that, except for the duct joint region, the polyethylene duct was impermeable to chlorides. Although the epoxy-coated duct allowed some penetration in this severe test, the value is only about one-fifth of the assumed corrosion threshold of 0.15 percent. Galvanized ducts were found to be more than twice as effective as bare steel duct. They are about 1/30 as effective as the epoxy-coated ducts, but still allow a penetration in excess of the assumed threshold value. Unexpectedly, the chloride penetration values for the calcium nitrite-modified grout exceed those of the normal cementitious grout for both the bare and galvanized steel ducts. Silica fume grout, on the other hand, had chloride content values of about one-fifth those for normal grout.[8]

Table 1. Chloride analysis of grout from post-tensioning duct specimens (from Ref. 8).

Duct specimen parameters			Acid-soluble chloride ion content percent by weight of grout	
Duct (1)	Grout (2)	Joint (3)	Average at joint	Average at 1/4 point
P	C	T	0.187	0.006
P	C	S	0.037	
E	C	T	0.331	0.027
E	C	S	0.017	
B	C	T	0.491	2.536
B	C	S	0.009	
B	N	T	0.417	2.951
B	N	S	0.053	
B	S	T	0.208	0.525
B	S	S	0.032	
G	C	T	0.123	0.925
G	C	S	0.008	
G	N	T	0.159	1.877
G	N	S	0.012	
G	S	T	0.149	0.203
G	S	S	0.038	

Notes: (1) P = Polyethylene
E = Epoxy-coated steel
B = Bare steel
G = Galvanized steel
(2) C = Normal cementitious
N = Calcium nitrite modified
S = Silica fume modified
(3) T = Duct tape
S = Heat-shrink tubing

Electrostatically applied epoxy is suitable only for bare metal, not galvanized ducts. Further, only rigid ducts should be epoxy-coated as the epoxy cannot bridge the spiral seam in a corrugated duct when it is flexed. Epoxy-coated duct has been used only on one project in the United States; there has been a definite trend toward the use of polyethylene ducts for severe exposure conditions.

A major concern in the use of plastic ducts is the ability of the duct to transfer stresses to the concrete by bond. In several early projects utilizing corrugated polyethylene ducts, project specifications required the duct to withstand a pull-out load equal to 40 percent of the guaranteed ultimate tensile strength (GUTS) of the enclosed prestressing steel. The embedment length of the duct during these tests was equal to the development length of the prestressing strand.

Failure at the grout-duct or the duct-concrete interface before reaching the proof load constituted failure of the test. The basis for the 40 percent criterion is unknown (at least to the author). It is assumed to be associated with a minimum effective prestress force at the time of grouting equal to 60 percent of GUTS. These pull-out tests were successfully attained with the prestressing steel pulling out of the grout rather than bond failure of the ducts.

Spirally corrugated and hoop-corrugated polyethylene ducts have been introduced into the marketplace. A concern has been expressed regarding the use of a hoop-corrugated duct (as opposed to a spirally corrugated duct) with regard to a non-smooth flow of grout that may lead to entrapment of air in the corrugations and grout voids. However, recent tests[22,23] indicate that, at least for a particular configuration of hoop corrugation, no problems were encountered with grouting, entrapped air or grout voids. If there is any question regarding the performance of the grouting procedure with respect to a specific corrugation configuration, it is suggested that a confirmation test be conducted and autopsied to determine if the corrugations are completely filled with grout or if grouting procedures require modification.

Recent research[22,23] conducted at the Institute of Structural Engineering of the Swiss Federal Institute of Technology at Zürich on the fatigue of post-tensioned concrete beams led to further investigation of fretting fatigue in partially prestressed concrete beams. Tests indicated that when conventionally corrugated steel ducts are used, zones of friction develop between the ribs of the duct and the prestressing steel, which produces an early occurrence of fretting fatigue at the surface of the prestressing steel. There is also the possibility of fretting corrosion to exacerbate the problem.

For this reason, a polyethylene duct with a new corrugation profile was investigated (see Fig. 18). In regions of tendon curvature, conventional corrugation can develop large stress concentrations. The newly developed profile distributes the duct material to produce a more uniform distribution (see Fig. 19).

An additional concern with the use of polyethylene ducts involves the abrasion resistance of the material.

Fig. 18. Comparison of conventional metal duct and new polyethylene duct (Courtesy of VSL International, Inc.).

The primary purpose in using polyethylene ducts instead of metal ducts is to prevent chlorides and moisture from reaching the prestressing steel. However, should the duct be abraded and a hole develop during threading or tensioning the prestressing steel, the purpose is defeated.

Wall thickness is one of the most important parameters of polyethylene ducts. The relationship between lateral pressure and penetration depth, giving the total force, Q, on a polyethylene sample of 1 in. (25 mm) contact length between strand and the polyethylene, is shown in Fig. 20. The relationship of the number of 0.6 in. (15 mm) diameter strands, n, to the radius of curvature, abrasion and wall thickness is shown in Fig. 21. It can be seen that the wall thickness increases with tendon size and curvature. Dimensions of this newly developed polyethylene duct are presented in Table 2.

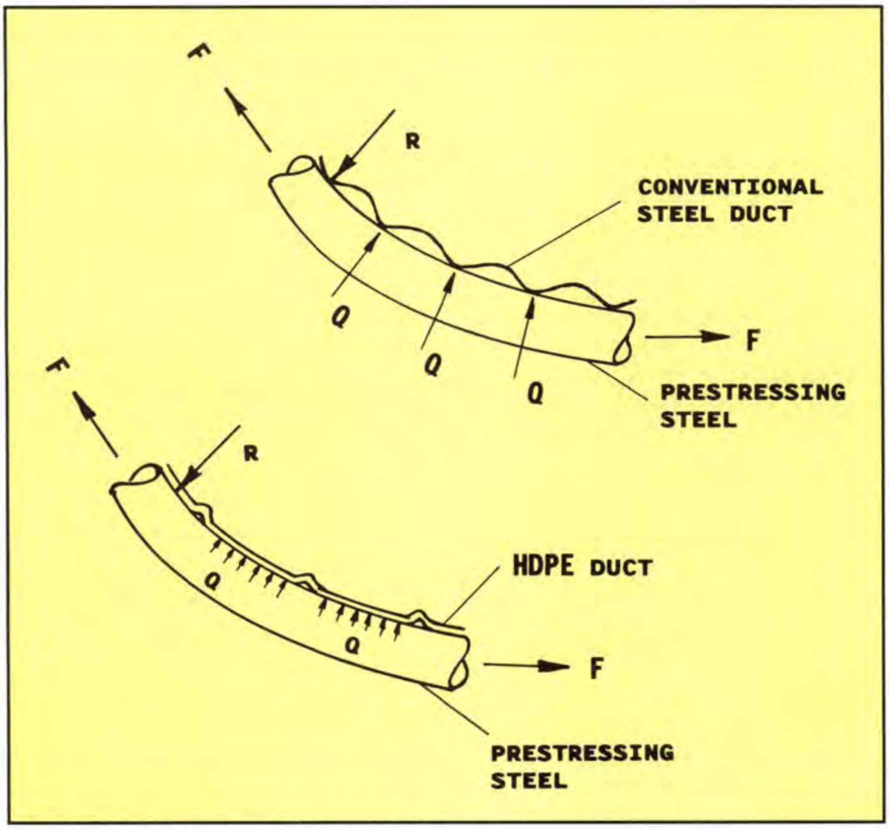


Fig. 19. Distribution of lateral pressure in ducts.

Duct Joints

In the corrosion tests reported in Ref. 8, in half of the test specimens, the midlength duct joints were sealed with standard duct tape. In the other half, they were sealed with a heat-shrinkable tubing developed for insulating and sealing electrical connections. When heated, the tubing shrinks and the thermoplastic adhesive-sealant internal coating melts and flows to provide a moisture seal. The data presented in Table 1[8] indicate the superiority of the heat-shrink tubing in comparison to the duct tape in these tests.

Separate field installation tests[24] were conducted on a bridge under construction to determine the implementability of heat-shrink materials for sealing joints of post-tensioned ducts. Two products were tested, sleeves and a wrap tape, and two methods of applying heat were used, a propane torch and a heat gun. Citing the need to quickly heat the material, the manufacturer recommended using a torch.

During the comparative tests, the extreme care required in applying the flame while avoiding damage to the polyethylene duct obviated the slight time saving. The sleeves showed a marked advantage over the tape wrap and could provide a watertight positive seal on round ducts. The sleeve seal appears to be less effective on flat duct couplers and a complete failure on the coupling to the polyethylene trumpets could occur. This may, in part, be due to the thinner material in the coupler, the relatively loose fit-up of the coupler to the trumpet, and the geometry of the flat couplers. A joint made with conventional duct tape provided a clearly superior joint in this application.

All tests were done under optimum conditions — unrestricted access, warm ambient temperatures, no wind and no time constraints — all conditions unlikely to be found on the construction site. Since proper installation is somewhat operator-sensitive, the positive seal that can be made, at least on the round duct, may not be achieved 100 percent of the time and cannot be verified by inspection. A satisfactory connection to the polyethylene trumpet was not made even under these optimum conditions. It is apparent that, although heat-shrink joints performed well in laboratory testing and hold considerable promise, substantial development work has to be accomplished for implementation to actual construction conditions.

CEMENTITIOUS GROUT

Grouting with a properly injected, good quality cement grout is the most widely used and one of the most reliable methods of providing corrosion protection for post-tensioning steels in low to moderate severity exposure environments. The two primary purposes a grout must fulfill in post-tensioned members are to inhibit corrosion by encapsulation of the steel in an alkaline environment and to have the ability to transfer bond stresses between the prestressing steel and duct enclosing the grout.

In addition, an effective grout must possess the following characteristics:

- Low permeability and high resistivity
- Adequate fluidity to allow pumping and filling of the duct void
- Minimum or no shrinkage in the plastic or hardened state and not suffer shrinkage cracking after hydration of the cement
- Little or no segregation

A grout must have other desirable characteristics that relate to grouting installation procedures. Recommendations for the grouting of tendons are published elsewhere[25-27] and are not discussed here.

The most serious problem with cementitious grouted post-tensioned tendons results from improper grouting techniques, which can lead to air voids at various locations along the tendon length (see Figs. 22 and 23).[11,28,29] These voids will permit an oxygen gradient to develop, leading to corrosion.

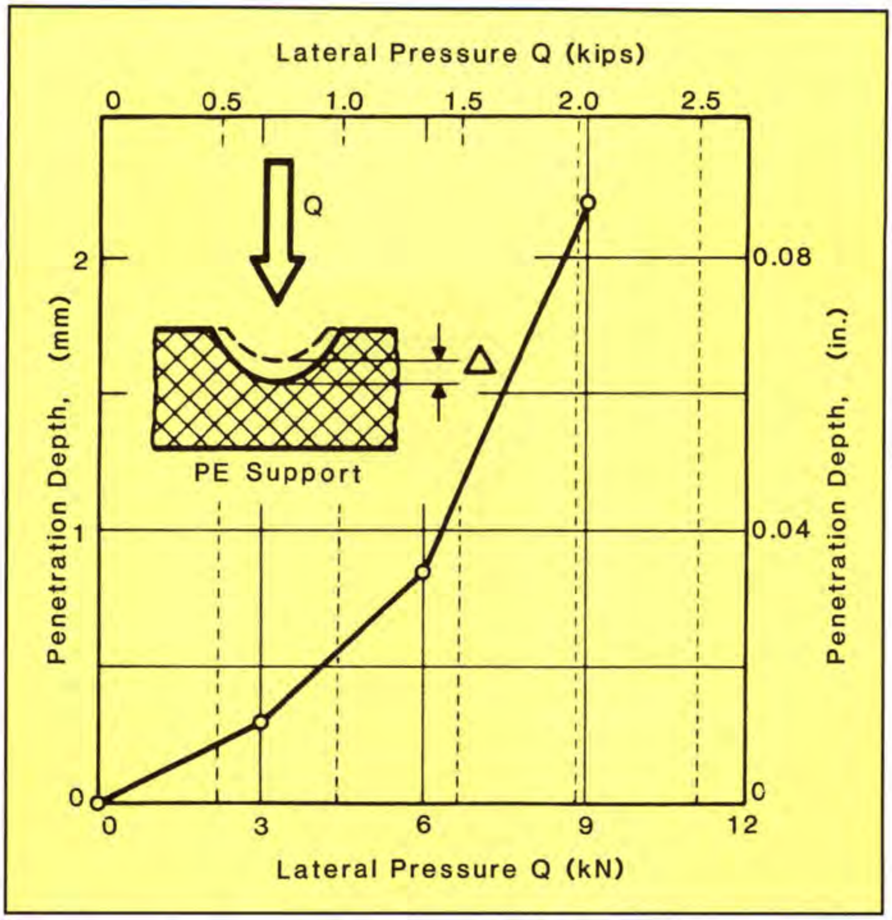


Fig. 20. Relationship between lateral pressure and penetration depth (Courtesy of VSL International, Inc.).

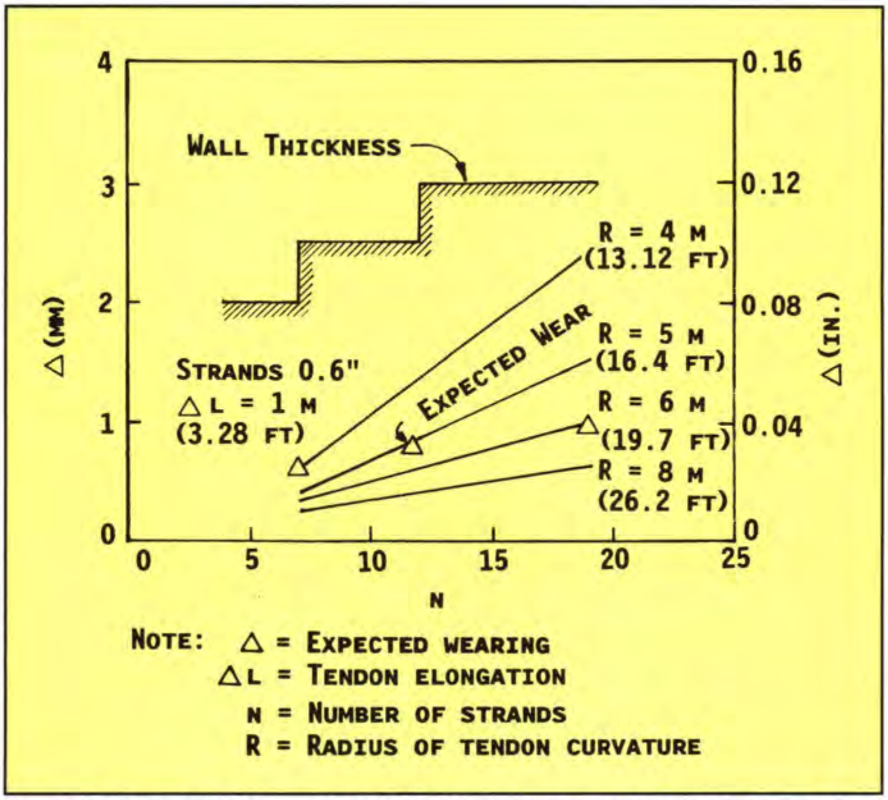
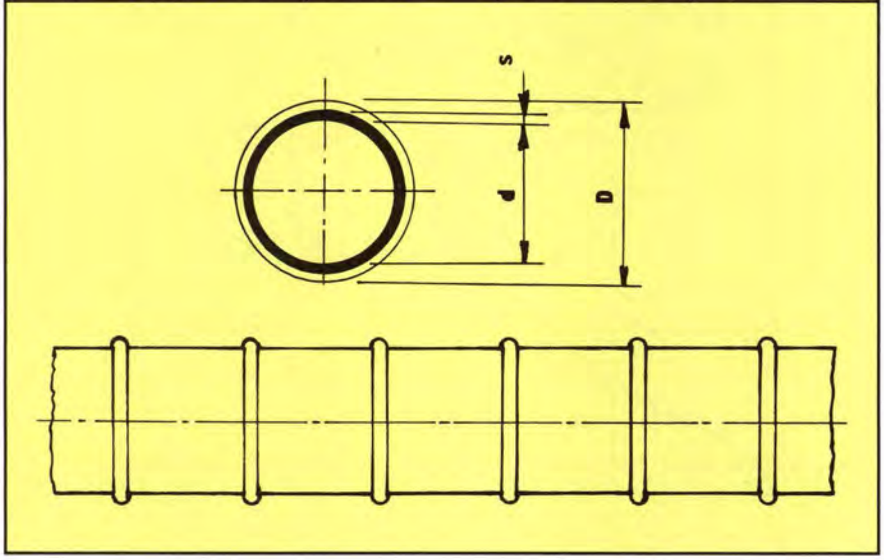


Fig. 21. Relationship of number of 0.6 in. (15 mm) diameter strands to radius of curvature, abrasion and wall thickness (Courtesy of VSL International, Inc.).

Table 2. Dimensions of polyethylene ducts PT-PLUS™ (Courtesy of VSL International, Inc.).

Strand type 13 mm (0.5 in.)	Strand type 15 mm (0.6 in.)	Dimensions of duct mm (in.)		
Tendon unit	**Tendon unit**	**d**	**D**	**s**
5-12	6-7	59 (2.33)	73 (2.87)	2 (0.08)
5-19	6-12	76 (3.00)	91 (3.58)	2.5 (0.01)
5-31	6-19/6-22	100 (3.94)	116 (4.57)	3 (0.12)



Grouting may be complemented by a subsequent regrouting where entrapment of water is expected.[25] Regrouting should commence no sooner than 10 minutes and no later than 20 minutes after grouting, depending on setting time and ambient temperature. Regrouting to displace water can be achieved by using an inlet and outlet near the locations where accumulations of bleed water are anticipated. Such locations may be at anchorages, couplers, high points of vertically curved tendons and at top anchorages of vertical tendons.

If tendons consist of strands, pressure grouting may be applied. When the duct has been filled with grout, the grouting should be continued by gradually increasing the pressure to a maximum of not greater than 145 psi (1 MPa). The anchorages should be sealed in such a manner that the ends of the strands protrude from the anchorages to provide a drainage conduit in the form of the interstices between the individual wires of the strand.

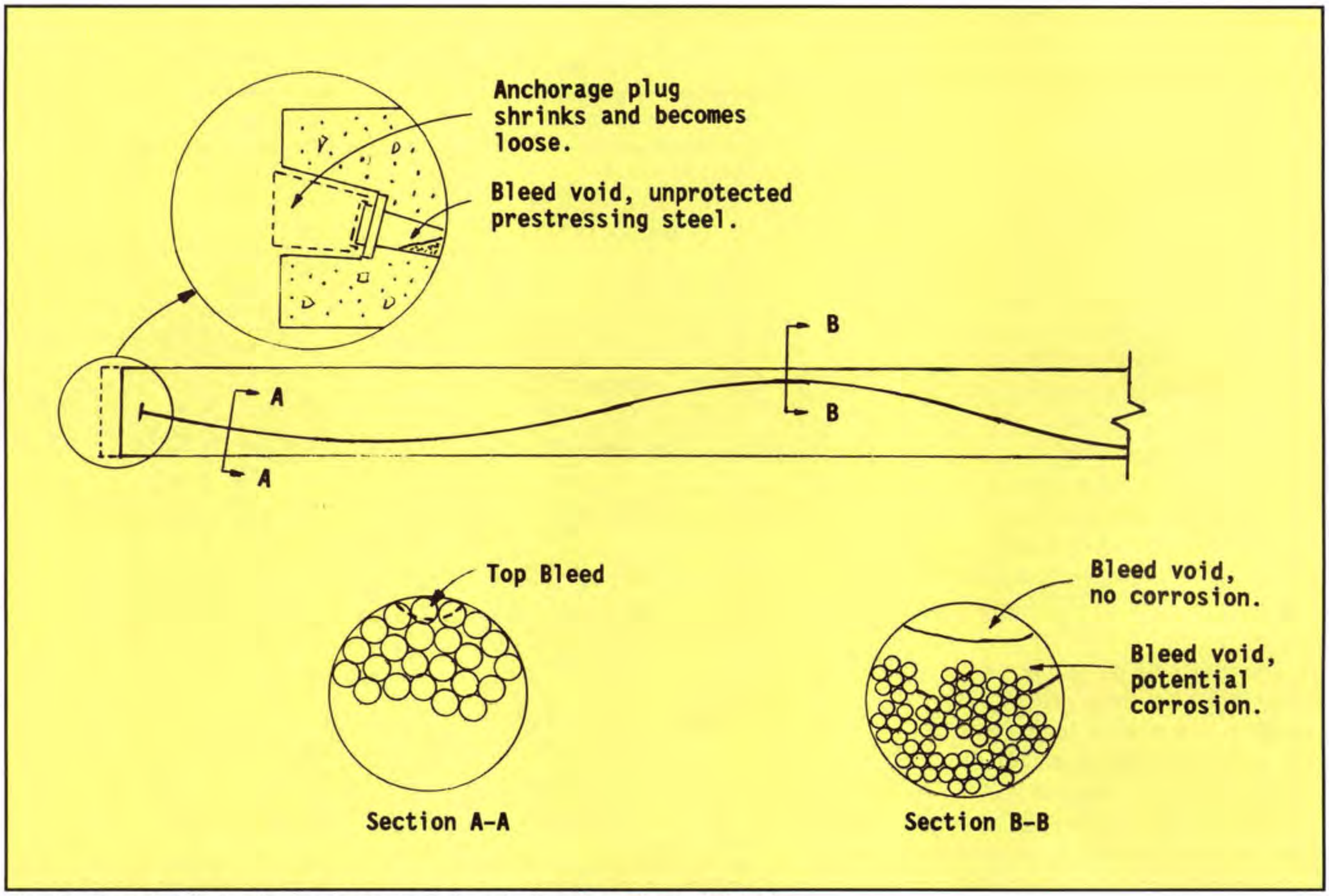


Fig. 22. Poor details leading to corrosion in bonded tendons (from Ref. 28).

When the grout in the ducts has taken an initial or permanent set (stiffened), and control procedures at inlets and outlets indicate that water pockets or air voids have formed, post grouting should be carried out. Voids should be filled with freshly mixed grout by simple topping up. Vacuum grouting may be required in cases with unacceptably large voids.[30]

ALTERNATIVES TO CEMENTITIOUS GROUT

Rather recently, various materials have been used as alternatives to injected cementitious grout for cable stay and external post-tensioned tendon applications.

Polymer Cement Grout

A polymer cement grout has been used in Japan to achieve a crack-resistant grout under design load. The injection method is the same as that used for normal cement grout. Advantages are that it is 20 times more ductile in elongation than normal cement grout, and no special techniques or equipment are required for grouting. Disadvantages are that it is relatively expensive, and the viscosity and hardening are temperature dependent.[31]

Polybutadiene Polyurethane

A polybutadiene polyurethane has also been used in Japan to produce a crack-free grout. It is a two-component material of polybutadiene polyurethane polyol and isocyanate hardener. The two liquids can be premixed in batches or pumped through separate hoses at a rate producing the specified mixing proportions and mixed at the grouting inlet port.

This material has a very low viscosity and easily penetrates into the small voids between the wires. When hardened, it is very flexible and has a very high ultimate elongation. Specific gravity is one-half that of cement grout. No water is used during the injection process and, therefore, there is no concern for corrosion. Disadvantages are that it is relatively expensive in material and execution costs, delicate to handle, highly temperature dependent and flammable.[31]

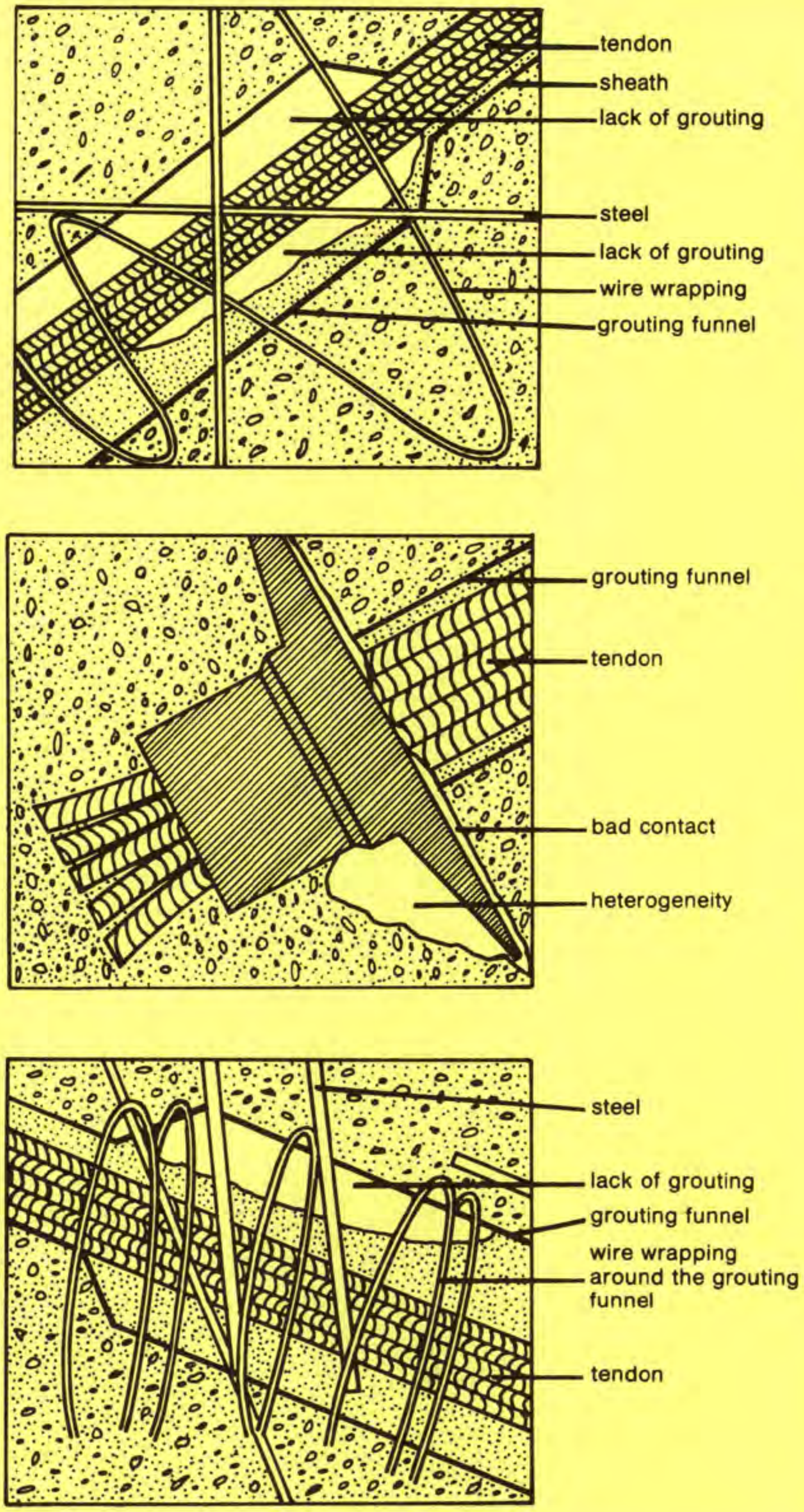


Fig. 23. Grout voids (from Ref. 29).

Petroleum Wax

Another alternative to cement grout is petroleum wax enriched with corrosion inhibiting additives. The wax is a homogeneous material with a microcrystal structure that is reportedly[32] reversible at any temperature, stable in time and easily injected. It does not passivate the prestressing steel as cementitious grout; however, it cannot be cracked or sheared, and its viscosity at ambient temperature, its tremendous adhesive strength and hydrophobicity make it an effective moisture screen, which considerably limits the risk of corrosion. The wax has a lesser density than cement grout, of approximately 0.90. At its injection temperature of 176°F (80°C), the wax is in a totally liquid state, which, under low pressure, provides excellent filling of the space between the wires.[32]

However, research conducted for the Kemijoki River Bridge at the Arctic Circle in Rovaniemi, Finland, yielded some surprising results.[33] This research indicated a general unsuitability of "wax-like" injected materials. The term "wax-like" refers to materials that must be heated and melted for injection and which solidify upon cooling. As a general rule, these materials have a melting temperature varying between 140 to 185°F (60 to 85°C).

During the cooling process the material shrinks, and upon reaching the solidification point, and lower temperatures, the shrinkage is restrained. Internal stresses, bond stresses with respect to the strand and other components, and possible cavities can occur. A further complication is that solidification is not uniform through the thickness — the surfaces tend to solidify first with respect to the interior. At or near the solidification point, the material can accept these stresses. At a further lowering of the temperature, the stresses developed cannot be accommodated and cracks develop at the surfaces to be protected. Once cracks and cavities develop, the stresses are relieved. The process is not reversible; the corrosion protection is lost.

A cold injected soft material has been developed that also shrinks, but it is capable of remaining adhered to the surrounding surfaces, with cavities occurring in the interior of the material that are self-healing upon returning to a normal ambient temperature; that is, the process is reversible. The substance is reported[33] to be thixotropic, to have an approximately constant viscosity over a wide temperature range and remain pumpable down to a temperature of 0°F (–18°C). Tests of complete anchorage specimens were conducted with a temperature range from –58 to +122°F (–50 to +50°C).

Waxes should be carefully evaluated before being used.

SHEATHED STRAND SYSTEMS

Another system of corrosion protection uses greased and sheathed individual unbonded strands, the so-called mono-strand tendon illustrated in Fig. 24. The word "greased" as used in this context is generic. The material may be wax, grease, epoxy-tar or some other appropriate material.


Fig. 24. Mono-strand tendon.

The corrosion protection of unbonded tendons relies to a large extent on the prevention of moisture and corrosive materials from reaching the prestressing steel. Therefore, the sheathing must be completely watertight throughout its length, up to and including the anchorages. Various materials have been utilized for the sheathing. Thus far, plastics appear to be the most suitable.[34] The sheathing material should have the following properties:[34,35]

- Nonreactive with concrete, prestressing steel and the prestressing steel corrosion preventative coating
- Watertight over the entire sheathing length
- Durable and sufficient strength to resist damage and abrasion during fabrication, shipping, installation, concrete placement and tensioning
- Chemical stability, without embrittlement or softening over the anticipated exposure temperature range and the service life of the structure
- Resistant to aging by exposure to ultraviolet light
- Low creep properties
- Sufficient strength to bridge any fine cracks that may occur in the concrete

It is recommended that a high density polyethylene or polypropylene be used for the sheathing. Both materials are tough, durable and nonreactive. High density polyethylene is more flexible and less liable to embrittlement at extremely low temperatures, while polypropylene is more stable at high temperatures. Both materials have high resistance to abrasion and creep, although polypropylene is slightly superior in these respects.[34]

One method of sheathing consists of a longitudinal seamed plastic tube which is heat sealed. When this method is utilized, it is important to ensure that the seams are properly made since it is difficult to detect burst seams after the tendon is uncoiled. The coils should be of sufficient diameter to preclude seam bursting when the tendon is being coiled or uncoiled. To avoid this potential problem, a seam-free sheathing is to be preferred. Extruding the plastic over the coated tendon is the most satisfactory method of ensuring a continuous, seam-free, waterproof tube of uniform thickness.[34]

Sheathing thickness of high density polyethylene or polypropylene for corrosive environments should be a minimum of 0.04 in. (1.00 mm). The sheathing should have an inside diameter of at least 0.01 in. (0.25 mm) greater than the maximum diameter of the strand to permit the free longitudinal movement of the tendon.[35] Loose sheaths have excess space (see Fig. 25) which will allow ingress of water from the time of fabrication to installation as well as during service life.[36]

Corrosion protection materials used in conjunction with sheathed strand systems must ensure protection of the prestressing steel throughout the service life of the structure. These materials generally take the form of greases,

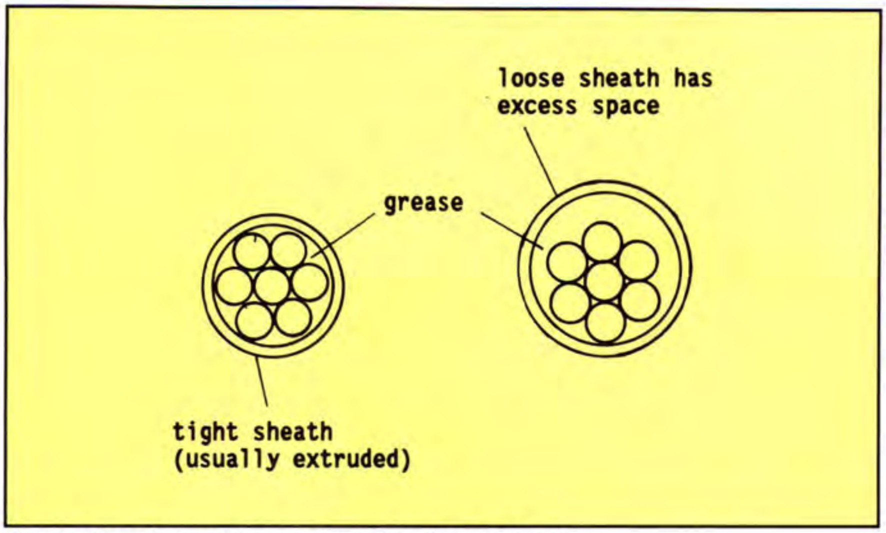


Fig. 25. Strand sheathing configuration (from Ref. 36).

bitumastics or waxes. In general, the coatings should have the following properties:[34,35,36]

- Provide corrosion protection to the prestressing steel and a barrier to moisture and air.
- Be chemically stable and nonreactive with the prestressing steel, the sheathing material and the concrete.
- Provide lubrication between the prestressing steel and the sheathing.
- Adhere to and be continuous over the entire tendon length to be protected and should completely fill the sheathing without air pockets.
- Remain ductile and free from cracks and should not become brittle or fluid over the anticipated range of temperature during fabrication, shipping, installation, concreting, tensioning and while in service. In the absence of specific requirements, this is usually taken as 0 to 160°F (–20 to 70°C).
- Provide a self-healing film and displace water.
- Contain no solvents to leave trapped residue that might become a fire hazard or react with the sheathing material.

Testing methods, acceptance criteria and data for corrosion protection greases, waxes, bitumastic and tar

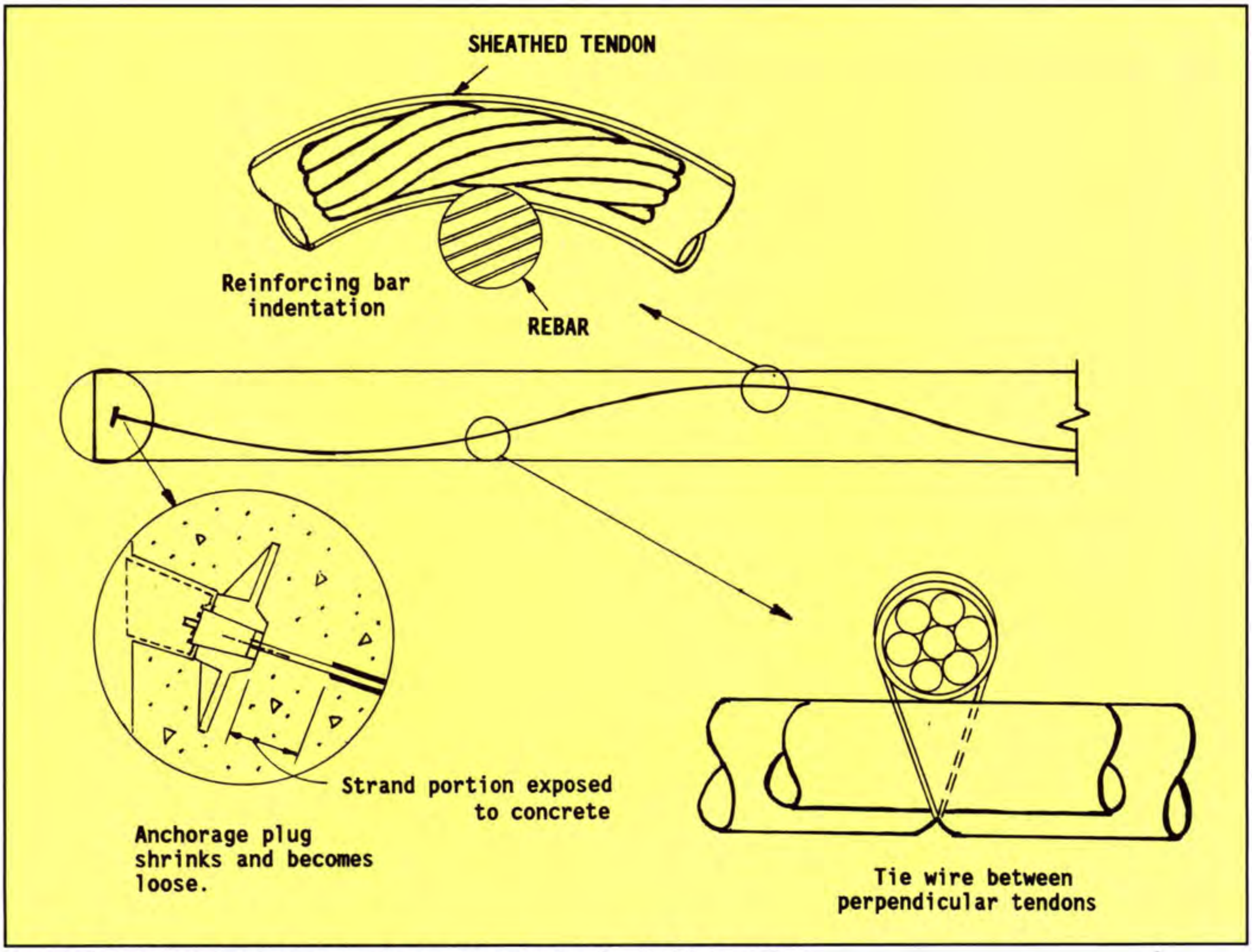


Fig. 26. Defects in unbonded tendons that lead to corrosion (from Refs. 28 and 36).

are given in Refs. 11, 27, 34, 35, and 38 to 42.

Actual flaws discovered in unbonded mono-strand post-tensioning tendons are illustrated in Fig. 26.[28,36] Poor bond and nonexpansive mortar allows the anchorage plug to shrink and become loose. This gives aggressive materials and contaminants access to the anchorage and prestressing steel. After the strand extension has been cut off, a pressure grease gun should be used to fill any holes in the anchorage, especially between the wedges, with a grease that is compatible with that used to protect the strand.

The conical hole in the concrete at the anchorage should be cleaned and coated with a bonding agent to achieve proper bonding of the mortar plug. The anchorage pocket should be filled with a high quality, low permeability mortar that bonds to the surface of the pocket. If there are any indications of poor bond or porosity, the mortar should be removed and replaced.[36]

Corrosion can be initiated at the strand cut-off if inadequate cover is provided and/or the mortar quality is inadequate and, with time, progress to critical parts of the tendon. Recommended cover over the end of the strand (see Fig. 27) should be 1 in. (25 mm) in normal environments and 2 in. (50 mm) in aggressive environments. The PTI Specifications[35] call for a watertight cap filled with grease to enclose the cut end of the strand, at both the stressing and dead ends, if the environment is corrosive.

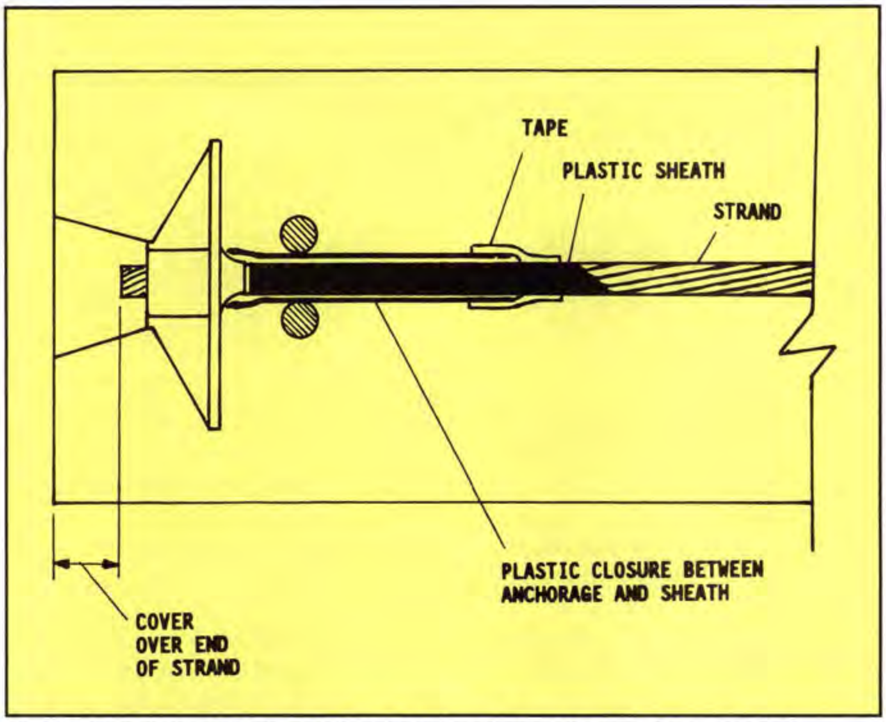


Fig. 27. Detail of greased and sheathed strand at anchorage (from Ref. 36).

The gap between the end of the sheathing and the anchorage (see Fig. 26) obviously violates the intent of the corrosion protection system of "greased" and sheathed strand. During stressing, an elongation of the strand occurs and the unsheathed strand is pulled through the concrete, producing a cylindrical configuration and probably losing some of the grease protection.[28] The sheathing should be continuous to a positive waterproof connection to the anchor (see Fig. 27).

A tough sheathing of at least 0.04 in. (1.00 mm) thickness should be used, such that tie wires between particular tendons will not cause local indentations in the sheath (Fig. 26). The sheaths tend to shear off when the tendon is tensioned. Sharp angles in the

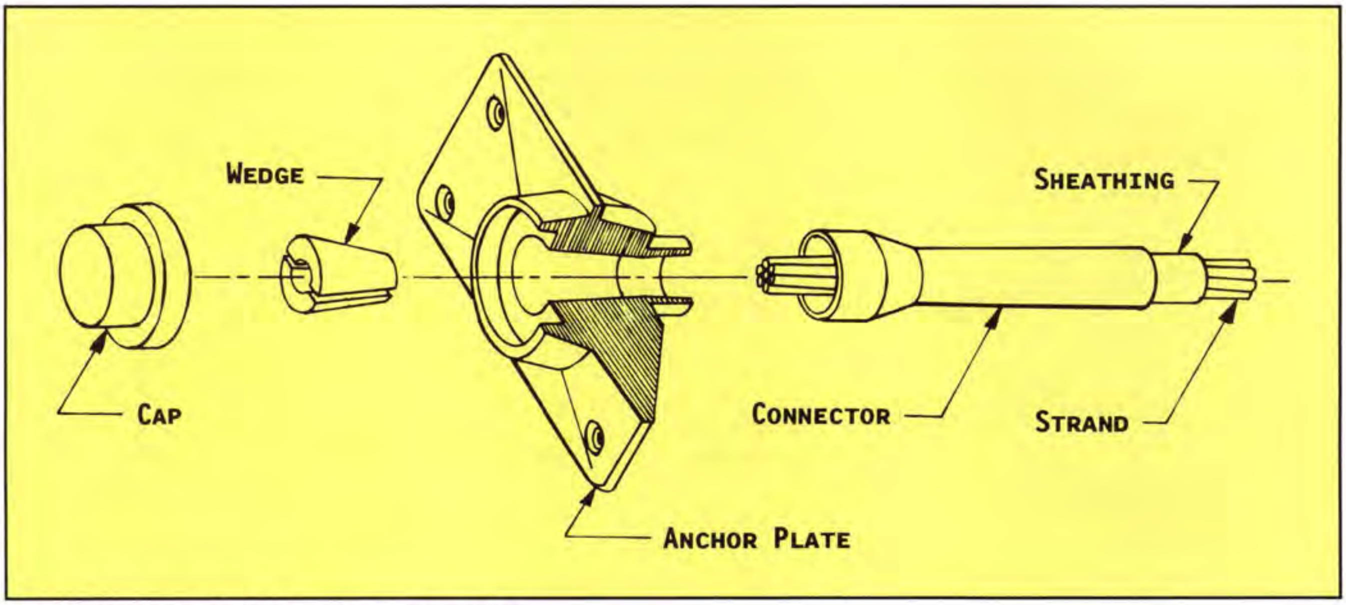


Fig. 28. Electrically isolated mono-strand tendon.

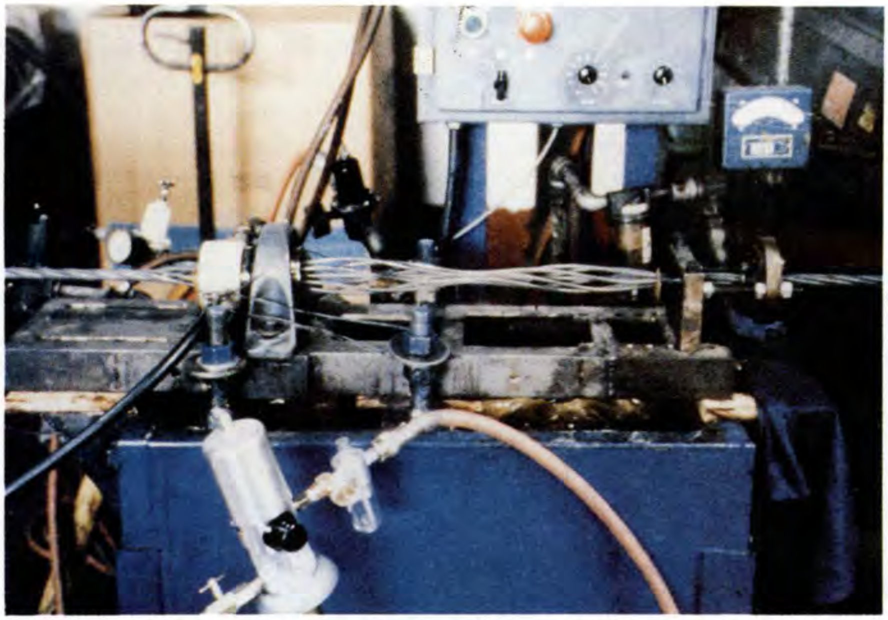


Fig. 29. Destranding and coating operation (Courtesy of VSL International, Inc.).

tendon geometry should be avoided. Radial forces developed during tensioning can tear or shear the sheathing, particularly if the tendon is supported by reinforcing steel (see Fig. 26).[28,35]

An electrically isolated mono-strand tendon (EIT) concept is patented in the United States and is available from several suppliers. Details of the system are presented in Fig. 28. This system provides complete electrical isolation, preventing electric currents which must be present for the corrosion process, and precludes moisture or chloride ion penetration to the steel.

Workmanship normally provided for the end anchorage protection tends to be erratic and often of poor quality. Sealing of the end anchorage in a nonconductive enclosure provides a positive corrosion protection to a critical zone. The EIT concept allows a lesser concrete cover, thus, thinner members. Cover required is that needed for fire protection of the sheathed strand, to allow proper concrete placement and to ensure that splitting in line with the tendon does not occur at anticipated stress levels.

A recent innovation is a double corrosion protection sheathed strand system. The primary difference between this and conventionally sheathed strands is the additional level of corrosion protection provided by applying a corrosive inhibiting material directly to each of the seven individual wires of each 0.6 in. (15 mm) diameter strand and extruding a polyethylene jacket over each strand.

During the application of the corrosion-inhibiting material, the seven-wire strand is put through a destranding op-

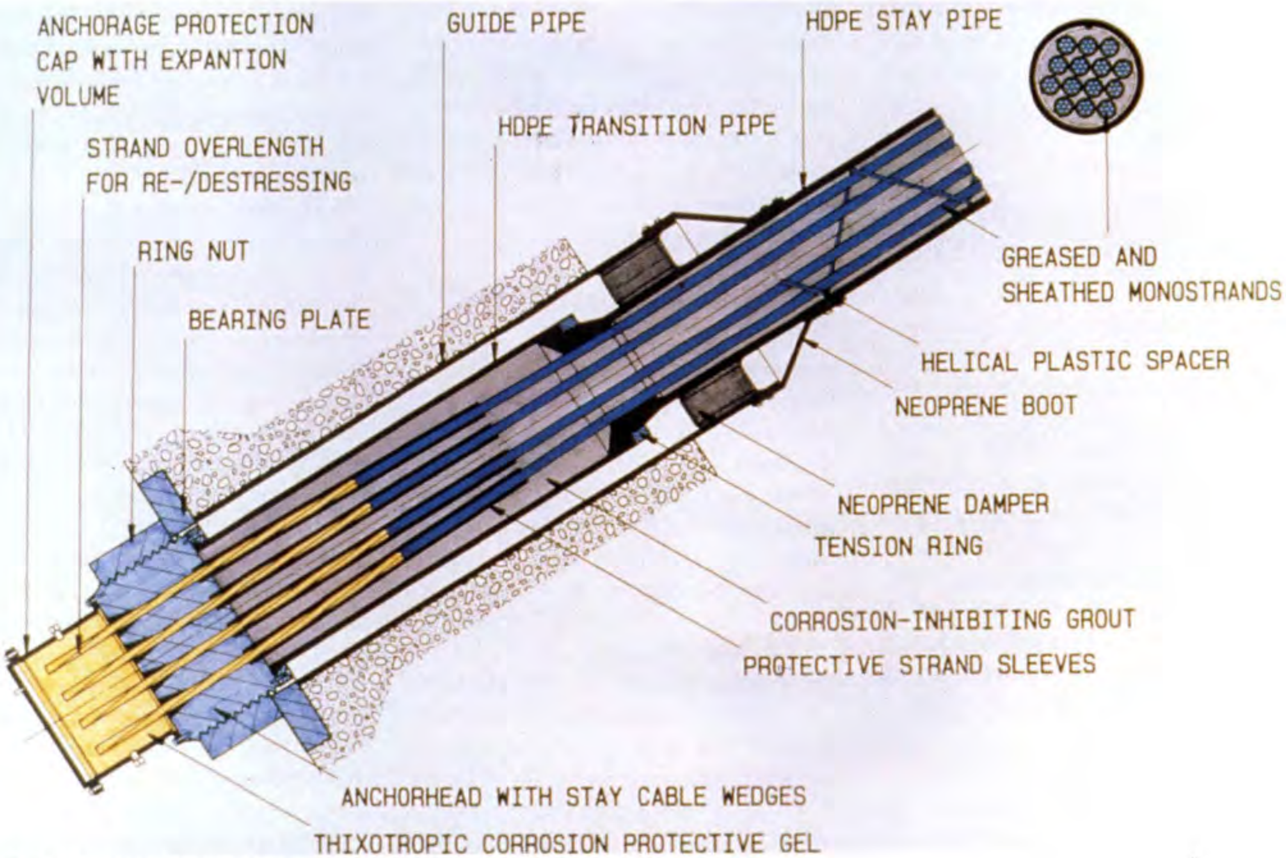


Fig. 30. Mono-strand cable stay system (Courtesy of VSL International, Inc.).

eration, a coating operation that covers the entire surface of each wire, restranding to the original configuration, and jacketing the strand with polyethylene (see Fig. 29). The corrosion-inhibiting material is a soft petroleum base wax that can be applied at ambient temperature, displaces any moisture on the surface, has a melting point over 500°F (260°C) and offers superior corrosion protection.

A concern developed over this product regarding the effect of destranding and restranding on load-elongation characteristics, and the potential of slip of the straight center wire with respect to the outer six helical wires. Test results indicate that 1 percent elongation load, breaking strength and modulus of elasticity with this product do not appear to be significantly different from conventional bare seven-wire prestressing strand.

The "greased" and sheathed monostrand system described here, used for parking garage and flat slab construction, has been adapted for use in cable stays of bridges. The stay consists of a parallel bundle of 0.6 in. (15 mm) diameter unbonded prestressing strands that are individually greased and sheathed, enclosed in a high density polyethylene pipe and grouted (see Fig. 30). This transfer of technology could include multi-strand post-tensioning tendons.

DIRECT COATING OF PRESTRESSING STEEL

In the search for corrosion protection methods and materials, consideration has been given to coatings applied directly to the prestressing steel. This approach has the advantage of providing the protection directly to the component most vulnerable to corrosion, as opposed to an indirect method such as provided by a concrete sealer, concrete cover or coating a duct. However, the coating must have the strain compatibility to withstand the elongation of the prestressing steel during tensioning without cracking.

Zinc Coating

Zinc is a well known, common and relatively inexpensive coating material for iron and steel; thus, it is an obvious material to consider for the coating of prestressing steels. Zinc coating or galvanizing has the additional advantage that it is not easily damaged in handling and installation. However, it is a sacrificial coating; it is consumable with time in a corrosive environment.

The galvanizing process affects the mechanical properties of prestressing steel. Ultimate strength is reduced and the ultimate elongation and long-term relaxation are increased.[43] In addition, fatigue resistance may be reduced by as much as 20 percent.[44] With some steel formulations, ductility may also be affected.

The zinc coating may also react with some cements, releasing hydrogen gas. This reaction is apparently dependent upon the cement alkalies and the composition of the galvanized coating. The released hydrogen produces an increased porosity at the steel interface, reducing bond strength. Poor bond may also result if the galvanized strand is not kept free of zinc carbonate (so-called "white rust") prior to embedment in the concrete.

Variable results have been reported regarding the bond strength of galvanized steel with respect to bare steel. Some researchers report an increase in bond for galvanized strand while others report a significant reduction, indicating that there may be other parameters to be considered. There is also a concern for the possibility of hydrogen embrittlement; however, there is no evidence to support this suspicion.

Epoxy-Coated Prestressing Strand and Anchorages

In recent years, research has focused on the use of epoxies to coat prestressing strand. One manufacturer produces an epoxy-coated, low-relaxation, seven-wire, 270 ksi (1860 MPa) prestressing strand.[45] Coated strand of all sizes from $^3/_8$ to 0.6 in. (9.5 to 15 mm) diameter are available on a production basis. Coating thickness over the crowns of the outside wires of a strand have a thickness of 30 +/– 5 mils (0.76 +/– 0.13 mm). In the valleys between the outside wires, the coating is thicker.

There is no coating on the center wire or on the inside surfaces of the outer wires; however, since the coating is virtually holiday-free, this is not considered a problem as long as the end of the strand is properly sealed. Sealing the cut end of the strand is required to prevent moisture and corrosive agents from entering the strand and traveling into the strand by capillary action in the interstices between the wires.

To avoid compromising the effectiveness of the system, attention must be paid to anchorage details. Special wedges are required that bite through the epoxy coating thickness and grip the prestressing steel strands.

Recently, after fatigue tests, failures induced by fretting corrosion on the uncoated inner surfaces of the strand were observed. This led to the development of a strand where the interstices are filled with epoxy resin during application of the exterior coating.[46]

Two grades of epoxy-coated strand are available, namely, a smooth coated grade and a bond-controlled grade. The smooth coated grade has poor bond characteristics and is intended for use with end anchors, as an unbonded tendon. When encased in concrete, the strand is not easily pulled out, but it does not develop sufficient resistance to provide any appreciable bond. The bond-controlled grade is identical to the smooth grade except that particles of grit are embedded in the surface of the epoxy to provide bond with concrete.

Extensive testing has been conducted on this product. The standard tests of ultimate strength, yield strength, percent elongation and other properties are identical to those of corresponding uncoated strand. It has successfully been tested for chloride ion permeability (FHWA-RD-74-18), impact resistance (ASTM G14), resistance to applied voltage (ASTM G8), salt spray (ASTM B117) with no visible indication of corrosion after 3000 hours, sand abrasion (ASTM D968), cathodic disbonding (ASTM G8) and chemical resistance (ASTM G20).

However, bond slip occurs somewhere in the temperature range of 150 to 200°F (65 to 93°C). This means that this product should not be used in a pretensioned or bonded post-tensioned application where fire protection is required. It could be used in an unbonded post-tensioned application, where loss of bond capability would not endanger the member or structure. This also has implications for steam curing applications of precast concrete members. However, additional research is being conducted to establish more definitive values.

The epoxy-coating process has an effect on the relaxation properties of low-relaxation strand. Epoxy-coated low-relaxation strand meets all the other properties of low-relaxation strand itemized in ASTM A416. Pure relaxation values (as used in prestressed concrete applications) for epoxy-coated strand (at a stress level of 0.7 GUTS) are increased by a factor of 2.0 for 0.5 in. (12.7 mm) diameter strand and 2.5 for 0.6 in. (15.24 mm) diameter strand.

In the application for cable stays, the phenomenon is not relaxation, but creep of the strands (at a stress level of approximately 0.4 GUTS). It is suggested that, for design purposes, creep (elongation) in the strand should be assumed at 0.025 percent for the life of the structure, based on the dead load stress level, at least until such time as test data are available.

The epoxy-coating technique has also gained popularity for corrosion protection of post-tensioning anchorage hardware. Coated single and multi-strand anchorages are now being employed in the construction and rehabilitation of a number of bridges and parking garages. Coating requirements are the same as that required for conventional reinforcing steel (ASTM A775 or AASHTO M284). Epoxy-coating of the basic strand should be in accordance with ASTM A882.

Ceramics

Recent technology in the automotive industry for parking brake cables shows promise for a technology transfer to prestressing tendons.[47] The minimum ultimate tensile strength of the 1/8 in. (3.18 mm) diameter 19-wire strand is 235 to 260 ksi (1620 to 1793 MPa), and the strand is not a low-relaxation grade. In harsh environments, the brake cable eventually undergoes stress corrosion cracking due to the combined action of tensile stress and a corrosive environment.[48] Evolving requirements for automobiles expect component life to be 100,000 miles (160,000 km) in an extremely harsh environment.[49]

The mechanisms of failure are typically due to crevice corrosion, electrolytic corrosion (parking brake cables are frequently used for grounding the rear axles) and the effect of sulfate-reducing bacteria from soil splashed onto the cables.[49] One reported solution to these conditions is the development of a corrosion control system, using a combination of upgraded thermoplastic polyester jacket and new type of ceramic sub-coat material based on silicate technology, which effectively isolates the wire from the environment and excludes chloride-laden water.

During the stranding process, individual galvanized wire is coated with an organic-based alkyl silicate-zinc mixture.[48] An applicator die located in front of the closing die provides for the complete coating of each wire. The organic solvent of the coating evaporates and the alkyl silicate-ester will hydrolyze and polymerize upon exposure to air to form an inorganic silicate film on the wire.[48] After the coating film is cured, the 19-wire strand cable is over-coated with an extruded copolyester or other suitable plastic jacket.

This new patented corrosion protection system was reported by the manufacturer to resist cracking and failure for a period of time extending over 100,000 miles (160,000 km) in the life of the automobile. The level of corrosion resistance can be adjusted by changing the viscosity of the solution applied to the wire.[48]

The corrosion resistance of the strand was tested in accordance with ASTM B17, Salt Spray. The corrosion protection level can extend to 2000 hours in this test, which is equivalent to 18 to 20 years of automobile life. The manufacturer states that the minimum bend radius of the cable without cracking the coating is 6 in. (152 mm). As long as the cable is operating within this limit, the stress level for the coating does not exceed its fracture point.

The adaptation of ceramic coatings to bridge stays is being investigated. Bridge stays are similar to brake cables in that the same environmental exposure to chloride ions and other chemical attack is present. The current designs, validated by years of service and millions of feet of production, appear to be readily adaptable to the bridge stay environment.

The prestressed concrete environment presents a new challenge. Some of the proprietary ceramic coatings will react with the alkalies in the concrete or grout. New formulations have been developed to provide similar corrosion protection while reducing the reactivity to the alkaline substrate. The coatings for the prestressed marketplace will feature the ceramic coating encapsulating each wire, with an additional polymeric jacket to protect the ceramic during handling and installation. The polymeric coating is designed to dissolve in the uncured concrete and provide intimate contact between the cured concrete and the ceramic coating.

NON-METALLIC TENDONS

During the last decade, an intensive research effort has been undertaken in Germany and Japan on the feasibility of using fiber reinforced plastic (FRP) tendons in prestressed concrete structures. The emphasis in Europe has been to use glass fiber products whereas in Japan considerable work has been done on carbon based materials. Several prototype prestressed concrete bridges have already been built using FRP tendons in Europe and Japan, and their structural behavior and durability are currently being closely monitored. One major advantage of FRP materials is that they possess excellent corrosion resistance characteristics. However, before these materials can be used in large scale applications, much more research needs to be conducted. Also, the relatively high cost of using FRP tendons needs to be justified.

A detailed discussion of FRP materials is beyond the scope of this paper. Nevertheless, for more information on this new emerging technology, readers should consult Refs. 50 to 52.

CONCLUDING REMARKS

As a result of technological advancements and economic advantages, prestressed concrete construction has been increasingly utilized for large, major structures in recent years. At the same time, there has been an increased awareness and concern among engineers with regard to the potential for corrosion of prestressing steel subjected to harsh environments.

The consequences of corrosion of prestressing steel in structures under moderate to severe exposure conditions, in terms of structural failure, safety and economic impact, are so potentially severe that prevention measures beyond current common practice are being sought and considered. New and improved corrosion protection systems have evolved in recent years as a result of research and innovation and will continue to do so. Only time will determine which systems will withstand the comparative tests of effectiveness, implementability and economics.

The cost of providing an additional measure of corrosion protection is usually about 1 to 2 percent of the total structure cost. Because of the size and economic investment in these structures, it is no longer a question of whether we can afford to provide increased corrosion protection, but whether we can afford to not protect this investment.

To achieve prestressed concrete structures with an improved resistance to corrosion, the following determinations and decisions need to be made during design:

1. Determination of the severity of the environment. Is the structure located in a saltwater coastal environment? Will it be exposed to deicing chemicals? Will it be exposed to industrial pollution and, if so, what kind and to what degree?

2. Based upon the environmental considerations, determine a corrosion protection strategy (preferably, in the case of an extreme environment, in consultation with a corrosion engineer).

3. In choosing a corrosion protection system, the following should be considered:

- Cost-benefit ratio.
- A redundant system, such that the failure of one component does not result in the loss of the total system.

4. The vulnerability of the chosen system to construction operations should be understood, such that appropriate repair methods can be implemented in the field.

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