

ACI 222.2R-14

Report on Corrosion of Prestressing Steels

Reported by ACI Committee 222



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Report on Corrosion of Prestressing Steels

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

Report on Corrosion of Prestressing Steels

Reported by ACI Committee 222

Mohammad S. Khan, Chair

Antonio J. Aldykiewicz Jr.
 Michael C. Brown
 David Darwin
 Marwan A. Daye
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 Hamid Farzam
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 David Trejo

Yash Paul Virmani
 Jeffrey S. West*
 Richard E. Weyers
 David W. Whitmore
 Consulting Member
 Richard O. Lewis

*Subcommittee member

This report covers various types of prestressing steel, including some discussion on metallurgical differences, and supplements information presented in ACI 222R to include topics specifically related to prestressing steels. Deterioration mechanisms are discussed, including hydrogen embrittlement and stress-corrosion cracking. Methods to protect prestressing steel against corrosion in new construction are presented, along with a discussion of field performance of prestressed concrete structures. Finally, field evaluation and remediation techniques are presented. Appendixes present detailed information on stress-corrosion cracking and hydrogen embrittlement issues in prestressed concrete and mitigation techniques.

Keywords: anchorage; bonded; corrosion; duct; durability; grout; hydrogen embrittlement; post-tensioned; prestressed; tendon; strand; stress-corrosion cracking; unbonded.

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CHAPTER 1—INTRODUCTION

1.1—Background

Several attempts were made to prestress concrete in the 1800s, but modern development of prestressed concrete began in 1928 and is credited to E. Freyssinet of France (Lin and Burns 1981). Freyssinet understood the importance of prestressing using high-strength steel to avoid prestressing losses that significantly reduce the applied prestressing force. Use of prestressed concrete began in the United States with circular-wrapped prestressed tanks in 1941 (Schupack 1964). The first prestressed segmental concrete bridge in the United States was constructed in Madison County, TN, and opened to the public on October 28, 1950 (Bennett et al. 2002). The Walnut Lane Memorial Bridge, located in Pennsylvania, was completed in the fall of 1950 (Manning 1988). Applications of prestressing in bridge and building construction then spread rapidly and have proven to be a successful construction method. Prestressed concrete construction enhances structural efficiency, improves control of flexural cracking, and allows for structural members with reduced dimensions.

Although corrosion is not as well documented in prestressed concrete structures as in nonprestressed concrete structures, prestressed concrete members have a number of advantages regarding corrosion performance over conventional nonprestressed concrete elements. In general, prestressed concrete construction follows higher-quality control prac-

tices and material standards than conventional nonprestressed construction. These practices result in improved concrete properties that limit diffusion of chloride, which is further reduced in prestressed concrete members due to absence or reduced-level cracking. Corrosion of prestressed concrete structures appears to be restricted to specific circumstances, including improper design, construction details, and construction practices. The potential for accelerated corrosion still exists in environments contaminated with chloride ions and hydrogen sulfide and it is imperative to protect prestressing steel. Corrosion of prestressing steel in bridges and buildings may not display outward signs of corrosion. Because failure of prestressing tendons could compromise the integrity of the structure, structures subjected to corrosive conditions should be periodically inspected with specific attention focused on the condition of the prestressing system.

A number of surveys provide information concerning the potential for corrosion of prestressed structures. Burdekin and Rothwell (1981) summarized practice, specifications, and corrosion mechanisms (1981) and reported that failure to provide adequate structural details and follow proper construction practices, as well as use of low-quality materials, account for the vast majority of poor performance. Schupack reached similar conclusions in additional surveys (Schupack 1978a, 1994; Schupack and Suarez 1982). More recently, corrosion problems were discovered in grouted post-tensioned bridges (Poston et al. 2003; Hartt and Venugopalan 2002; Muszynski 2003). The problems were largely attributed to inadequate post-tensioning details and grouting practices and deficient grout materials that led to accumulation of bleedwater voids.

Because corrosion in prestressed concrete members can potentially result in fracture-critical modes of failure, more information needs to be developed, disseminated, and used. The magnitude of the corrosion problem, its projected extent, and measures that can resolve it are of vital concern to designers, contractors, and owners, and form the basis of this report.

Prestressed concrete is used in several types of construction and is described as either pretensioned or post-tensioned, depending on whether the tendons are stressed before (pre) or after (post) the concrete is placed. Pretensioned concrete refers to systems in which high-strength wires or strands are stressed in forms between bulkheads before placement of the concrete. Concrete is cast and allowed to cure to a specified strength. Because the prestressing steel is bonded with the concrete, when the steel is released from the bulkheads, the concrete is placed in compression to equilibrate the tensile forces present in the steel. Pretensioning is common practice for both standardized precast bridge girders and in precast structural building members, such as solid joists, solid and hollow-core planks, and single- and double-tee joists.

Post-tensioned concrete refers to systems in which the concrete is placed and allowed to cure to a specified strength before prestressing. Post-tensioning is applied using either bonded or unbonded tendons. Bonded post-tensioning requires that tubes or ducts with deformations be placed in

the forms before concrete placement. After the concrete is placed and cured to a specified strength, bundles of strands, wires, or bars in the ducts are stressed against and anchored to the concrete. These bundles are called tendons.

In the case of bonded tendon, after tendons have been installed and stressed and concrete has been placed and reached a strength such that tendon stressing can be performed, a grout that is a mixture of portland cement, water, and admixtures is pumped into the ducts. Ducts can be metallic or nonmetallic and include uncoated or coated steel, high-density polyethylene (HDPE), and polypropylene. The grout fills spaces among the individual tendon strands, wires, or bars and between the tendon and duct. The grout provides two benefits: corrosion protection for the tendon with the highly alkaline environment provided by the grout, and bond between the concrete and the tendon. Bonded prestressing is popular in bridges, buildings, dams, tanks, and tie-backs, and may be used with both precast and cast-in-place concrete construction.

Unbonded post-tensioning commonly uses single-strand tendons. Each strand is surrounded by an individual sheath and the annular space is filled with a post-tensioning coating (grease or wax) that inhibits corrosion and reduces friction between prestressing steel and sheathing. The tendon is installed in the formwork before placement of concrete. The sheath provides a barrier between the coated strand and the concrete, and allows the strand to be stressed after concrete placement. Usually, anchorages are cast into the concrete along with the tendon. Unbonded multistrand tendons have been used extensively in nuclear pressure vessels. Multiple wires or strands are placed in a cast-in-place duct that is usually filled with heated, corrosion-inhibiting, wax-like hydrophobic grease.

Prestressing bars are widely used in bonded post-tensioning of liquid-containing tanks, in geotechnical applications such as foundation tie-downs and foundation wall tie-backs, and in segmental bridge construction.

Prestressing wire is used in the construction of prestressed concrete tanks and the manufacture of concrete pipe. In tank construction, the wire under tension is wrapped around the tank circumference. This provides a circumferential compressive prestressing force that resists the radial tensile stresses developed by filling the tank. Prestressed concrete pipe is manufactured in a similar manner where the pipe is wound with high-strength prestressing wire.

1.2—Scope

This report covers practices and research relating to corrosion in prestressed concrete systems, including prestressing tendons and other hardware associated with prestressing such as anchorages and ducts that also affect corrosion resistance. In general, **ACI 222R** covers mechanisms of corrosion of nonprestressed steel in concrete, measures for protecting embedded metal in concrete, techniques for detecting corrosion in structures, and remedial procedures. Many of the mechanisms reported in ACI 222R are valid for and apply to prestressing steels in concrete, and this report

supplements ACI 222R. The metallurgy of various common prestressing steels is presented to provide necessary information to understand the mechanisms of deterioration of prestressing steels. Current and proposed techniques for evaluation of prestressed concrete structures with respect to corrosion of strands and tendons are also reviewed. A history of field performance, covering documented cases of corrosion-induced failures in prestressed concrete members, is included in this report. Finally, this document describes methods of protection and remedial techniques applicable to existing structures that exhibit corrosion. Information within this report is applicable to most forms of prestressed concrete construction, including buildings, bridges and parking structures. Prestressed tanks, pipes, and ground anchors are not specifically addressed.

CHAPTER 2—DEFINITIONS

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <http://www.concrete.org/Tools/ConcreteTerminology.aspx>.

CHAPTER 3—PRESTRESSING STEELS

3.1—Wire

Prestressing wire contains high carbon and manganese contents and relatively small amounts of alloying elements, such as chromium, vanadium, or both, to achieve the minimum required mechanical properties in hot-rolled rod. The hot-rolled rod is rapidly cooled to impart the microstructure and mechanical properties required for drawing into high-tensile-strength wire. Cold-working results in a 60 to 85 percent reduction in cross-sectional area and is carried out by drawing the wire through a number of consecutive wire-drawing dies of decreasing diameter in a continuous operation. The final step is stress-relieving that increases wire ductility without sacrificing the increased yield strength achieved through cold-working. Details of the chemical compositions and manufacturing techniques for wire production are described in **Appendix A**.

3.2—Strand

Strand is produced from cold-drawn, high-strength wire. Before stress-relieving, the finished wire is wound into a seven-wire bundle in which six wires are helically wrapped around a single straight king wire. The strand may then be stress-relieved or, more commonly, stabilized and stress-relieved. Stabilization reduces relaxation characteristics of the strand by thermal-mechanical treatment—simultaneously stretching and heating the strand. The mechanical action of stretching compacts the individual wires in the strand, which reduces relaxation characteristics to below the specified level. For example, low-relaxation strand produced in accordance with **ASTM A416/A416M** limits relaxation loss to 3.5 percent in 1000 hours when loaded to 80 percent of its specified minimum ultimate tensile strength. Thermal treatment stress relieves the strand.

3.3—Bar

As with prestressing wire, high-strength bar is manufactured with controlled additions of carbon and manganese to iron. Threaded prestressing bars are manufactured from billet steel produced in an electric furnace in which the steel is melted, alloyed, and cast into billets for use in the bar hot-rolling process. The billets are reheated and hot-rolled into the bar configuration. The rolling process involves continuously feeding a bar through several stands that successively reduce bar diameter to the desired size. The last rolling places thread impressions into the bar. Unlike the strand-drawing operation, the bar is rolled under tension-free conditions so the threads on the bar are not distorted. Following the rolling operation, bars are cut to length and cooled. After cooling, the yield point of the bars is raised by cold stretching. Residual stresses from cooling and stretching are then removed with thermal stress relieving by heating to 700°F (370°C) in a furnace or with electrical induction heating.

CHAPTER 4—DETERIORATION OF PRESTRESSING STEEL

As noted in [Chapter 1](#), prestressing steel is used in both pretensioned and post-tensioned applications. Pretensioned applications involve direct contact between concrete and prestressing steel. The alkaline environment provided by chloride-free concrete protects prestressing steel from corrosion just as for reinforcing bars. The same is true of post-tensioned concrete structures with grouted tendons. Satisfactory protection depends on the concrete or grout quality, cover depth, and the degree to which good practices are followed throughout the design and construction operation.

Unbonded tendons are generally protected by a plastic sheath and anticorrosive grease filling the annular space around the strand. Tendon technology and field experience with unbonded tendons has improved over the past 15 years. [ACI 423.4R](#) covers the history of unbonded tendons, including field problems, and provides guidance on evaluating corrosion damage and repair methods. [ACI 423.4R](#) does not cover the metallurgy and deterioration mechanisms in as much detail as this report.

Pretensioned and post-tensioned systems that are properly detailed and constructed are adequately protected for the life of the structure. Prestressing corrosion occurs in poorly detailed or constructed systems, when inadequate materials are used, or in systems subjected to environments more severe than expected. Experience shows that a reduction in the cross-sectional area in nonprestressed steel reinforcement due to corrosion is generally not a primary concern. Corrosion of nonprestressed steel causes problems such as unsightly staining, spalling, and other serviceability-related issues, long before the loss of the steel cross section becomes an issue. On the contrary, loss of cross-sectional area of prestressing steel due to general or pitting corrosion is a major problem for two reasons.

1. Prestressing steel experiences a continuous applied stress level of 55 to 65 percent of its ultimate tensile strength throughout its life. This value can be temporarily higher

during stressing. Loss of cross section increases net tension stress and can lead to local yielding and fracture.

2. Prestressing steel strength is normally four to five times higher than that of nonprestressed reinforcing steel and, as a result, is typically used in the form of smaller diameter wires than typical for nonprestressed reinforcement. The smaller-diameter prestressing steel wires will lose relative cross-sectional area faster than larger nonprestressed reinforcing bars undergoing the same corrosion rate. Remedial efforts for corrosion-damaged, prestressed concrete structures should consider this difference.

ACI defines corrosion as destruction of metal by chemical, electrochemical, or electrolytic reaction within its environment. The fundamental mechanisms for corrosion of prestressing steel in concrete are essentially the same as those for lower-grade reinforcing bars ([Manning 1988](#); [Perenchio et al. 1989](#); [Whiting et al. 1993](#)). [ACI 222R](#) provides complete details of the fundamental mechanisms of general and pitting corrosion of metals in contact with concrete.

Bonded, post-tensioned tendons are in contact with a portland cement grout. This grout is pumped into a polyethylene or galvanized steel duct embedded in the concrete. This system should give superior corrosion protection over pretensioned construction because of the additional barriers ([Whiting et al. 1993](#)). This can be true when the duct is properly and solidly filled with grout. A number of problems have been attributed to the lack of grout or improper pumping techniques ([Novokshchenov 1989a, 1991](#); [Ohta et al. 1992](#); [The Concrete Society 2002](#); [Woolley and Clark 1993](#)). In addition, the performance of prestressing steel embedded in concrete may not necessarily be indicative of the behavior of bonded post-tensioned systems where ducts, grouts, and anchorage hardware can also have an impact on corrosion behavior ([Perenchio et al. 1989](#)). Most problems associated with bonded post-tensioned construction occur as a result of a grout deficiency. Further discussion of this issue is presented in [Chapter 8](#).

In addition to general or pitting corrosion damage of reinforcing bars, prestressing strand and wire have increased susceptibility to other types of damage that are not usually of concern for lower-grade steel. Damage from environmentally assisted cracking mechanisms (that is, hydrogen embrittlement [HE] and stress-corrosion cracking [SCC]), fretting fatigue, and corrosion fatigue all can significantly affect the performance of the prestressing steel. HE is caused by the diffusion of atomic hydrogen into the metal lattice, limiting the ability for plastic deformation to occur and thus embrittling the steel. SCC can occur when local or general corrosion occurs in the presence of high tensile stresses, leading to the formation of transverse intergranular or transgranular cracking in the steel. In both cases, reduction in tensile strength and ductility can occur. Immediately before failure, there can be relatively little visible warning of these mechanisms, such as corrosion product. In addition, failures are usually brittle, with little elongation before fracture. Although relatively few failures have been attributed to one or more of these mechanisms, designers need to be

aware of the potential problems and the environments that may cause them. The mechanisms and manifestations of these phenomena are discussed in detail in Appendix B.

CHAPTER 5—PROTECTION AGAINST CORROSION IN NEW CONSTRUCTION

5.1—Introduction and history

Corrosion-protection measures for prestressed concrete structures are essentially the same as for structures with nonprestressed reinforcement. For unbonded tendons, however, additional measures are required because protection depends more on the sheath and the protective coating. Much of the information provided in [ACI 222R](#) is applicable to prestressed concrete structures and is referenced herein to avoid duplication. This chapter addresses issues unique to corrosion protection of new prestressed concrete structures. Those unfamiliar with corrosion of metals in concrete are referred to [ACI 222R](#).

Corrosion of prestressed and nonprestressed reinforcement is complex and influenced by many factors. The best corrosion protection provides several measures to guard against different influences and against breakdowns or limitations in any one protective measure. This is often referred to as providing multilevel protection. Corrosion-protection measures in prestressed concrete structures should be considered at all stages of design. Corrosion protection for prestressed concrete falls into three categories:

1. Measures that maximize the protection provided by concrete
2. Measures that prevent chlorides from entering the concrete
3. Measures that directly prevent corrosion of the prestressing system

The first two categories are the same as those for nonprestressed concrete structures with the exception that prestressed reduces cracking and its associated reductions in durability by accelerated ingress of chlorides, carbonation, or both. The third category focuses on hardware unique to prestressing systems (for example, ducts and anchorages) that must also be protected from corrosion.

For prestressing elements encased in concrete, concrete quality is the single most important factor in ensuring structural longevity, affecting all aspects of durability, including corrosion of reinforcement. The effectiveness of concrete as corrosion protection for prestressing steel depends on two equally important factors: concrete material properties, and design and construction practices. Refer to [ACI 222R](#), [ACI 201.2R](#), and [Perenchio et al. 1989](#) for more information on the effect of concrete quality on corrosion protection. These sources address requirements for material properties, design, and construction. [ACI 301](#) and [ACI 318](#) provide additional guidance in the form of standard specifications or codes. The second category of corrosion-protection measures involves techniques for preventing chlorides from entering the concrete. These include waterproof membranes, overlays, and polymer impregnation. Refer to [ACI 222R](#) for more information on this subject. The final category of corrosion protection measures involves aspects unique to prestressed

concrete and is the focus of this chapter. Items considered include selection of prestressing tendon materials, protection systems for pretensioned and post-tensioned concrete, and cathodic protection.

Historically, post-tensioned systems have performed well due to their multi-layer protection measures. In 1999, corrosion problems were detected in externally grouted tendons in several Florida Department of Transportation bridges ([Corven Engineering 2001](#)). No structural failures occurred, but grout voids and strand corrosion were found, and a completely failed tendon was also found. Other states with segmental bridges investigated for problems in external tendons. Although voids were found, a void did not necessarily indicate an area of corroded tendon. Improper grouting, both in the grouting material and in construction practice, was the most common reason for these voids. In 2000, the Post-Tensioning Institute (PTI) published a comprehensive grouting specification ([PTI 2000](#)), and later the [American Segmental Bridge Institute \(2014\)](#) produced a grouting certification program. The third category focuses on hardware unique to prestressing systems (for example, ducts and anchorages) that must also be protected from corrosion. These measures are aimed at assuring proper practices for grouting material selection and construction practices. Improved grouts, including prepackaged grouts, are now commonly used and are therefore included in this report.

Unbonded single-strand (also known as monostrand) tendons have improved considerably in the area of corrosion protection. Early tendons consisted of a grease coating and paper wrap. They often exhibited defects in the quality and coverage of the grease and improperly protected the anchorage areas. PTI (2000) addresses these issues and further guidance is provided in [ACI 423.7](#). Recent improvements in corrosion-resistant post-tensioned coating, sheathing, and anchorage protection are incorporated into this report.

5.2—Prestressing tendon materials selection

Selecting material for prestressing tendons is dictated by both structural and durability requirements. This chapter describes choices for prestressing tendon materials when corrosion is a concern.

Materials and manufacturing processes for prestressing steels used in North America are governed by standard specifications and building code requirements, such as [ACI 301](#) and [ACI 318](#). In some countries, quenched and tempered steels are used for prestressing. Using these methods, without special alloying and manufacturing processes, can leave the steel more susceptible to SCC than cold-drawn prestressing steels ([ACI 423.3R](#); [Schupack 1976](#)). The material requirements of [ACI 301](#) and [ACI 318](#) preclude the use of quenched and tempered steel for prestressing; therefore, only cold-drawn prestressing wire or hot-rolled bar are used in North America.

Metallic and nonmetallic coatings have been investigated as protection methods for mild steel reinforcement ([ACI 222R](#); [McDonald et al. 1993](#); [Natarajan et al. 2005](#)).

The two most common coatings are epoxy coating and zinc galvanizing. Good results have been obtained in laboratory testing of stainless steel-clad bars, copper-clad bars, and zinc alloy-clad bars (McDonald et al. 1996). Some coatings have been considered for prestressing steels (Moore et al. 1970; Perenchio et al. 1989). Prestressing steel coatings should have certain important properties that often preclude the use of some coatings normally applied to nonprestressed reinforcement (Moore et al. 1970). The coating should not have an adverse effect on steel strength or ductility. It should have sufficient flexibility and ductility to withstand stranding during manufacture and elongation during stressing without cracking or peeling. Coatings should not have a detrimental effect on bond between the steel and concrete and should be able to withstand handling, placement, anchoring, and stressing without damage. Finally, the improved corrosion protection provided by the coating should not be at a prohibitive price. Only epoxy coatings and zinc galvanizing have been successfully applied to prestressing steels. Each is discussed in this chapter.

Ongoing development of advanced composite materials or fiber-reinforced polymers has produced an additional choice in the selection of prestressing tendons. These materials are not susceptible to electrochemical forms of corrosion, but long-term durability information is still limited.

5.2.1 Epoxy coatings for prestressing steel—Epoxy is a widely used organic coating for corrosion protection that can isolate the steel from oxygen, moisture, and aggressive chemicals. Epoxy-coated, seven-wire prestressing strand and threaded prestressing bars are available in the United States and require specific considerations in design and construction.

5.2.1.1 Epoxy-coated strand—Epoxy-coated strand is available in two configurations: coated and coated-and-filled (Fig. 5.2.1.1). In the coated configuration, a thick epoxy coating is provided around the exterior circumference of the seven-wire strand. In the coated and filled configuration, spaces between individual wires are filled with epoxy, preventing migration of moisture and chlorides along strand interstices. Both configurations are available either with a smooth surface or with grit particles embedded on the surface to improve bond-transfer characteristics. Smooth surface epoxy-coated strand is used in applications where bond is not critical, such as unbonded systems, external post-tensioning systems, and stay cables. When used in unbonded systems, such strand should be encased in a duct because smooth epoxy coating is not equivalent to sheathing used in single-strand post-tensioning systems. Epoxy-coated strand with a grit-impregnated coating is intended for use in bonded systems and in pretensioned applications.

Epoxy-coated strand is manufactured to meet the requirements of ASTM A882/A882M and ASTM A416/A416M. Physical properties of epoxy coating used for prestressing strand are significantly different from those used for nonprestressed reinforcement. The epoxy coating developed for prestressing strand is tough and ductile, with good bond to the steel to withstand the elongation during stressing.

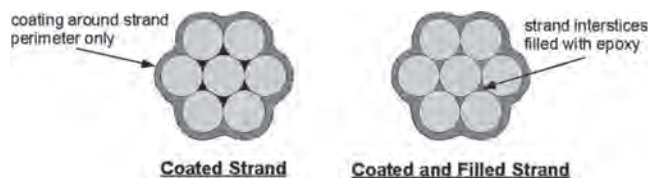


Fig. 5.2.1.1—Epoxy-coated strand types.

The coating is durable and abrasion-resistant to minimize damage during handling, placement, and stressing. The finished coating thickness for the strand is usually 0.03 in. (0.76 mm) (Moore 1994), but can range from 0.025 to 0.045 in. (0.63 to 1.14 mm), according to ASTM A882/A882M. This is thicker than the coating thickness for nonprestressed reinforcement (0.007 to 0.012 in. [0.18 to 0.30 mm]) (ASTM A775/A775M).

Thermo-setting, fusion-bonded epoxy coating is applied in a continuous process to the bare strand (Moore 1994). The manufacturing process starts with a strand that meets ASTM A416/A416M. The strand is mechanically cleaned and preheated to 572°F (300°C) before application of the coating. The strand is then run continuously through a fluidized bed of electrostatically charged epoxy particles. As the electrically grounded strand passes through the bed, charged particles are attracted to the strand surface. To manufacture the coated and filled strand, the outer six wires are separated from the center king wire just before entering the fluidized bed. When wires are restranded with the epoxy still in a plastic state, the interstitial space between the wires is completely filled with epoxy.

The increased coating thickness along with flow filling of the interstitial space between the wires has been found to provide improved corrosion protection and resistance to the formation of coating defects when compared with epoxy-coated nonprestressed reinforcement. Improved construction quality typically present in prestressed concrete also lowers susceptibility to the formation of coating defects during handling and construction.

Using epoxy-coated strand in post-tensioning applications and stay cables requires special wedges that bite through the epoxy coating and into the underlying strand. These wedges are larger than standard wedges and require compatible anchor heads. Concerns have been raised because the protective barrier of the epoxy is broken at a critical location by the wedges. Experimental work has confirmed the occurrence of corrosion at locations where the wedge teeth were embedded in the steel (Hamilton 1995). Corrosion also occurred under the epoxy coating between the marks created by the wedge teeth. The significance of corrosion at the wedge locations varies. In bonded post-tensioned construction, corrosion at the wedges should not significantly affect structure integrity when the tendon is properly grouted and the anchorage protected, particularly when coated and filled strands are used. In unbonded tendons or stay cables, however, corrosion at the wedges could lead to tendon or cable failure. In these situations, additional protection should be provided at wedge locations (Hamilton 1995).

Details of installation and stressing procedures are provided by PCI (*PCI Ad Hoc Committee on Epoxy-Coated Strand 1993*) in a report on the use of epoxy-coated strand. Strand tails should be painted with the manufacturer recommended epoxy patch material.

5.2.1.2 Epoxy-coated prestressing bars—High-strength threaded bars commonly used for post-tensioning may be specified with epoxy coating. Epoxy-coated threaded bars are coated according to *ASTM A775/A775M*, the same standard used for epoxy coating mild steel reinforcement. Anchorage hardware, including bearing plates, nuts, and couplers, is also epoxy-coated. Nuts and couplers are proportioned to allow free movement over threads without damaging the epoxy coating.

The fusion-bonded, epoxy-coating process is similar to that for prestressing strand. Bars are first cleaned and preheated, and then epoxy powder is applied electrostatically. The required final thickness of the epoxy coating ranges from 0.007 to 0.012 in. (0.18 to 0.30 mm) (*ASTM A775/A775M*).

Epoxy-coated prestressing bars face issues in quality control similar to those with epoxy-coated mild steel reinforcement. The effectiveness of the corrosion protection provided by the epoxy coating depends on the quality of the coating and the amount of damage to the coating. Transportation and handling are common sources of coating damage. Padded bundling bands, closely spaced supports, and nonmetallic slings are required to prevent damage during transportation. Care should also be taken to minimize coating damage during placement and stressing of bars. Damaged coating can be repaired on-site using a two-part liquid epoxy, but it is more desirable to adopt practices that prevent damage to the coating.

5.2.2 Galvanized prestressing steel—Zinc galvanizing is an effective metallic coating for corrosion protection. Zinc provides protection by corroding sacrificially to the steel when exposed to a corrosive environment. Zinc is anodic to steel in the electromotive force series and corrodes sacrificially to steel when electrical contact between them and a conductive electrolyte is present. Sacrificial protection is advantageous because it theoretically does not have to completely cover the part. Damaged coating areas may not be visible after placing and stressing. Localized nicks and abrasions in the zinc are not likely to reduce the galvanic protection of the underlying steel.

Zinc is widely used to protect exposed steel from atmospheric corrosion. The corrosion resistance of zinc-coated nonprestressed reinforcement in concrete varies. Galvanizing increases time-to-cracking (that is, the time at which expansive corrosion products have generated tensile stresses exceeding the tensile cracking strength of the concrete) in some cases but reduces time-to-cracking in others (*ACI 222R*). There are additional concerns related to the influence of the coating itself on the long-term mechanical properties of the reinforcement when using zinc-coated steel, especially high-strength steel, when in contact with cement paste. In the highly alkaline environment of concrete or cement grout, the corrosion rate of zinc can be very high.

Zinc corrosion produces hydrogen gas and raises concerns of hydrogen embrittlement (HE) of the high-strength steel; however, research cited in *Chapter 4* indicates that HE, due to the hydrogen gas, is unlikely.

5.2.2.1 Galvanized prestressing strand—The use of galvanized prestressing strand is not common in North America and is prohibited by the Federal Highway Administration (FHWA) for use in bridges. The use of galvanizing in prestressing applications and stay cables, however, is popular in Europe and Japan (*fib 2012*).

The galvanizing process affects the mechanical properties of the strand. Galvanizing cold-drawn wire for prestressing strand may reduce tensile strength of the wire and degrade relaxation properties. Ultimate elongation of the wire may increase, and the elastic modulus of the seven-wire strand normally decreases. Questions have also been raised about the effects of zinc galvanizing on the bond of prestressing strand (*Moore et al. 1970*).

Galvanized seven-wire strand for prestressing applications is commercially available in sizes from 3/8 to 0.6 in. (9.5 to 15.2 mm) diameter and in standard grades. The strand is stress-relieved (normal relaxation) and conforms to all requirements of *ASTM A416/A416M* except that the wires are galvanized. During production, the wires are zinc-coated individually and then stranded. Minimum weight of zinc coating for the strand ranges from 0.90 to 1.0 oz/ft² (275 to 305 g/m²). Before galvanizing, the single wires need to meet the requirements of Grade 270 strand (*ASTM A416/A416M*) when fabricated to the corresponding finished strand size.

5.2.2.2 Galvanized prestressing bars—Threaded galvanized prestressing bars are commercially available in standard sizes and strengths.

Although prestressing bars are not cold-drawn like prestressing wire or strand, zinc galvanizing still raises concerns for HE. A specification has been developed for galvanizing prestressing bars to minimize the effects of galvanizing on the potential for HE and on mechanical properties (*Dywidag 2009a*). The highest potential for damage due to HE occurs during acid pickling of the bars performed to clean all mill scale off of the bars before hot-dip galvanizing. Acid pickling of the bars should be carefully controlled in terms of pickling time and acid temperature, and hydrogen inhibitors should be used in the acid bath. The bars should be galvanized immediately after pickling (*Dywidag 2009a*, *ASTM A123/A123M*). The maximum permissible weight of zinc coating is 0.82 oz/ft² (250 g/m²) (*Dywidag 2009a*). Measures for maintaining threadability of the bars after coating should also be considered (*ASTM A123/A123M*).

Zinc galvanizing may lower the yield strength of the bar by 5 percent and may alter the stress-strain relationship; ultimate strength and ductility, however, are not adversely affected by the galvanizing process (*Dywidag 2009a*).

5.2.3 Metallic clad prestressing materials—Metallic clad products such as stainless-clad and copper-clad bars or strand are under development at this time. Stainless-clad mild reinforcement has been introduced in the United States.

but stainless-clad prestressed reinforcement remains in the research phase.

5.3—Corrosion protection for prestressing systems

5.3.1 Pretensioned construction—Basic corrosion protection for pretensioned concrete elements is provided by the quality and thickness of the concrete over the prestressing steel. Because pretensioned concrete is usually fabricated on a repeated basis in a plant, quality control is generally higher than is found in cast-in-place concrete. For increased production, high-strength concrete is generally used to accelerate removal of formwork and transfer of prestressing force to the concrete at early ages. High-strength concrete also typically has reduced chloride permeability and improved durability when compared with normal-strength concrete. Construction in a plant environment provides controlled curing conditions, contributing to lower permeability.

In aggressive environments, corrosion protection is provided by adequate cover of high-quality, low-permeability concrete, corrosion-inhibiting admixtures, or epoxy-coated strands, either single or in combinations. Adequate cover and protection should also be provided for nonprestressed reinforcement in pretensioned elements to ensure that steel corrosion does not lead to cracking and spalling of the concrete and loss of protection for the prestressing tendons.

Trimmed ends of the prestressing strands should be protected with suitable end cover to resist the particular corrosion environment and climatic conditions. Otherwise, moisture and chlorides may reach the strand ends, causing corrosion. In addition, cover may be minimal at the ends of prestressing strands and has a tendency to spall because of poor bond or freezing-and-thawing damage, providing a direct path for moisture and chlorides to reach the strand end.

5.3.2 Unbonded single-strand post-tensioned systems—Unbonded single-strand tendons represent the largest volume of post-tensioning steel used in North America (Schupack 1994c). Single-strand tendons are used primarily in buildings, parking structures, and slabs-on-ground. As described in 1.1, the single-strand system uses a coated and sheathed seven-wire prestressing strand and single-strand anchorages. Details of a typical single-strand system are shown in Fig. 5.3.2a and 5.3.2b. The *Post-Tensioning Manual* (PTI 2006) provides additional information on single-strand systems.

The manufacturing process for single-strand tendons begins with standard seven-wire prestressing strands. First, strands are coated with a post-tensioning (PT) coating (grease or wax that normally contains a corrosion-inhibitor). Then, excess PT coating is removed, and tightly fitting, high-density polyethylene sheathing is extruded over the coated strand. The sheathing protects the strand and acts as a barrier to moisture and chlorides. The PT coating provides lubrication that allows post-tensioning and acts as secondary corrosion protection if moisture and chlorides penetrate the sheathing. The general preference for tightly fitting extruded sheaths was largely in response to corrosion problems with loose push-through sheaths and heat-sealed sheaths

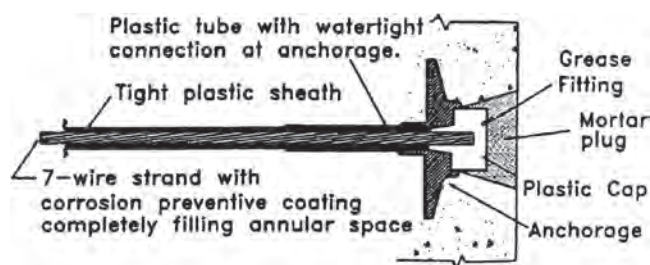


Fig. 5.3.2a—PTI recommended single-strand system details (Schupack 1994c).

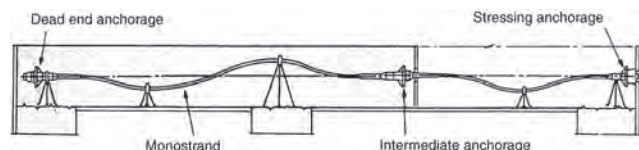


Fig. 5.3.2b—Typical single-strand post-tensioning system components (VSL 2010).

(Schupack 1994c). Tightly fitting sheaths minimize voids in the PT coating and provide less opportunity for moisture movement into and along the length of the single-strand tendon.

PTI (2000, 2012) includes requirements for sheathing materials and corrosion-preventive PT coating. Detailed requirements for single-strand tendons are beyond the scope of this report, but are covered in ACI 423.3R, 423.4R, 423.7, and 301.

The multiple levels of corrosion protection for single-strand tendons are described in the following sections.

5.3.2.1 Corrosion-preventive coating—The PT coating used to coat the strand should be continuous over the entire tendon length and should meet the requirements of PTI (2000) and ACI 423.7. In general, the PT coating contains corrosion-inhibiting admixtures and should not be water soluble, dry out, or become brittle.

5.3.2.2 Tendon sheath—Sheathing should be continuous over the entire tendon length and meet the requirements of PTI (2000) and ACI 423.7. The sheath should be protected from damage during transportation, handling, and construction, and all damage should be repaired before concrete placement. Damage to the sheath during post-tensioning cannot be detected or repaired because the concrete is in place. Common locations of sheath damage during stressing include crimped sheathing caused by tie wire, tendon supports, and mild steel reinforcement. Sharp curvatures in the tendon profile may also cause sheath damage during stressing due to high frictional forces.

5.3.2.3 Transition between sheathing and anchorage—In nonaggressive environments, sheathing is often cut short of the anchorage (Fig. 5.3.2.3). In such cases, the unsheathed portion of the strand is protected by the PT coating and the surrounding concrete.

Since 1985, PTI (2000) has required that sheathing be “connected to all stressing, intermediate, and fixed anchorage in a watertight fashion” in aggressive environments. There are considerable disagreements regarding what constitutes

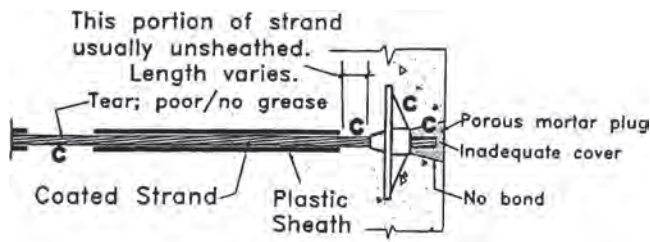


Fig. 5.3.2.3—Inadequate sheathing coverage in single-strand systems (Schupack 1994c).

an aggressive environment, but [ACI 423.3R](#) provides examples for aggressive environments. For the purpose of this document, an aggressive environment can be defined as any external condition that may initiate corrosion of prestressing tendons and their anchorage systems. In a loosely fitted sheath, water can enter through the unsheathed portion of the tendon. The strand should be completely enclosed and sleeves joining the sheath to the anchorage should be filled with PT coating.

5.3.2.4 Anchorage protection—The anchorage and end stub of the strand can provide access for moisture to travel along the strand within the building, so protecting this area is important. Anchorage corrosion may damage the concrete near the anchorage and lead to increased penetration of moisture and chlorides. According to recent recommendations, minimum anchorage protection should consist of a plastic, PT coating-filled cap over the strand stub and a mortar or concrete plug filling the anchorage recess (Fig. 5.3.2a). The mortar or concrete plug should have low permeability and good bond with the surrounding concrete for effective corrosion protection. Effectiveness of the anchorage protection provided by the mortar or concrete plug can be determined using a vacuum tester ([Schupack 1991](#)).

5.3.2.5 Encapsulation and electrical isolation—Encapsulation and electrical isolation of single-strand systems provide additional protection against corrosion. Encapsulation and electrical isolation are sometimes used interchangeably, but encapsulated systems are not necessarily electrically isolated. Normally, encapsulation refers to strand encapsulation only, provided by the sheathing, transition sleeve, and PT coating-filled plastic cap over the strand stub. Although the strand is completely encapsulated, the anchorage may still be exposed. The anchorage is electrically connected to the strand through the wedges, so electric isolation of the strand usually requires coating the anchorage with a nonconductive material, such as plastic (Fig. 5.3.2.5). This approach provides positive corrosion protection for the anchorage and protects the entire system from corrosion induced by stray currents or coupling with uncoated mild steel reinforcement. The electrically isolated single-strand system was first developed in 1980 ([Schupack and Suarez 1980](#)) and in 1982 for multi-tendon systems ([Schupack 1982](#)).

Encapsulated single-strand systems can provide complete encapsulation and electrical isolation, including coating the anchorage with high-density polymers. Other systems provide encapsulation for the strand while the anchorage remains uncoated.

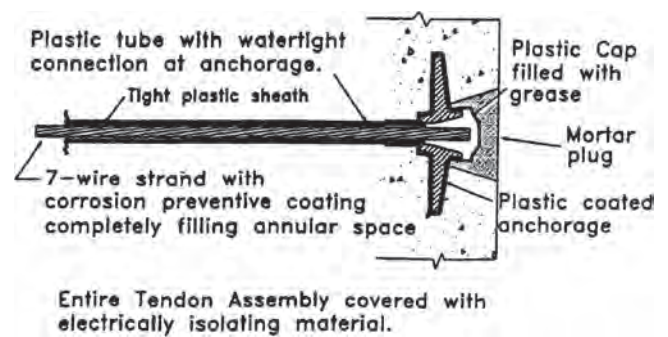


Fig. 5.3.2.5—Fully encapsulated, electrically isolated single-strand system details (Schupack 1994c).

5.3.3 Bonded post-tensioned systems—The most common bonded post-tensioned systems are multiple-strand tendons and bonded prestressing bars. Typical hardware for each is shown in Fig. 5.3.3a and 5.3.3b. Typical components of a multistrand system are shown in Fig. 5.3.3c. For more information on bonded post-tensioning systems, refer to [PTI \(2006\)](#) and manufacturers of post-tensioning hardware.

Corrosion protection specific to bonded post-tensioning includes the surrounding concrete, duct, grout, and anchorage protection. Coatings on prestressing steel provide an additional layer of corrosion protection. Epoxy-coated and galvanized prestressing steels are options in bonded post-tensioned systems. Corrosion protection for bonded systems is described in the following.

5.3.3.1 Ducts for post-tensioning—Ducts have several functions in post-tensioned concrete. They provide a void to allow placement and stressing of tendons after concrete has been cast, they transfer stresses between the grouted tendon and the concrete, and they are a barrier to moisture and chlorides. To be an effective barrier, ducts should be impervious to moisture and corrosion-resistant and, therefore, duct splices and connections to anchorage hardware should be watertight.

5.3.3.1.1 Galvanized steel ducts—Corrugated galvanized steel is the most widely used duct material for internal tendons. Steel duct is sufficiently strong to prevent crushing or other damage during concrete placement and can withstand the frictional forces of post-tensioning. These ducts are spirally wound from a sheet of steel and do not have water-tight seams. While galvanizing provides some corrosion resistance, research studies ([Perenchio et al. 1989](#); [West 1999](#)) and field performance (refer to [Chapter 8](#)) have shown that this protection is limited. Severe corrosion damage, including corrosion through the duct, can occur under exposure to marine environments or deicing salts, particularly with little concrete cover.

Some galvanized steel ducts are manufactured with a longitudinal crimped seam. This seam may not be watertight, allowing moisture ingress even when the duct is undamaged. Observed leakage of grout bleedwater from such ducts through cracks along the tendon profile has confirmed the potential moisture pathway. In addition, the leaky duct seams present problems when vacuum grout bleeding is a repair to fill voids.

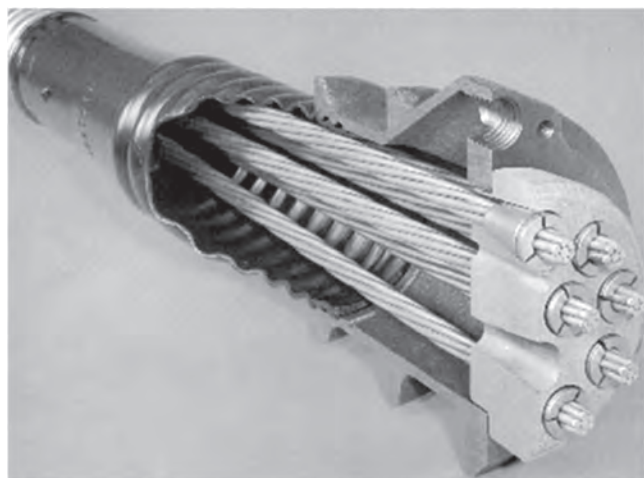


Fig. 5.3.3a—Multistrand tendon anchorage details, cut away view (Dywidag 2007).

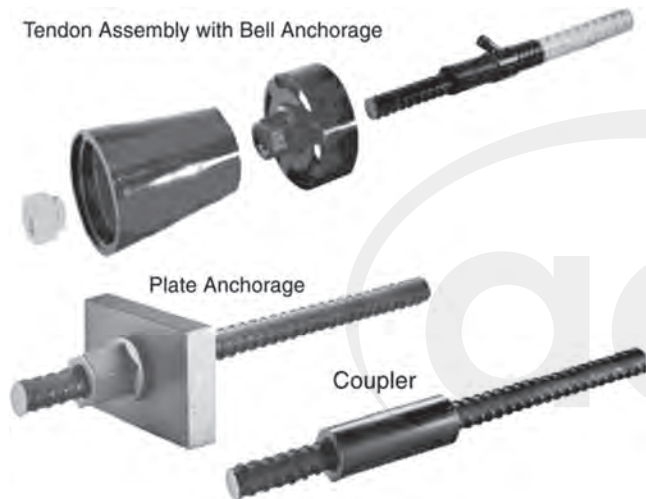


Fig. 5.3.3b—Threadbar post-tensioning system anchorage details (Dywidag 2009b).

Galvanized steel ducts are spliced in many ways. One common practice is to wrap the joint between ducts with duct tape. Sometimes a short length of oversized duct is used to span the joint between duct segments to maintain alignment. Heat-shrink tubing developed for sealing electrical connections has also been used for duct splicing. Laboratory tests found that duct tape splices were not waterproof and heat-shrink tubing "...produced essentially water and chloride-tight joints..." (Perenchio et al. 1989). Long-term performance testing has shown that moisture trapped under the heat-shrink splice can accelerate corrosion of the splice area to almost total duct metal loss under the splice (Salas et al. 2003). This testing showed better performance from standard oversized duct splices than with heat-shrink splices.

Considering the aforementioned limitations, galvanized steel ducts should not be used in situations where exposure to deicing salts or seawater may occur.

5.3.3.1.2 Epoxy-coated duct—Epoxy-coated steel duct eliminates several of the problems associated with galvanized steel duct. The epoxy coating protects the duct from

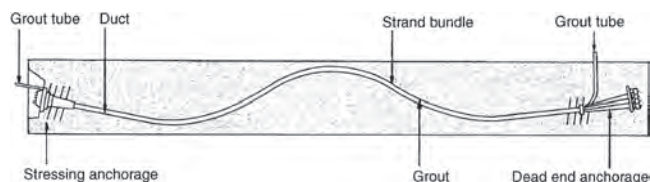


Fig. 5.3.3c—Typical multistrand post-tensioning system components (VSL 2010).

corrosion and seals the longitudinal duct seams. One laboratory study showed excellent performance of epoxy-coated ducts in comparison with galvanized steel ducts (Perenchio et al. 1989). Performance was evaluated in terms of grout chloride levels and extent of duct and strand corrosion damage.

Epoxy-coated ducts, however, are not widely used. As with epoxy-coated reinforcement, quality of the epoxy coating and level of coating damage influences the effectiveness of the coating as corrosion protection. The ability of the epoxy coating to withstand coiling for shipping and the deformations associated with fitting the duct to the desired profile have also been questioned (Perenchio et al. 1989).

5.3.3.1.3 Plastic duct—Plastic ducts can provide the highest level of corrosion protection for post-tensioning tendons because they are noncorroding and impermeable to aggressive agents. Plastic ducts have been developed with sufficient strength, rigidity, abrasion resistance, and bond properties to satisfy structural requirements. Testing has shown lower friction losses (Ganz 1992; Perenchio et al. 1989) and reduced fretting fatigue (Ganz 1992; Wollman et al. 1988) for plastic ducts compared with steel ducts. Commercially available plastic ducts for post-tensioning are normally provided with fitted watertight couplers for duct splices and connection to anchorage hardware.

Corrugated polypropylene ducts for internal post-tensioning are commercially available in flat-duct systems for slabs and in circular-duct multistrand systems for a large range of tendon configurations.

5.3.3.2 Duct continuity in segmental construction—In segmental construction, care must be taken to ensure a tight seal of the duct between segments. Double-faced epoxy coating of match-cast segments has shown to be very effective (West 1999), but still does not provide full protection. Water-tight couplers are now available and can be used as additional layer of protection.

5.3.3.3 Temporary corrosion protection—To minimize the risk of corrosion while the tendons are unprotected, time between stressing and grouting of internal tendons should be as short as possible (refer to 8.5.1). Many specifications limit the time between stressing and grouting. PTI (2000) limits time for grouting between 7 and 40 days, depending on ambient humidity. When these limits are exceeded, temporary corrosion protection is required.

Many temporary protection measures are available. Coating prestressing steel with water-soluble oils or using vapor-phase inhibitors is the most common. Vapor-phase inhibitors may pose health risks and are only effective if the tendon is completely sealed. Other materials, including

sodium silicate and biodegradable soap, normally used as coolant for cutting metal, have also been used. With the exception of the vapor-phase inhibitor, these materials can reduce friction losses during post-tensioning when applied to the strands before stressing (Kittleman et al. 1993). Other options for temporary corrosion protection include sealing the ducts to prevent moisture entry, continuous pumping of dry air through the ducts, and purging with compressed air or dry gas (PTI 2000).

A comprehensive study of materials for temporary corrosion protection and lubrication of post-tensioning tendons found that water-soluble oils could not be completely flushed from the strands (Kittleman et al. 1993). Tendons should not be flushed even when oils are used. Water retained in the duct can have adverse effects on grout bleed resistance. Research shows that water-soluble oils are effective for corrosion protection and retain a significant portion of the bond between the grout and steel (Salcedo et al. 2004). This study found a wide variance in corrosion protection, in some cases accelerated corrosion, and variance in bond pull-out test results from 30 percent bond reduction to nearly complete bond loss. This testing program recommended several oils to be evaluated in large-scale specimens to determine the effect of reduced bond on the overall system.

An effective and proven method for temporary corrosion protection is to keep tendons sealed between stressing and grouting and to grout as quickly as practicable.

5.3.3.4 Cement grout for post-tensioning—Cement grout bonds post-tensioning steel to surrounding concrete and provides corrosion protection for the steel. Cement grout is a barrier to moisture and chloride penetration and produces an alkaline environment for the tendon.

The best grout for post-tensioning combines appropriate fresh grout properties, including bleed resistance, with corrosion protection. The fresh properties of the grout influence how well grout fills the duct. Corrosion protection provided by the grout is rendered ineffective when the duct is only partially or intermittently filled with grout. These situations can lead to severe corrosion (refer to 8.5.2.1). Voids or discontinuities may also permit movement of moisture and chlorides along the tendon length. Important fresh grout properties are listed in the following.

5.3.3.4.1 Fluidity—Fluidity is a measure of how well the grout flows or pumps. Insufficient fluidity leads to difficulties in placement, blockages, and incomplete grouting. Excessive fluidity leads to void formation near crests in draped tendon profiles and to incomplete grouting. Grout fluidity influences the ability of the grout to fill space between strands in a multistrand tendon (Schupack 1974a).

5.3.3.4.2 Bleed resistance—Resistance to bleeding is important for post-tensioning grouts. Unlike concrete where bleedwater can evaporate, bleedwater in grouted ducts tends to migrate to high points in the duct, forming bleed lenses and voids. Eventually, the bleedwater is reabsorbed into the grout, leaving a void. Bleed lenses and voids are a problem in ducts with significant elevation changes.

5.3.3.4.3 Volume change—Reduction in volume or shrinkage in the plastic state leads to voids and should be

minimized. In some cases, it may be desirable for plastic grout to be slightly expansive to offset shrinkage.

5.3.3.4.4 Setting time—Rapid-setting grouts have insufficient fluidity that hinders placement and leads to incomplete grouting.

Fresh grout properties are determined by water-cement ratio (w/c), chemical and mineral admixtures, and cement type. Without using admixtures, fluidity is primarily a function of w/c . In most cases, it is desirable to lower the water content to lower permeability and reduce bleedwater. In this situation, using a high-range water-reducing admixture (HRWRA) can increase fluidity. Replacing some cement with fly ash increases fluidity for the same water-cementitious material ratio (w/cm). Adding silica fume or using it as a partial cement replacement tends to decrease fluidity due to its small particle size. Silica fume may also agglomerate in grouts, causing reduced corrosion protection (Pacheco 2003). Reducing the w/c and using fly ash or silica fume can reduce bleeding. Where the tendon profile has large elevation variations and bleed water accumulation can be severe, antibleed admixtures can be used. Antibleed admixtures, called thixotropic admixtures, give the grout gel-like properties that minimize bleeding while permitting the grout to become fluid when agitated by mixing or pumping. Chemical admixtures can provide expansive properties, but are not effective for filling bleed-induced voids. Corrosion protection provided by crack-free grout is primarily related to its permeability. Low permeability slows the ingress of moisture and chlorides. Grout permeability, like concrete, can be lowered by reducing the w/c and using supplementary cementitious materials, such as fly ash and silica fume. Reduced w/c may require the use of an HRWRA to provide sufficient fluidity. Corrosion-inhibiting admixtures have not performed well in grouts (West et al. 1999; Pacheco 2003).

Selecting suitable grout proportions and admixtures requires careful consideration of fresh grout properties and corrosion protection. Several researchers have studied this topic (Hamilton 1995; Schokker et al. 1997; Schupack 1974a; Thompson et al. 1992; Ghorbanpoor and Madathapalli 1993). Information on mixture proportioning and guide specifications for grouts for post-tensioning are provided by PTI (2012) and by The Concrete Society (2002).

Corrosion protection provided by grout depends heavily on construction practices (Schupack 1994b). Many corrosion problems result from poor construction practices and inexperienced contractors (refer to 8.5.2.1). An optimized grout design is useless when it is not placed properly and ducts are not completely filled with grout. Attention should be given to batching; pumping equipment; tendon profile; bleeding due to vertical pressure head; locations of vents along the duct; and grouting procedures, including sequences of injection points and vent closing, inspection after grouting, and remedial grouting. For guidance on these construction practices, refer to PTI (2000) and The Concrete Society (2002).

5.3.3.5 Anchorage protection—Tendon anchorages and strand end stubs should be protected. Anchorage corrosion can lead to anchorage failure, but the grout when it is bonded to the concrete by grouting, a complete loss of

prestress is prevented. Anchorage hardware corrosion, however, can lead to cracking and spalling of the concrete near the anchorage and to continued corrosion. Corrosion of the anchorage and strand stubs can also allow moisture into the duct, causing subsequent tendon corrosion. To protect strand ends, anchorages can be fitted with a sealed, permanent, nonmetallic end cap that is grouted when the tendon is grouted. Anchorages are commonly recessed in a pocket at the ends or edges of the concrete member. It is common practice to coat the anchorage, end cap, and pocket surfaces with an epoxy bonding agent before filling the anchorage pocket with a nonshrink mortar or concrete, often called a pour-back. Finally, the area is sealed with a water-proof membrane. Additional information on long-term behavior and durability of end anchorage protection methods, as well as grouted and unbonded tendons, is available (Schupack 1994a, 1992; Schupack and O'Neill 1997).

Anchorage locations within the structure can affect corrosion protection and corrosion damage. The location of post-tensioning anchorages is often dictated by the construction method. In many structures, anchorages are located at member ends below expansion joints (for example, bridge girders) or at exterior member ends or edges. These locations are often exposed to moisture and chlorides that lead to severe anchorage corrosion. When the anchorage cannot be located away from a possible source of aggressive agents, the anchorage should be detailed with multiple levels of corrosion protection. The Concrete Society (2002) reports two approaches for anchorage protection. The first approach provides an anchorage that is not encased in mortar or concrete after stressing. Exposed anchorage hardware is protected by end caps and a waterproof membrane that allows the anchorage to be readily inspected for corrosion damage. Unprotected anchorages are not recommended in the U.S. (PTI 2000). The second approach provides a higher level of corrosion protection at the expense of inspectability by recessing the anchorage in a filled pocket. Details of multilevel corrosion protection for buried anchorage are shown in Fig. 5.3.3.5a. Details of the member end can also be designed to minimize contact with moisture and chlorides draining through expansion joints, as shown in Fig. 5.3.3.5b. The member end is detailed to prevent water from dripping onto the anchorage region. An abutment gallery is provided to allow inspectors to gain access to the anchorage area.

Post-tensioning component manufacturers make anchorages that allow easier inspection of the grouted tendon through the grout port. When there is a question about a potential void in the anchor region, the port can be drilled to remove enough grout to insert a borescope for inspection before pour-back placement.

5.3.3.6 Encapsulated and electrically isolated systems—

As with single-strand post-tensioning systems, full encapsulation and electrical isolation of the multi-strand post-tensioning system provides the highest level of corrosion protection. As mentioned in 5.3.2.5, encapsulation normally refers to the post-tensioning tendon only and not necessarily the anchorage. Tendon encapsulation is provided by an impermeable duct, full grouting, and a sealed end

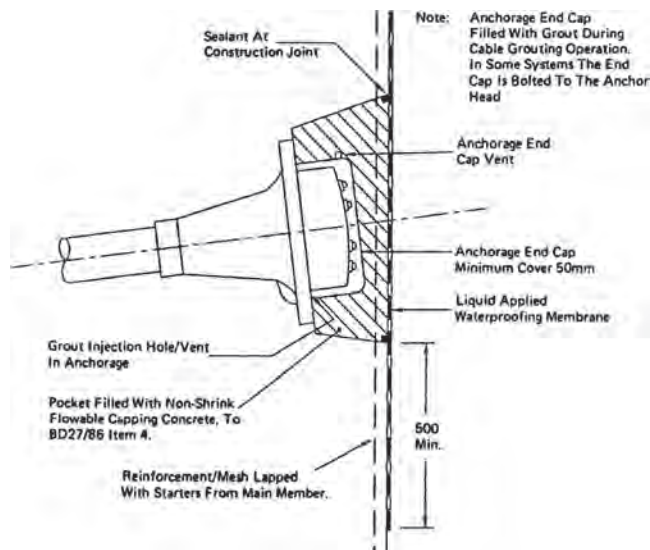


Fig. 5.3.3.5a—Multilayer corrosion protection for buried post-tensioning anchorages (dimensions in mm; 1 in. = 25.4 mm) (The Concrete Society 2002).

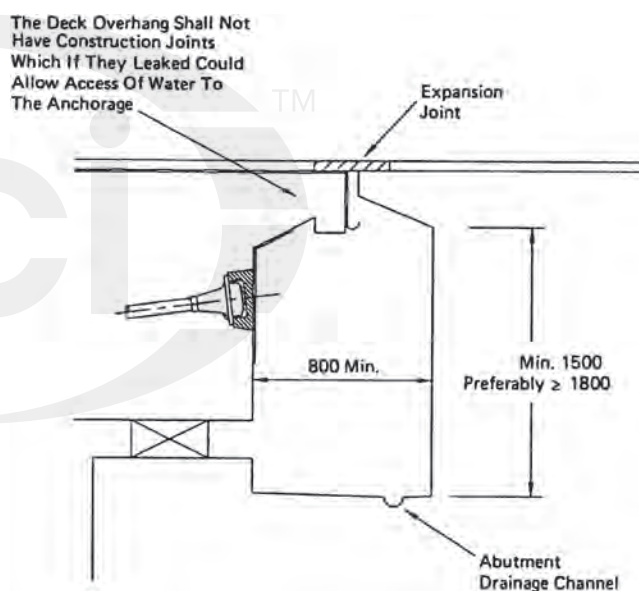


Fig. 5.3.3.5b—Member end details for anchorage corrosion protection (dimensions in mm; 1 in. = 25.4 mm) (The Concrete Society 2002).

cap over the strand or bar stubs. Complete encapsulation and electrical isolation includes coating the anchorage or using nonmetallic anchorage components. This approach can provide an impermeable barrier around the entire post-tensioning system, and protect the system from aggressive agents and corrosion induced by stray currents or coupling with uncoated mild steel reinforcement.

Encapsulated, watertight post-tensioning systems can be tested for leaks. Pressure testing is performed immediately before grouting with all vents closed and end caps sealed. The duct is pressurized with air and the leakage rate is monitored using a flow meter. Leak sources can be identified using soapy water or other commercially available leak indicator

solutions. If leaks are a concern, they should be repaired, including resealing of end caps, grouting or patching, and crack sealing. Using a watertight and airtight duct system permits vacuum-assisted grouting, in which negative pressure is applied at one end of the duct while grout is pumped under pressure from the opposite end. Vacuum grouting is useful for long tendons or those with large elevation differences. For vertical tendons when antibleed grout is not used, vacuum grouting can facilitate removal of bleedwater, laitance, and topping off when regrouting is required.

Encapsulated multistrand post-tensioning systems are commercially available (VSL 2010). All ducts, connections, and trumpets are plastic. The bearing plate is a composite of metal and high-performance mortar, and a sealed end cap is provided. The highest level of protection is provided by a configuration that provides electrical isolation for the tendon and noninvasive methods to electrically monitor the tendon throughout the life of the structure. PTI provides field personnel training and certification for bonded post-tensioning that includes modules on proper tendon installation, stressing, grouting, and inspection.

5.3.3.7 Venting—Proper venting of the duct during grout pumping can reduce air pockets and the resulting grout voids in the tendon. Some heavily thixotropic grouts travel as a front through the tendon without entrapping air, but most grouts entrap air as they move through the duct, particularly near tendon crests and changes in duct cross section. In addition to the inlet and outlet, vents are recommended at all high points or crests, and then shortly downstream from the crest. Vents should also be placed at low points to aid in blowing out moisture in the duct before grouting. These low point vents may also serve as potential injection points when problems occur with grouting the full tendon length. All vents should have a positive shut-off. Bending a vent tube and fastening with tie wire is not adequate. Vents should remain closed before grouting so that moisture and aggressive agents cannot enter the tendon. After leak testing and just before grouting, all vents should be opened. During grouting, vents slightly downstream of a crest vent should be closed immediately before the associated crest vent. All other vents should be closed in order from inlet to outlet. Grout should flow freely with proper consistency and lack of air or water pockets before a vent is closed.

5.3.3.8 Pumping and equipment—A standard grout plant consists of a mixer and pump. Pumping equipment should be capable of pumping grout through the entire duct in a continuous flow. For thixotropic grouts, a high shear or colloidal mixer is preferred and the grout plant includes a holding tank capable of agitating the grout. Pumping pressures should be monitored and backup equipment should be available in case of primary equipment failure.

5.3.3.9 Training—Knowledgeable field personnel and inspectors are vital to a successful grouting operation. The American Segmental Bridge Institute (2014) provides training and certification for grouting post-tensioning systems.

5.3.4 Unbonded multi-strand and bar post-tensioned construction

5.3.4.1 Embedded post-tensioning—Although not as widely used as bonded post-tensioned systems, unbonded multistrand post-tensioning systems and unbonded post-tensioned bar systems are available. Unbonded multistrand and bar post-tensioning can be used for various applications and structural design criteria. Common applications include flat slabs and foundations, joining precast-concrete elements together, precompression of bearing systems, structures that are to be disassembled later, and nuclear pressure vessels.

Multilevel corrosion protection in unbonded multistrand and bar systems is similar to that of bonded systems with the exception of the cement grout. Corrosion-protection options include plastic or noncorroding ducts and epoxy-coated or galvanized strands or bars. Some multistrand systems can be fitted with coated and sheathed strands normally used in single-strand systems (refer to 5.3.2). Anchorage protection for unbonded systems is the same as for bonded post-tensioning (refer to 5.3.3.4).

5.3.4.2 External post-tensioning—External post-tensioning is used for precast segmental bridge construction, strengthening of structures, and stay cables. External post-tensioning tendons are not embedded in the concrete but are connected to the structure at discrete locations, including anchorages and deviators.

Several options are available to provide multilevel corrosion protection for external tendons. Most external multistrand tendons are encased in a steel or plastic sheath (Fig. 5.3.4.2). This provides an exterior protective barrier around the tendon. As with post-tensioning ducts, a plastic or other noncorroding sheath provides the highest level of corrosion protection. Thick-walled, smooth polyethylene duct is typically used for external tendons. The duct should be manufactured from 100 percent virgin polyethylene resin meeting ASTM D3350 with a minimum cell class of 34464C and include antioxidants (Florida Department of Transportation 2013). These stringent requirements are necessary to avoid splitting and degradation of the duct.

Strands or bars used for external tendons can be epoxy-coated or galvanized. Coated and sheathed strands, as used in single-strand systems, are commonly used for both external

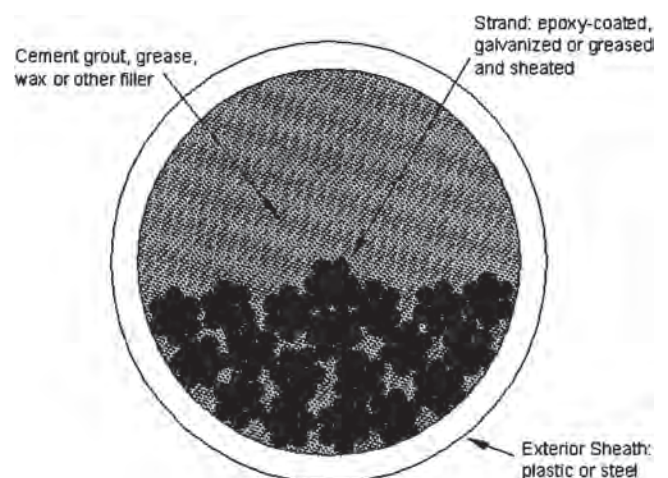


Fig. 5.3.4.2—External post-tensioning tendon corrosion-protection cross section shown at tendon high point

multistrand and single-strand tendons. The space between strands or bars inside the outer sheathing can be filled with cement grout or post-tensioning coating to provide additional corrosion protection. Grout properties should meet similar requirements as grouts used in bonded post-tensioned construction (refer to 5.3.3.3). Greases should be similar to those used for coated and sheathed single-strand tendons (refer to 5.3.2.1). For a higher level of protection, nuclear industry requirements should be used (Ashar et al. 2007).

5.4—Cathodic protection

Several factors render cathodic protection of prestressing steel in concrete more complex than for conventional reinforcing steel. Hydrogen embrittlement (HE) is a particular concern when applying cathodic protection to prestressing steel in concrete. When a cathodic-protection system is installed and operated so that the magnitude of polarization is excessive, atomic hydrogen can be generated at the steel surface and embrittlement may occur. Significant HE is unlikely at steel potentials less negative than $-900 \text{ mV}_{\text{SCE}}$ (Bennett and Schue 1998). This is more of a concern with impressed current cathodic protection than with galvanic anode systems.

Another concern of using cathodic protection in post-tensioned concrete structures is the shielding effect. When a metallic duct is used in conjunction with a bonded post-tensioning tendon, it will typically be electrically continuous with the steel tendon. When cathodic protection is applied to such a structure, however, the metallic duct receives most of the current and shields the tendon within. When a plastic duct is used, it also acts as an electrical insulator and shields the current. This shielding effect reduces the possibility of excessive polarization and potential HE, but also reduces the effectiveness of cathodic protection of tendons in steel or plastic ducts. Cathodic protection can provide corrosion control for the metal ducts which, in turn, protects the grout and tendon inside from contamination. Cathodic protection also can be effective in controlling corrosion of uncoated anchors and nonprestressed reinforcing steel that are present in post-tensioned systems.

Most cathodic protection for prestressing steel in new construction is for prestressed concrete cylinder pipe. Both impressed-current and galvanic-anode systems are installed in soil for corrosion control of prestressing wires in pipe. Cathodic protection, however, was applied to over 1,075,000 ft² (100,000 m²) of new post-tensioned segmental concrete viaducts in Italy. In the viaducts, a mixed metal-oxide, titanium-anode mesh (impressed current method) was used in conjunction with concrete overlay on new bridge decks (Bazzoni et al. 1996).

CHAPTER 6—FIELD EVALUATION

6.1—Introduction

Field evaluation of prestressing steel corrosion in concrete structures has many similarities to the evaluation of embedded nonprestressed steel reinforcement in concrete. Information on the field evaluation of embedded metals in

concrete is reported in ACI 222R. There are similarities between the evaluation of prestressed and nonprestressed steel reinforcement systems, but there are also important differences and additions. Moreover, there are distinctions between pretensioned and post-tensioned-system evaluations and, therefore, field evaluation of these systems is discussed separately.

6.2—Evaluation goals

Before evaluating a structure or structural system, it is important to establish the goals or purpose of the evaluation. The fundamental evaluation goal is to determine whether there is corrosion activity, or identify conditions that may promote corrosion activity, in a prestressed concrete structure. When conditions consistent with corrosion activity are observed, additional goals may include:

- (a) Determining the extent and severity of corrosion, including prestressing steel section loss or fracture and concrete spalling or delaminations, so that its effect on the strength and serviceability of the structure can be assessed
- (b) Identifying the causes of corrosion or conditions that promote corrosion, so that future corrosion-related deterioration can be mitigated
- (c) Conducting detailed engineering analysis of the consequence of future corrosion-induced failure

Various visual, nondestructive, and electrical techniques and material analyses are described to assess corrosion activity. It is important to collect condition evaluation information from multiple sources and techniques to provide the most complete assessment of corrosion activity.

6.3—Pretensioned structures

6.3.1 Introduction—Pretensioned high-strength strands or wires are completely embedded and bonded to the concrete of the member. The field evaluation of a pretensioned system is similar to a corrosion evaluation of nonprestressed steel reinforcement. ACI 222R provides extensive guidance on the field evaluation of embedded steel in concrete. There are important distinctions between pretensioned reinforcement and nonprestressed steel reinforcement.

6.3.2 Electrical evaluation methods—Pretensioned tendons are not electrically isolated from the concrete by a duct, as can be the case with post-tensioned systems. Therefore, electrical evaluation methods developed to evaluate nonprestressed steel reinforcement can be used, with the exception of pretensioned elements using epoxy-coated strands where the coating prevents the use of electrical evaluation methods. These methods can provide valuable information as part of a corrosion evaluation, but it may not be possible to determine the actual rate of corrosion in a prestressed concrete structure. These measurements only provide an indication of corrosion activity during measurement, so care should be taken when interpreting the results to assess the severity and possible consequences of corrosion using a single measurement. To provide the most complete assessment of corrosion possible, collect condition evaluation information from multiple sources including