

Monitorable post-tensioning systems

Sub task 2 – State-of-the-art report

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Summary

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1 Introduction

Prestressed concrete is a frequently used worldwide in infrastructure construction. It offers considerable advantages over conventional, reinforced concrete construction, particularly in bridge structures. In many countries most of the road and railway bridges are built with prestressed concrete and often the tendons are post-tensioned and bonded by grouting.

Although this construction method has generally performed well, a number of problems are known that may lead to a premature need for replacement or repair of post-tensioning tendons. Particularly, corrosion of the prestressing steel is well known to seriously affect the serviceability and load bearing capacity of post-tensioned bridges. One such form of corrosion, pitting corrosion, is caused by chlorides. These are present at the concrete surface in the case of sea-water or de-icing-salt exposure and may reach ducts through the concrete cover, joints or cracks. Through defects in the ducts, e.g. caused by corrosion of metallic ducts or initially present in non-metallic ducts, these chlorides may finally reach the prestressing wires or strands and cause serious loss of steel cross section. Another reason for the presence of chlorides in the duct is the use of chloride-contaminated grouts.

Various corrosion protection systems have been developed and marketed. In Switzerland, plastic ducts instead of metallic ducts were introduced in the early 1990s. These non-metallic ducts are corrosion resistant and restrict diffusion of chlorides, oxygen, and moisture to the prestressing steel, thereby limiting the extent to which corrosion reactions at the prestressing wires/strands can occur. Nevertheless, also these plastic ducts are likely to exhibit defects and may thus permit local penetration of corrosive substances to the prestressing steel.

A significant drawback of prestressed steel being encapsulated in metallic or non-metallic ducts is the fact that the condition of the wires or strands cannot easily be assessed by means of non-destructive test methods. Ongoing corrosion can thus hardly be detected from the outer concrete surface.

This led Switzerland to adopt the concept of electrically isolated tendons (EIT) [that was first proposed and patented in the U.S. by M. Schupack and M. G. Suarez in 1982 \[1\], promoted at the time for single strand tendons](#). The approach developed in Switzerland permits a non-destructive inspection and condition assessment over time by means of electrical resistance and other measurements. Based on the work carried out in Switzerland in the late 1990s, the Swiss Federal Roads Administration (ASTRA) and the Swiss Federal Railways (SBB) jointly issued the guideline "Measures to Ensure Durability of Post-Tensioning Tendons in Structures" in 2001 [2]. A revised version of this guideline was released in 2007 [3]. An English translation of this guideline is also available [4]; [the translated version is however not an official document](#). The concept outlined in these Swiss guidelines was essentially adopted in *fib* bulletin no. 33 "durability of post-tensioning tendons", published in 2005 by the International Federation for Structural Concrete (*fib*) [5].

In short, the technology of electrically isolated tendons (EIT) is a concept to protect and monitor tendons against corrosion attack from the outside of the tendon, which is the most frequent cause for premature degradation in chlorine exposure environments.

Today, the EIT technology and the related measurements are the most established methodology for monitoring post-tensioning systems with respect to their durability performance. The aim of this report is to thus review existing literature and guidelines concerning EIT, and to describe the principles of the EIT technology, the required components, performance testing, and monitoring procedures in order to provide a basis for potential implementation of this technology in the US.

EIT is commonly applied for internal bonded tendons and most of the experience summarized in this report refers to this case. Nevertheless the EIT technology may in principle also be applicable to internal unbonded tendons (e.g. greased and sheathed monostrands) and also to external tendons.

The first chapters of this report give an overview of the terminology, the historical background and the development and basic principles of the EIT technology (chapters 2–4). Since the quality of the components and the final installation on the structure are essential for the success of this technology, chapter 5 deals with “system approval”, chapter 6 with “detailing”, chapter 7 with “execution”, and chapter 8 with “quality assurance, quality control, EIT measurement and monitoring”. Finally, remarks on “safety” as well as suggestions for further research work are made in chapters 9 and 10. Appendix A presents details about measuring instruments, and in appendix B suggestions are made for specification language.

In September 2015,

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2 Definitions and Abbreviations

2.1 Technical Terms

AC	Alternating current.
Anchorage	A mechanical device, usually comprising several components, designed to retain the load in the stressed tendon, and to transmit the load to the structure [6].
Anchorage cap	A special cap made of steel or plastic to encapsulate the end of the tensile elements at the anchorage [6]. Also termed "protection cap" or "protective cap".
Anchor head	See "Wedge plate".
Bearing plate	A component of the anchorage, which supports the anchor head and transfers the prestressing load onto or into the structure [6].
Connector	A special element to join individual duct lengths/sections between each other or to join a duct segment to the anchorage [6].
Coupling	A component to join adjacent sections of tendons [6].
DC	Direct current.
Duct	An enclosure in which several tensile elements are placed. The remaining void within the duct is usually filled with filling material, such as grout [6].
EIT	Electrically isolated tendon This definition refers to a tendon that has no metallic contact to the reinforcing steel, other prestressing tendons, or to any other metallic components of a reinforced concrete structure. Additionally, in the ideal case, the grout that surrounds the tendon in the duct has no electrolytic contact to the concrete on the outside of the duct.
Encapsulated tendon	Post-tensioning systems which are sufficiently leak tight to assure full encapsulation [5].
Grout	A cementitious, alkaline filling material to be injected into the remaining void within a duct.
Layer of protection	In <i>fib</i> bulletin no. 33 [5], the term "layer of protection" refers to any measure that serves to protect the post-tensioned prestressing tendon from corrosion. This includes structural detailing such as drainage systems, surface treatments (waterproofing, hydrophobic treatments, coatings, etc.), or even inspection or monitoring methods. In combination with the exposure severity, these layers of protection provided by the structure form the basis to select an appropriate protection level (PL) for the post-tensioning tendons (Figure 14).
PL	<i>Protection level</i> according to the terminology used in in <i>fib</i> bulletin no. 33 "durability of post-tensioning tendons", published by the International Federation for Structural Concrete (<i>fib</i>) [5].

PL1	lowest protection level: the tendon is encapsulated in a metallic (steel) duct that is filled with an alkaline, cement-based grout with limited chloride content, which ensures corrosion protection of the prestressing steel (see Figure 11, section 0).
PL2	intermediate protection level: the tendon is encapsulated in a plastic (normally polypropylene (PP) or high density polyethylene (HDPE)) duct that is filled with an alkaline, cement-based grout with limited chloride content. The plastic duct itself is not susceptible to corrosion and presents a barrier to penetration of chlorides and other corrosive substances to the prestressing steel (see Figure 12, section 0).
PL3	highest protection level: the tendon is encapsulated in a plastic duct that is filled with an alkaline, cement-based grout with limited chloride content. Additionally, the tendon is electrically isolated from all other reinforcing or prestressing steel in the concrete structure. In addition to a higher level of corrosion protection, this solution also permits non-destructive monitoring of the integrity of the encapsulation over time (see Figure 13, section 0).
PT	Post-tensioning
Quality assurance	Actions taken by an owner, or another party on behalf of the owner, to provide assurance that the work meets the requirements specified in the project/design in addition to all applicable standards.
Quality control	Actions taken by a contractor, or another party on behalf of the contractor, to ensure that the work meets the requirements specified in the project/design in addition to all applicable standards.
Tendon	A single tensile element or a bundle of elements used for the prestressing of a structure, including the required protection and anchorages [6].
Vent	Tube or hose which permits air to escape the duct at high points of the tendon profile [6].
Wedge	Part, typically conically shaped, which holds an individual tensile element and transfers the prestressing load to the wedge plate/anchor head, or for an individual tensile element directly to the bearing plate [6].
Wedge plate	Also termed "anchor head": The hardware that holds the wedges of a multi-strand tendon and transfers the force from the strands to the bearing plate [7].

2.2 Organizations

fib Fédération internationale du béton (*fib*) / International Federation for Structural Concrete (headquarters in Lausanne, Switzerland).
<http://www.fib-international.org/>

ASTRA Swiss Federal Roads Office (Bundesamt für Strassen, ASTRA)
<http://www.astra.admin.ch/>

SBB Swiss Federal Railways (Schweizerische Bundesbahnen, SBB)
www.sbb.ch

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3 Development and Basic Principles of EIT

3.1 Development

3.1.1 Durability Issues with Permanent Ground Anchors

The development of electrically isolated tendons in Switzerland had its origin in the late 1980s / early 1990s during the design stage of the train station "Stadelhofen" in Zurich. This train station involved a massive retaining wall, up to 22 m in height, which included 900 permanent ground anchors (Figure 1) [8]. At that time, public owners in Switzerland were concerned with the long-term durability of permanent ground anchors due to a series of cases of failure of ground anchors in the early 1980s. Some even prohibited the use of permanent ground anchors. However, for the retaining wall in Stadelhofen, it appeared virtually impossible to find a reasonable and economic solution without permanent anchors. Due to the presence of nearby tramlines in the urban area, there were in this case additional concerns about DC (direct current) stray currents and the associated risks of corrosion and hydrogen embrittlement of the high-strength prestressing steel. Aggressive (corrosive) soil conditions made the situation even more severe.

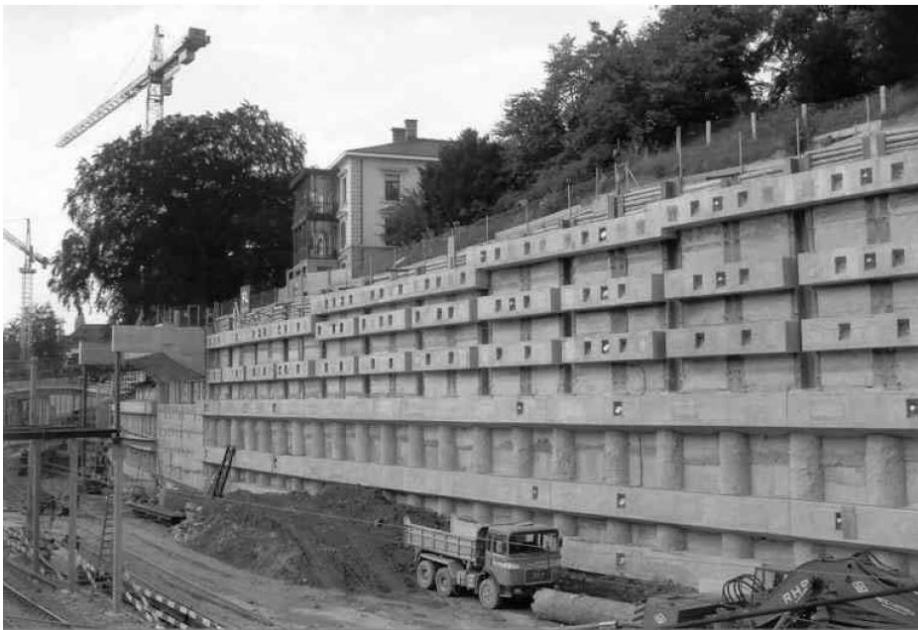


Figure 1. Retaining wall of the train station „Stadelhofen“ in Zurich, Switzerland, including 900 permanent ground anchors (around 1990) [8].

To protect the 900 permanent ground anchors against corrosion, the Swiss Society for Corrosion Protection (SGK) was involved in this project and the approach of the electrically isolated ground anchors was born. Initially, the anchors were simply encapsulated in corrugated plastic ducts over their full length and injected with grout. In this system, the alkaline grout protected the anchor from corrosion, while the plastic duct minimized the risk of stray current induced corrosion. Additionally, the duct acted as barrier against moisture and corrosive substances present in the soil even in the case of cracks forming in the grout.

Before applying the tension force and installing the anchor head (conventionally), it was possible, as quality control, to measure the electrical resistance between the tendon and the soil (Figure 2). Assuming perfect isolation, the resistance should theoretically be infinite. In

the initial phases of construction, however, ducts were often damaged seriously enough to disturb or eliminate electrical isolation. After a series of improvements in tendon detailing and construction practices, large resistances were indeed reached, which indicated that only minor defects were present in the electrical isolation over the tendon length. Note that after installation of the anchor head, long-term monitoring was not possible with this system due to metallic contact between the anchor head and the reinforcing steel of the reinforced concrete member.

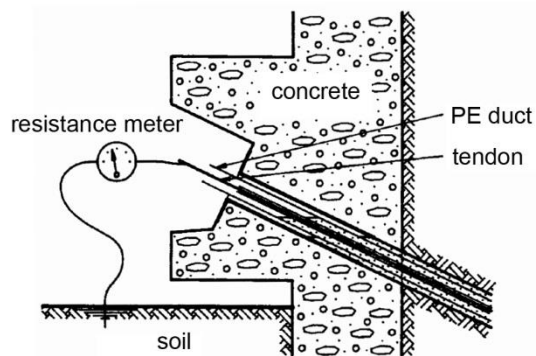


Figure 2. Anchor with electrical isolation over its length, prior to applying the tension force and installing the anchor head, permitting the measurement of the electrical resistance vs. the soil [8].

Later endeavors were thus aimed at achieving a system where the ground anchor (tendon) is completely electrically isolated from both the soil and the reinforced concrete structure. Only this permits monitoring the integrity of the isolation over time, i.e. during the service life of the structure. The solutions included electrically isolating discs (fiber-reinforced plastic) between the anchor head and the bearing plate. Additionally electrically isolating caps were used. Figure 3 shows the first successfully installed, completely electrically isolated ground anchor that demonstrated the technical feasibility of the approach of EIT.

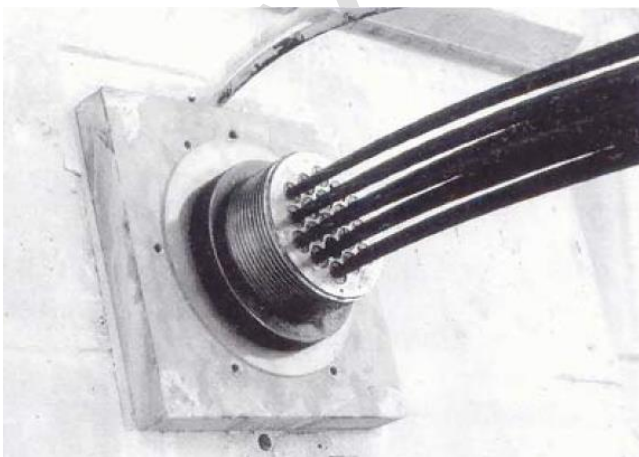


Figure 3. First-ever completely electrically isolated ground anchor installed in Switzerland in 1992 [8], demonstrating the technical feasibility of this approach.

3.1.2 Electrically Isolated Post-tensioning Tendons

In recognition of the essential significance of post-tensioning tendons for the serviceability, safety, and durability of post-tensioned concrete structures (primarily bridges) and cases of corrosion-related deterioration, systems with improved corrosion protection were envisaged in the 1980-1990s [8-10]. In addition to corrosion issues, there were also additional reasons such as fretting fatigue that led to the increased use of plastic instead of metal ducts for post-tensioned tendons [10].

In the early 1990s, a new generation of thick-walled and corrugated polymer ducts were developed for post-tensioned tendons bonded by grouting [10]. If properly manufactured and installed, these ducts – together with specific details at anchorages – provide a complete encapsulation of the tendon over its full length that shields it from corrosive substances and from stray currents.

Similar to the ground anchors described above, monitoring the electrical resistance between the prestressing steel in the tendon and the reinforcing steel in the surrounding concrete of a structural element is in principle possible. However, this requires a complete electrical isolation of the tendon (i.e. not only over the length of the tendon but also at its ends (anchorage)). The technology that was developed for the ground anchors was adapted to the situation of post-tensioning tendons. Suitable detailing was developed by various companies that permit such complete electrical isolation. Figure 4 shows an example of a commercial system that ensures electrical isolation of the tendon including the anchorage zone.

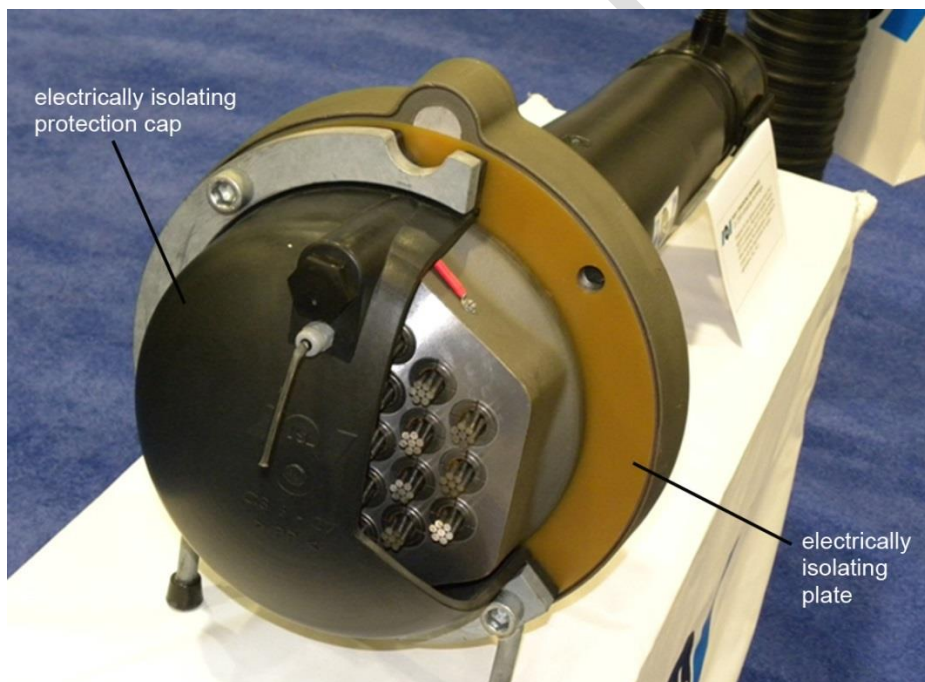


Figure 4. Example of the detailing at the anchorage zone of an electrically isolated post-tensioning tendon (courtesy of VSL international).

3.2 Basic principles of EIT

3.2.1 Corrosion Protection

The corrosion protection offered by EIT consists of a number of complementary beneficial effects.

Consider first the traditional system with a tendon in a metal duct, injected with cementitious, alkaline grout (Figure 5). Since the metal duct is susceptible to corrosion, it may be perforated by corrosion caused by the presence of chloride ions on its surface. This will permit access of corrosive substances (primarily chlorides) to the prestressing steel and initiate corrosion. Electrical connectivity among these steel components results in a macro-cell formation with the steel duct and reinforcing steel acting as the cathode and the prestressing steel as the anode. The large cathodic surface area thus strongly enhances the local corrosion rate and associated cross-section loss in the prestressing steel. This is important because the reinforcing steel, typically located at shallower cover depths than the prestressing tendons, has easier access to oxygen. Additionally, an increased number and size of perforations of the metal duct (when suffering corrosion) will facilitate the flow of the macro-cell current in the concrete, which will result in increased corrosion rates of the prestressing steel.

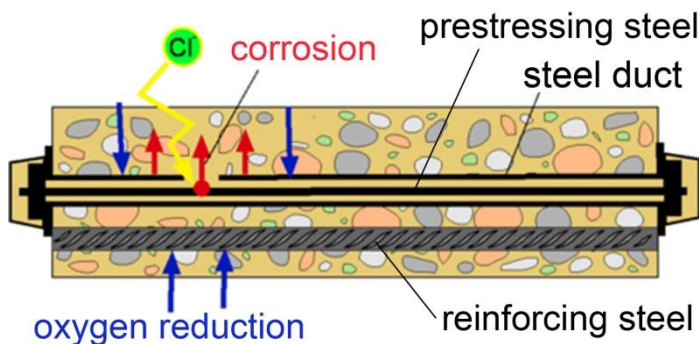


Figure 5. Corrosion mechanism in a traditional tendon embedded in a metal duct filled with grout. Red = iron dissolution (anodic reaction), blue = oxygen reduction (cathodic reaction), black = steel.

EIT systems, on the other hand, provide electrical isolation from the surrounding concrete and reinforcing steel. Furthermore, the plastic duct is not susceptible to corrosion and will not be subjected to perforation as a result of corrosion over its service life. Plastic ducts, however, may be damaged during handling or during post-tensioning, which may allow chlorides to gain access to the prestressing steel over the service life. This may lead to chloride-induced corrosion of the tendon. In contrast to the traditional system shown in Figure 5, however, the prestressing steel in the EIT tendon in Figure 6 will be protected from macro-cell interaction with reinforcing steel (or with the plastic duct, since the cathodic partial reaction cannot occur on the plastic surface). The cathodic reaction of the corrosion process can only occur on the prestressing steel itself and because it is strongly restricted due to the lack of oxygen available inside the duct, the corrosion rate will be comparatively low. Thus, even in the case of a duct perforation and chloride penetration to the prestressing steel, the corrosion rate is lower than that of the traditional case. This is schematically illustrated by the length of the arrows in Figure 5 and Figure 6.

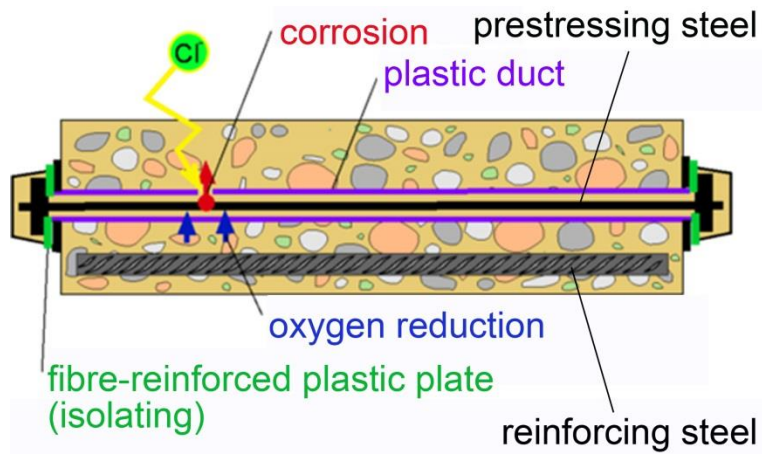


Figure 6. Corrosion mechanism in an electrically isolated tendon. Red = iron dissolution (anodic reaction), blue = oxygen reduction (cathodic reaction), black = steel, purple = plastic duct, green = isolating plates at anchorage.

3.2.2 Protection against Stray-Current Induced Corrosion

Stray currents, originating from DC powered railways or trams, may present a corrosion risk, particularly for long steel elements embedded in concrete such as prestressing steel tendons in bridges or other concrete structures.

Figure 7 shows a schematic example of the current flow in the electrical circuit powering the tram (blue arrows). While the current supplied from the power source reaches the tram through the overhead wire, the return flow of current, i.e. from the tram back to the power source, ideally occurs through the rail. This is the case when the rail is well electrically isolated from the concrete and/or when the ohmic resistance in the rail is much smaller than the resistance against current flow through the concrete (e.g. bridge deck).

Under certain conditions, part of the return current may preferably flow through the reinforced concrete of the structure, particularly through the steel parts in it (reinforcing steel, tendons). In the absence of an electrical isolation between rail and concrete, the reinforced and prestressed concrete can be viewed as a parallel conductor to the rail. Particularly in the case of relatively low electrical resistivity of the concrete (porous, moist, chloride-contaminated, etc. concrete), the magnitude of the current flow through the concrete member is expected to be high. In the presence of metallic conductors (e.g. reinforcing or prestressing steel) the current may also be picked up by these, particularly over long distances. This can significantly decrease the ohmic resistance acting against the current flow. Thus, the current may enter the prestressing steel at the location of the tram, and leave the tendon close to the power source.

While in steel (or any other metal) the current flows as electric current, in concrete (or any other electrolyte) the current is carried by the flow of ions. The conversion from ionic to electric current and vice versa happens in the form of electrochemical reactions. At the locations where the current enters the steel (tendon, reinforcing steel, rail), this is a cathodic reaction, which is harmless (or even protective) to the metal. At the locations where the current leaves the metal (tendon, reinforcing steel, rail), on the other hand, this is the anodic reaction which can be associated with the loss of metal. This may severely damage the rail, the tendon, or the reinforcing steel.

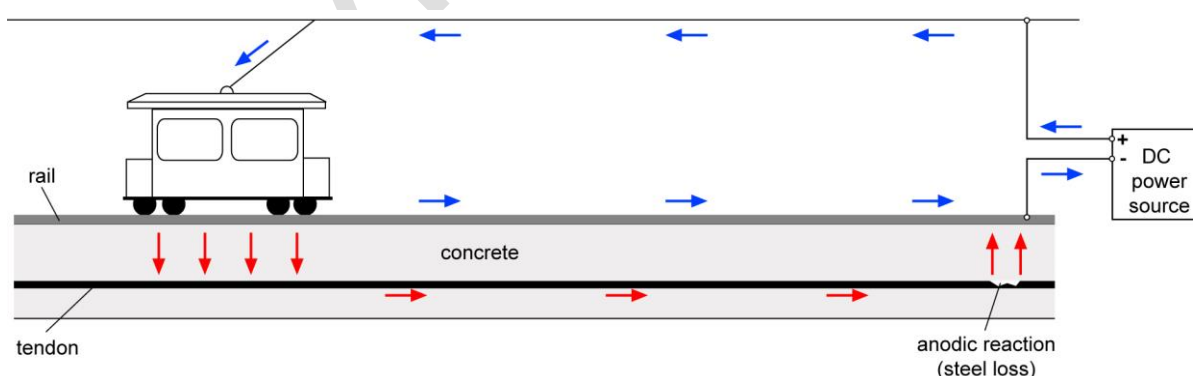


Figure 7. Schematic illustration of DC powered tram on a concrete structure. The blue arrows indicate the direction of the electric current of the railway system; the red arrows indicate stray currents entering the tendon (cathodic reaction) near the tram and leaving the tendon (anodic reaction) near the power source. This is possible in the case of tendons with no duct or with severely perforated ducts, i.e. largely unshielded tendons, and with reinforcing steel.

Figure 8 shows an EIT, i.e. a situation where the prestressing steel is shielded by a plastic duct. The high electrical resistance of the plastic duct forces the stray current to flow through the surrounding concrete and reinforcing steel, rather than the prestressing steel inside the plastic duct.

Note that also other situations may lead to the flow of a DC current through a concrete structure: For instance, a DC stray current may enter a bridge at one of the abutments and leave the bridge at the other abutment. In this case, the current enters the tendon at one anchorage and leaves it at the other anchorage, thereby causing corrosion where the current leaves the steel. Thus, in order to achieve full protection of prestressing steel tendons against stray current induced corrosion, also the ends of the tendon need to be encapsulated and electrically isolated. This requires the use of completely electrically isolated tendons.

Additionally, also cathodic protection systems may cause DC stray current induced corrosion. However, in the case of cathodic protection systems, the adverse effect of primary concern is hydrogen embrittlement (ISO 12696). [This risk of hydrogen embrittlement when applying cathodic protection to the reinforcing steel of a prestressed structure can be significantly reduced with EIT, because the fraction of applied current reaching the prestressing steel is strongly decreased.](#) This also decreases the (already small) risk of cathodic protection related stray-current induced corrosion.

[From the discussion above it becomes apparent that primarily tendons in longitudinal direction of structures are at risk of stray-current induced corrosion. For tendons perpendicular to the primary direction of flow of stray-current, such as transverse tendons in bridge decks, the risk of stray-current induced corrosion is often negligible.](#)

Swiss experience has indicated that if tendons are i) shorter than 100 m, and ii) shorter than one third of the length of a structure, the risk of stray-current induced corrosion can be considered small, as long as there is no DC-powered railway or tram directly on the bridge [3, 4]. When necessary, the presence or absence of potentially hazardous DC stray currents can be measured for a specific structural member or an entire concrete structure. Specialized knowledge and experience, however, are required for performing the measurements on-site and for interpreting the results (see e.g. EN 50162, IEC 62128-2).

For the case of Switzerland, the criteria for a risk of stray current induced corrosion are specified in a National guideline issued by the Swiss Society for Corrosion Protection [11].

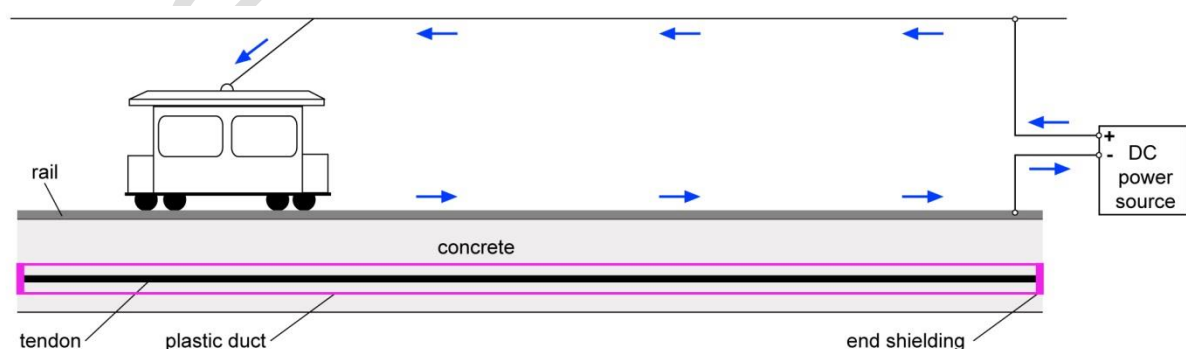


Figure 8. Schematic illustration DC powered tram on a concrete structure with a tendon shielded by a plastic duct (envelope). The blue arrows indicate the direction of the electric current. Due to the shielding of the tendon by the plastic duct, the stray current cannot enter the tendon.

3.2.3 Principles of EIT Impedance Measurements

This section briefly presents the principle of measuring electrical impedance on EIT. More details on the measurement, its application and the interpretation of the results are given in chapter 8. Details on the required instruments are in the appendix.

To assess the quality of the encapsulation of EIT (leak-tightness, etc.) and for monitoring the condition over time, the AC impedance between the tendon and the ordinary reinforcing steel is measured (Figure 9). In theory, if the tendon is electrically isolated, the ohmic resistance will be controlled by the resistance of the polymer duct, which is relatively high.

To simplify matters, the AC impedance measurements will also be referred to as “electrical resistance measurements”, which is the common term in Refs. [2-5]. This may be justified by the fact that the ohmic resistance is the main component of interest of the measured AC impedance.

AC impedance measurements are typically taken at a defined frequency and amplitude. A frequency of 1 kHz and amplitudes of no less than 0.5 V are suggested in Refs. [2-5]. At this measurement frequency, the grout and the concrete can generally be considered pure ohmic resistances, while the plastic duct can be considered the capacitive component of the impedance. To complete the circuit, the grout inside the duct and the concrete surrounding the duct can be considered to behave as electrolytes connecting the various components (Figure 10a).

The main idea of the impedance measurement is that in the presence of any defect in the plastic duct, the current may also pass through this defect, which has a much lower electrical resistance than the plastic duct. This adds an Ohmic resistor in parallel to the capacitor, as shown in Figure 10b. As a result, the measured impedance is significantly less than that of a tendon with an undamaged duct, thereby indicating the presence of imperfections in the encapsulation of the tendon.

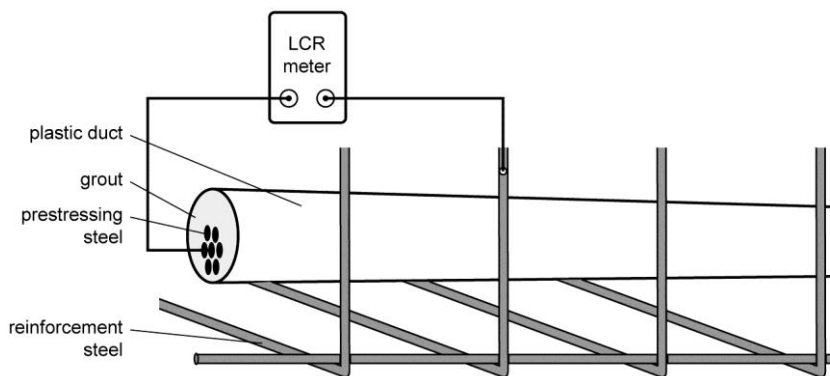


Figure 9. Schematic illustration of measuring the electrical impedance between the prestressing steel and the reinforcing steel of EIT.

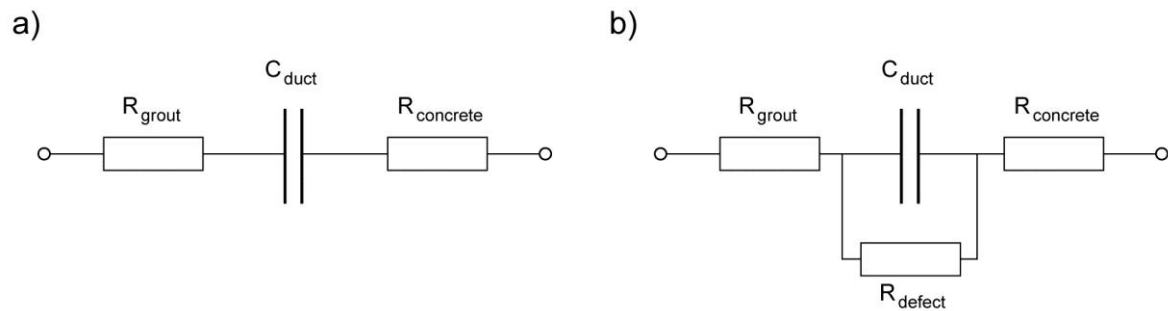


Figure 10. Equivalent electrical circuits for the interpretation of the impedance measurements; a) defect-free plastic duct (with assumed infinitely high ohmic resistance); b) plastic duct with a defect.

Based on this, threshold values can be specified to help distinguishing between undamaged and damaged (perforated) ducts. There are two aspects for specifying threshold values for the impedance for EIT:

1. The absolute value. This provides a relative measure for the overall magnitude of defects (combined effect of size and frequency of defects) during and after construction. The main objective of such measurements and threshold values is **quality control and quality assurance**. Corresponding acceptance criteria have been stipulated in the Swiss Guidelines [2-4], compare chapter 8 of this report.
2. The change of the value of resistance over time. The idea is to follow the development at defects. In general, the ohmic resistance should increase gradually over time due to an increased degree of cement hydration both in the grout and the concrete surrounding the duct. A sudden reduction of the impedance during the service life indicates the ingress of moisture or chlorides at the defect, which may potentially harm the prestressing steel by inducing corrosion (see section 3.2.1). This second point represents in fact the prime interest of the EIT **monitoring**. It may be noted that in the Swiss Guidelines [2-4], no threshold values are defined for the purpose of monitoring. In chapter 8 of this report, however, guidance on the interpretation of long-term monitoring data is given.

Common times of measurement are:

- **After applying the tensile force** to the tendon and prior to grouting (to detect short circuits caused by metallic contact between prestressing steel and reinforcing steel).
- **After grouting**, normally 28 days after grouting (to check the quality of the installation and the leak-tightness of the encapsulation; limiting values and acceptable failure rates will be discussed in chapter 8).
- As **monitoring during the service life**.

See chapter 8 for more details about the use of these measurements in quality assurance, quality control, and in monitoring.

A key advantage of the electrical impedance measurement is that it is non-destructive. Moreover, it takes relatively short time to perform (given all needed cable connections have been properly installed).

3.2.4 Applicability to External and Internal Unbonded Tendons

EIT is commonly applied for internal bonded tendons and most of the experience summarized in this report refers to this case. Nevertheless the EIT technology may in principle also be applicable to internal unbonded tendons (e.g. greased and sheathed monostrands) and also to external tendons.

Internal unbonded tendons

The principle of EIT was originally developed for earth anchors that are greased over large parts of the strands. In principle, due the absence of an electrolyte within the duct it is not possible to detect defects in the duct by means of an AC impedance measurement. However, for internal unbonded tendons, such as greased or sheathed strands, an AC impedance measurement may help to distinguish between cases of full encapsulation of the strands (and thus a high corrosion protection level) and cases where the prestressing steel has for some reason contact to the environment (e.g. infiltration of a liquid electrolyte, imperfect anchorage zones, etc.).

External tendons

EIT is only applicable to those zones, where a conductive medium is present inside the duct (between the prestressing steel and the duct wall) and outside the duct (between the duct wall and the reinforcing steel). For external tendons, all remarks made above for internal unbonded tendons apply, and additionally, it must be recognized that impedance measurements are only possible for zones where the external tendons are in contact (on their outside) with concrete, e.g. in anchorage or other zones.

Assessment criteria

Due to the pronounced differences between the case of internal bonded tendons and the cases addressed here, namely internal unbonded tendons and external tendons, obviously the threshold values used in quality control (see chapter 8.2) are not applicable.

3.2.5 Applicability to Epoxy Coated Reinforcing Steel

In the case of epoxy-coated reinforcing steel (ECR), the EIT technology is in principle also applicable, because ECR typically has defects that provide sufficient electrical connection and allow for AC impedance measurements comparable to plain reinforcing steel. A major concern may be that the electrical continuity is not ensured along the ECR. Thus, to guarantee the presence of a continuous conductor acting as counter electrode in the AC impedance measurement, it is recommended to install so-called "longitudinal main conductors" in the structure. It is recommended to have at least two of the "longitudinal main conductors" and to connect them to each other at least at both ends with help of "transverse main conductors". These longitudinal and transverse main conductors are usually reinforcing bars with large cross section (e.g. 40 mm in diameter); compare also section 6.2.2.

A benefit of ECR is that the major part of the coated reinforcing steel cannot act as a cathode and thus, any galvanic element formed between a zone on the prestressing steel at the location of a defect in the duct and the reinforcing steel, is suppressed.

3.2.6 Applicability Segmental Bridge Construction

When applying post-tensioning tendons in precast segmental bridge construction the match cast joint presents a zone of particular risk of corrosion for the tendon. The EIT technology offers thus particularly for this type of construction a major advantage because it permits monitoring the conditions of the tendon during the service life. To guarantee the electrical isolation at the joints, special duct couplers have by various suppliers been developed (compare 6.1.3).

A remark needs to be made to the fact that the reinforcing steel may be discontinuous, i.e. that no electrical continuity is ensured from segment to segment in the reinforcing steel. For the EIT technology to function, it is thus essential that the reinforcing steel of the individual segments has electrical continuity.

Revised Draft

4 Post-Tensioning System Protection Levels

Different post-tensioning systems are possible, ranging from traditional system with grouted metallic ducts to the fully electrically isolated tendons. An intermediate step is to aim at leak-tightness of the duct (plastic duct) without however requiring electrical isolation of the tendon from the reinforcing steel. Different documents, such as the Swiss guidelines [2-4], the *fib* bulletin no. 33 "durability of post-tensioning tendons" [5], and PTI/ASBI M50.3-12 [7], contain classifications of these different technical solutions. This chapter summarizes these classifications, termed "protection levels". Section 4.3 details criteria for the selection of appropriate protection levels.

4.1 Swiss / *fib* Protection Levels

The following three categories of protection levels for post-tensioning tendons evolved from the developments carried out in Switzerland in the early 1990s. In the Swiss guidelines [2-4], these are termed "category a", "category b", and category "c", where letter "a" indicates the lowest and "c" the highest level of corrosion protection. In *fib* bulletin no. 33 "durability of post-tensioning tendons" [5] – which has adopted the concept of three levels of protection of the mentioned Swiss guidelines – the term "protection level" is used instead of "category", and the letters "a-b-c" were replaced with the numbers "1-2-3". In the present report, the term "protection level" is in agreement with the terminology used by *fib*.

Protection level 1 (PL1)

Figure 11 schematically depicts the system of the lowest protection level, PL1, which represents the traditional form of post-tensioning tendons bonded by grouting. The tendon is in a metallic duct which is injected with cementitious grout. The latter is alkaline and has low levels of chlorides, and thus ensures corrosion protection; at least as long as no corrosive substances penetrate the duct. Normally, the anchor head, and thus the prestressing tendon, are in metallic contact with the steel reinforcement of the structural member.

Note that the protection cap on the anchorage (shown in Figure 11) of tendons with PL1 is required according to Swiss standards only. There is no such requirement for a protection cap for PL1 in *fib* recommendations Bulletin 33.

For PL1, the metal duct is potentially susceptible to corrosion damage. In the case of chlorides being present at the duct surface in sufficiently high quantities, pitting corrosion may initiate and lead to perforation of the duct. This will provide a route for the chlorides to the prestressing steel, which presents a risk of corrosion for the tendon. If chloride-induced corrosion initiates at the prestressing steel, the electrical connection to the metallic duct and to the reinforcing steel permits these to potentially act as cathode and thus strongly enhance the local rate of steel cross section loss at the prestressing steel. This is important because the reinforcing steel, typically located at shallower cover depths than the prestressing tendons, has easier access to oxygen.

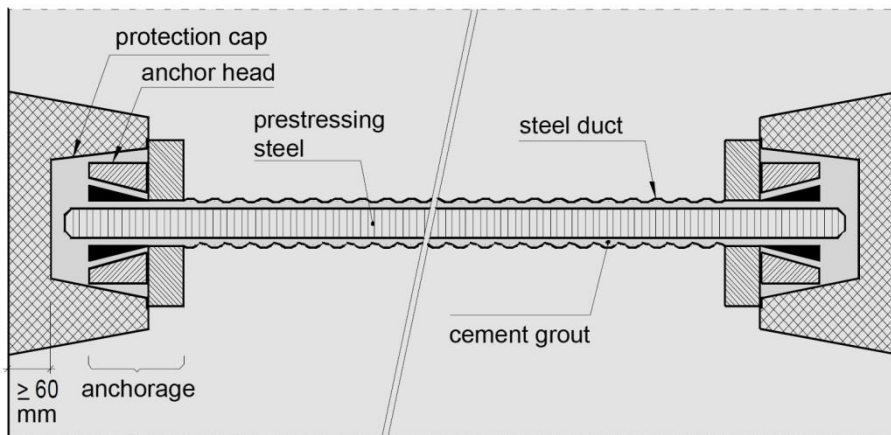


Figure 11. Tendon system for protection level 1 (PL1) (according to the Swiss guidelines [2-4])

Protection level 2 (PL2)

Figure 12 illustrates protection level PL2, where the duct provides a permanent leak-tight barrier over the full length of the tendon. Typically, this is ensured by using plastic ducts, such as polypropylene (PP) or high density polyethylene (HDPE) ducts.

As in PL1, it is also common that the anchor head, and thus the prestressing tendon, is in metallic contact (via a steel bearing plate) with the steel reinforcement of the structural member.

In contrast to PL1, the plastic duct of PL2 cannot suffer corrosion damage. Nevertheless, it may be damaged during handling on the construction site or during application of the tensile force during tensioning. Thus, in the case of partially damaged plastic ducts, chlorides gain access to the inside of the duct through the presence of perforations. This may lead to chloride-induced corrosion of the tendon. As in PL1, the corrosion rate may be enhanced through the electrical connection between tendon and reinforcing steel, so that the reinforcing steel can act as cathode. In contrast to PL1, however, the plastic duct can in PL2 not act as cathode, which may somewhat limit the macro-cell action in comparison to PL1.

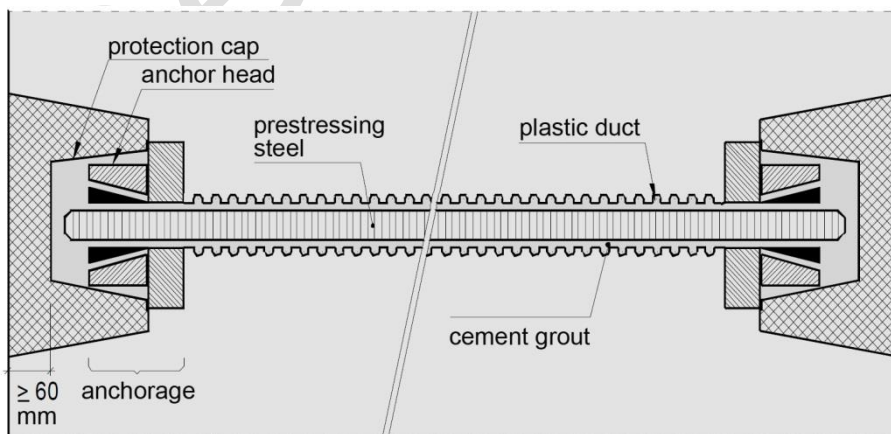


Figure 12. Tendon system for protection level 2 (PL2) (according to the Swiss guidelines [2-4])

Protection level 3 (PL3)

Finally, Figure 13 shows a diagrammatic view of protection level PL3. The main difference to PL2 is that the prestressing steel is electrically isolated from all other reinforcing and prestressing steel in the concrete structure. This is achieved by using electrically isolating materials not only for the duct (normally polypropylene (PP) or high density polyethylene (HDPE)), but also at the anchor head (protective cap and inserts as sketched in Figure 13).

In addition to the protection offered by PL2, the completely electrically isolated tendon in PL3 has no macro-cell interaction with reinforcing steel. Thus, even in the case of perforations in the duct and chloride penetration to the prestressing steel, the corrosion rate is lower than in the cases PL1 and PL2. The cathodic partial reaction of the corrosion process can only occur on the tendon itself. As the required supply of oxygen to the tendon is strongly restricted, the corrosion rate is expected to be comparatively low.

The main advantage of electrically isolated tendons and PL3 is that this solution is non-destructively monitorable over time. Figure 13 shows "electrical connections" at both ends of the tendon. These connections permit contacting the tendons with measurement equipment that allows assessing the condition of the encapsulation or other parameters at any point in time during the service life of the structure.

Finally, PL3 offers also the highest level of protection against stray current induced corrosion of the tendon.

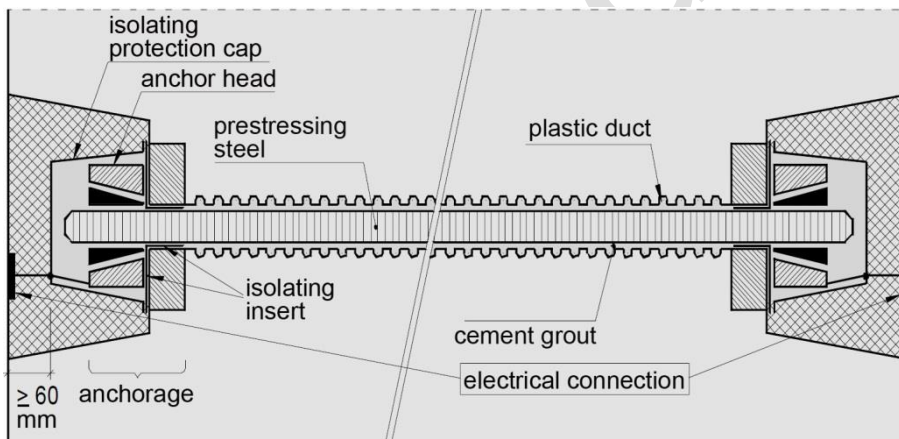


Figure 13. Tendon system for protection level 3 (PL3) (according to the Swiss guidelines [2-4])

4.2 PTI / ASBI M-50 Protection Levels

Similarly to the Swiss Guidelines [2-4] and *fib* bulletin no. 33 “durability of post-tensioning tendons” [5], the document PTI/ASBI M50.3-12 [7], the first edition of which was jointly issued by the Post-Tensioning Institute (PTI) and the American Segmental Bridge Institute (ASBI) in 2012, specifies different protection levels. In principle, these three protection levels are equivalent to the three levels discussed in the previous section.

Protection level 1 (PL-1A and PL-1B)

This lowest protection level describes a system where the prestressing steel is protected by a duct and fill material. The requirements for the duct are that it is “sufficiently strong and durable for fabrication, transportation, installation, concrete placement, and tendon stressing” and that it is “sufficiently leak-tight for concrete placing and grout injection”. There are, however, no specific requirements with respect to a permanent leak-tight barrier. While protection level PL-1A is the lowest, protection level PL-1B has more strict requirements concerning the grout (“engineered grout”) and also requires a permanent grout cap. Permanent grout caps should be made of a non-corrosive material such as fiber reinforced plastic, stainless steel, or galvanized ferrous metal.

Protection level 2 (PL-2)

This protection level corresponds to PL-1B with the additional requirement of an envelope enclosing the tensile element bundle over its full length and providing a *permanent* leak-tight barrier. To ensure this, only plastic ducts/pipes are permitted (no metal ducts) and the post-tensioning system is required to meet the “system pressure test” described in Ref. [7] and summarized in chapter 5. Specific requirements are also made for precast segmental duct couplers at segment joints in precast segmental construction.

Protection level 3 (PL-3)

This protection level corresponds to PL-2 with the additional requirement of “electrical isolation of the entire tendon or encapsulation to be monitorable at any time”.

4.3 Criteria to Select the Protection Level

4.3.1 Exposure Severity and Structural Protection

The durability design strategy proposed in *fib* bulletin no. 33 [5] relates the three protection levels to the aggressivity of the exposure environment and to the structural protection. It can be summarized with Figure 14.

The cornerstone of this “multi-layer philosophy” is the recognition of the difficulty of achieving full protection by any single means. By using several complementary protective “layers”, the overall protection will be ensured even if one of the layers of protection fails (partially or completely). Note that the term “layer of protection”, as used in *fib* bulletin no. 33 [5], does not necessarily refer to a physical layer (e.g. a coating or a plastic duct), but includes any measure with the purpose to protect the tendon. Thus, even inspection or monitoring techniques can be considered as layers of protection.

As is apparent from Figure 14, the higher the exposure severity and the lower the degree of protection inherently provided by the structure, the higher the required protection level (PL) is as additional protection for the post-tensioning tendons. Note that this is only a conceptual description and that it does not specifically define selection criteria for the different PL. Such a specific selection procedure is given in the Swiss guidelines [2-4] as outlined in the following section.

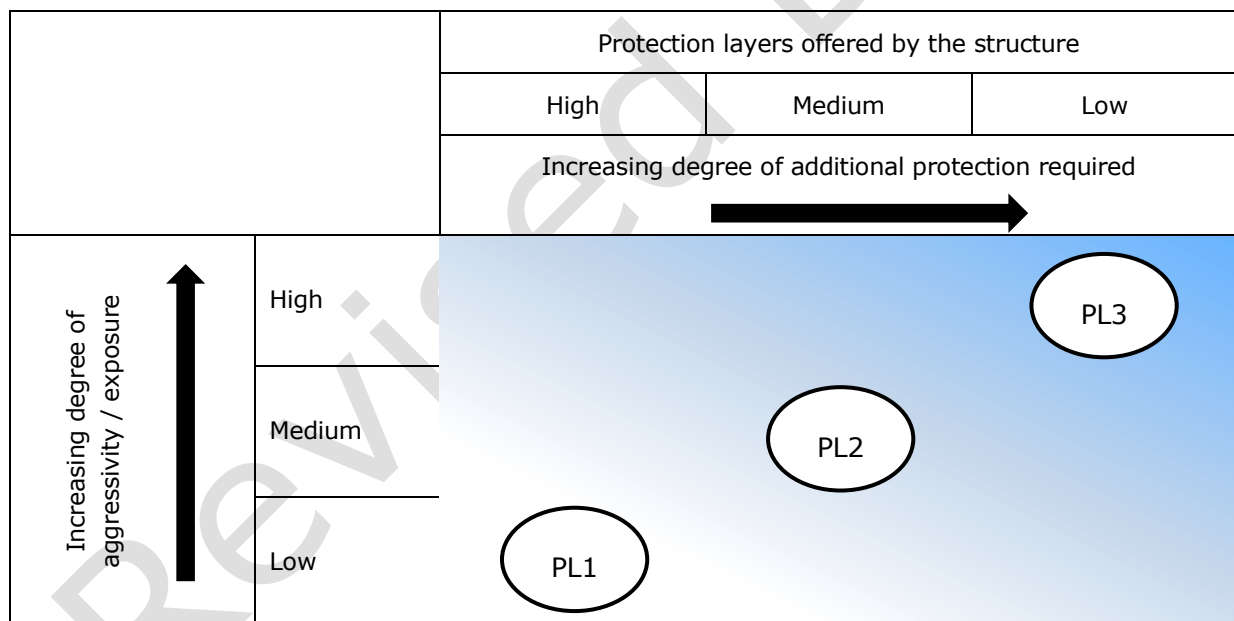


Figure 14. Concept of selecting the protection levels for post-tensioning tendons, based on exposure aggressivity and structural protection layers (according to [2-5])

4.3.2 Detailed Criteria in the Swiss Guideline

In the Swiss guidelines [2-4] detailed criteria to select appropriate protection levels for post-tensioning tendons are stipulated. These can be summarized as shown in Table 1. In this approach, the PL is selected on the basis of the type of structure (railway vs. road bridge), the importance of the structure for the society, on the exposure conditions, the protection “levels” provided by the structure (e.g. hydrophobic coatings, concrete cover depths), the need for a monitorable structure, and the risk of fatigue or stray currents.

An owner may require a continuously monitorable structure in severe exposure or when assuming a limited lifetime of one of the primary layers of protection (e.g. the waterproofing or drainage system). Non-destructive monitoring will in such a case permit to easily identify tendons at risk. The possibility of locating defects in the plastic duct will provide additional useful information at the decision making level when planning maintenance work at later stages in the life of a structure.

If a risk of fatigue is identified, the use of plastic ducts instead of metal ducts has been claimed to improve the fatigue behavior (number of load cycles to failure) of the post-tensioning tendons [2-4].

A risk of stray currents may exist in the presence of trains, trams, etc. operated by DC (compare section 3.2.2). To assess the risk of stray current induced corrosion for a certain structure, specialized expertise and measurements on-site are required.

Table 1. Criteria to select the appropriate protection level (PL) for post-tensioning tendons according to the Swiss guidelines [2-4]

Criteria	PL
Railway bridges	
Tendons needed for assuring the structural safety	PL3
All other tendons	PL2
Highway / road bridges	
Risk of stray current induced corrosion	PL3
Monitoring required	PL3
Risk of fatigue	PL3
Exception: transverse prestressing of deck that is protected with high cover depth and/or hydrophobic coating	PL2
Exposure to chloride bearing environments (depending on cover depth or additional measures such as hydrophobic coatings, PL2 or PL3 may be appropriate)	PL2, PL3
Any construction of vital importance ¹	PL3

¹ such as hospitals, fire station buildings, bridges of great importance for the access to a specific area, etc. (these are defined as “importance class III” (Bauwerksklasse III) in the Swiss code SIA 261)

5 System Approval

5.1 Overview of Approval Documents in Europe

In Europe, technical approval is done according to the *Construction Products Regulation* by *Technical Assessment Bodies* (TABs) that are designated by the member states of the European Union [12]. The *European Organisation for Technical Assessment* (EOTA) coordinates the development of *European Assessment Documents* (EADs) for construction products, which form the basis for the technical approval by TABs. An EAD is a harmonized technical specification that contains at least:

- a general description of the construction product and its intended use
- the list of essential characteristics relevant for the intended use
- methods and criteria for assessing the performance of the product
- principles for the applicable factory production control

Formerly, *European Technical Approval Guidelines* (ETA Guidelines or ETAGs) were elaborated upon the mandate of the European Commission in order to establish how Approval Bodies should evaluate the specific characteristics/requirements of a construction product. ETAGs were used as basis for European Technical Approvals (ETAs) until June 2013 [12]. They are currently updated into EADs.

The relevant document for the technical approval of post-tensioning systems is the ETAG 013 "Guideline for European technical approval of post-tensioning kits for prestressing of structures" [6]. The test procedures and criteria described in this guideline have also been widely accepted in Asia. This guideline is currently in the process of being updated into European Assessment Document EAD-16. Many of the tests described in document ETAG 013 have been removed in the draft version of EAD-16, because the performance criteria and test methods are described in the recently issued *fib* bulletin no. 75 "Polymer duct-systems for internal bonded post-tensioning" [13]. The draft version of EAD-16 only makes reference to *fib* bulletin no. 75.

A wide variety of system approval tests exist for post-tensioning systems, e.g. concerning dimensional tolerances, wear resistance of ducts, bond behavior of ducts, etc. In this chapter, only those tests related to the EIT technology, i.e. those contributing to achieving the electrical isolation and full encapsulation of a tendon, are discussed.

5.2 Approval Tests Described in *Fib* Bulletin No. 75

The systematic approach of *fib* bulletin no. 75 [13] is to consider components of PT systems and assembled systems separately. The following tests are described:

Components:

- Leak tightness of duct (duct and duct connectors) (appendix A.6 in [13])
- Precast segmental duct couplers (appendix A.11 in [13])

Systems:

- Leak tightness of anchorage-duct assembly (including anchorage, trumpet, duct and duct connector) (appendix B.1 in [13])
- EIT performance of duct system (including duct, connectors and vents) – only for PL3 (appendix B.2 in [13])
- EIT performance of anchorage-duct assembly (including anchorage, trumpet, duct and duct connector) – only for PL3 (appendix B.3 in [13])
- Leak tightness of full scale assembled duct system (including all components) – only for PL3 (appendix B.5 in [13])

These tests will in the following sections be shortly summarized. For a full description, please consult *fib* bulletin no. 75 [13].

5.2.1 Leak tightness of duct

The requirements differ for the different protection levels. For PL1 the duct system (duct and connectors) must be mortar tight (as for steel ducts); for PL2 and PL3, on the other hand, the duct system must be leak-tight. It is important to recognize that this requirement must be fulfilled after transporting, jobsite handling, installation, pouring and compacting concrete, installing the tendon, and applying the tensioning force.

The test described in appendix A.6 in [13] employs specimens of 1.1 m in length with a duct connector placed in the center. The specimens tested must previously have been subjected to other tests, namely longitudinal and lateral load resistance of the duct as well as flexibility of the duct. It is not permitted to reassemble the duct connection for the leak tightness test.

During testing, the specimen must be bent (with help of a template) to the specified minimum radius of curvature for field installation. Both ends of the duct are sealed and a positive water pressure of 0.5 bar (inside) is applied. The specimen is then submerged into a water tank and the pressure is maintained during 5 minutes (PL2) or 30 minutes (PL3). Subsequently, a negative pressure test (0.5 bar vacuum inside the duct) is performed for the same durations as the positive pressure test. No visibly detectable leaks are permitted for both tests and for the specified durations. In the positive pressure test, this means expulsion of air; in the negative pressure test, this means infiltration of water.

5.2.2 Precast segmental duct couplers

The objective of the test described in appendix A.11 in [13] is to ensure that precast segmental duct couplers perform in the field. The test includes procedures to confirm that the gasket thus not act as a shim, that the system maintains pressure and that it remains intact, free of epoxy intrusion, and without crushing or tearing.

To test that the system maintains pressure, a complete segmental duct coupler system, including all components, is cast into a two part concrete test block (at least 300 mm x 300 mm x 300 mm) using match cast techniques. After hardening, the blocks are separated and cleaned. They are then clamped together with a defined force, and the duct coupler is subjected to an inside air pressure (3.5 bar for PL2 and PL3). The acceptance criterion is that the pressure loss over the test period of 5 minutes is not larger than 10% of the initial pressure.

5.2.3 Leak tightness of anchorage-duct assembly

The objective of this test described in appendix B.1 in [13] is to confirm that the anchorage-duct assembly maintains mortar tightness (PL1) or leak tightness (PL2 and PL3). The test specimen is an assembly of a piece of duct (>300 mm in length), trumpet / transition to anchorage, anchorage (bearing plate, anchor head and cap), connector between duct and trumpet as applicable, any other component forming part of the anchorage-duct assembly. A steel rod is then installed and the nominal pre-compression between anchor head and bearing plate (1 kN total force) is applied. This setup (

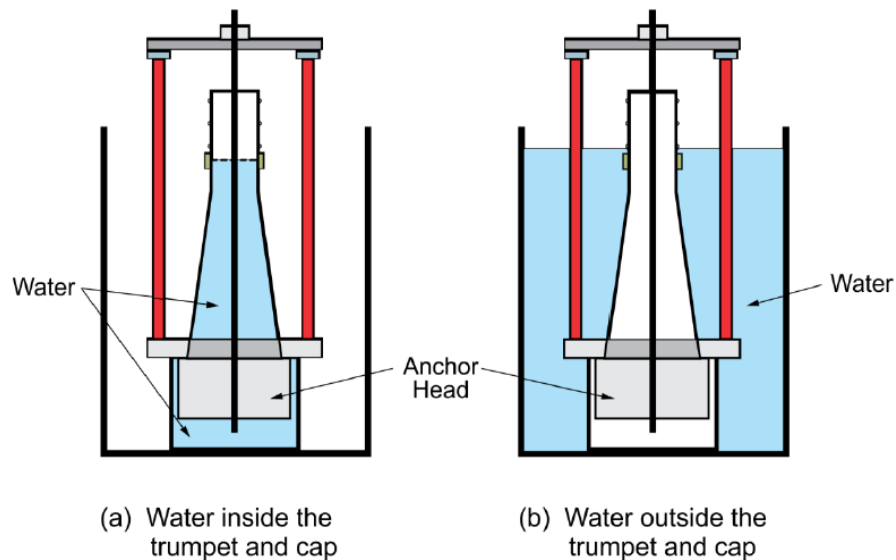


Figure 15) is then subjected to first a positive pressure test and then a negative pressure test identical to the leak tightness test of ducts described in section 5.2.1.

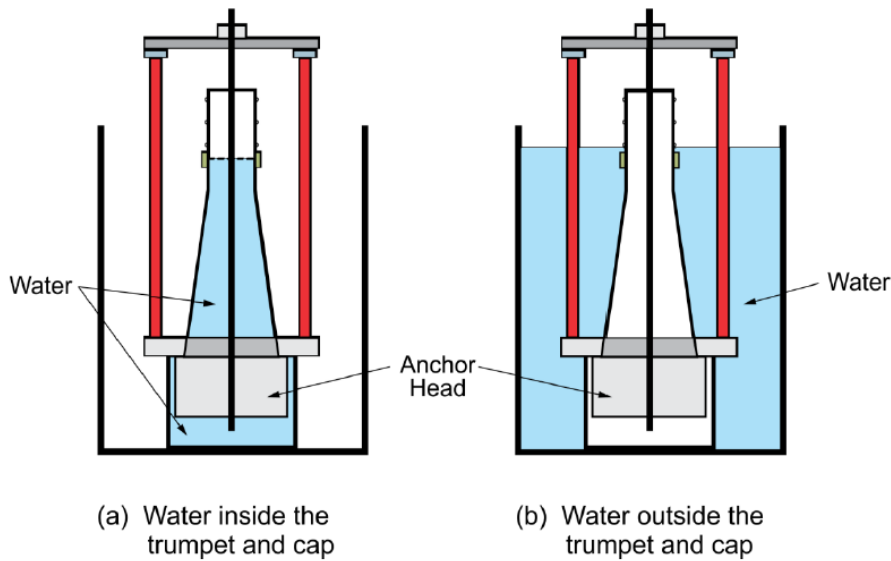


Figure 15. Test setup for anchorage-duct assembly leak tightness testing; a) positive pressure test, b) negative pressure test [13]

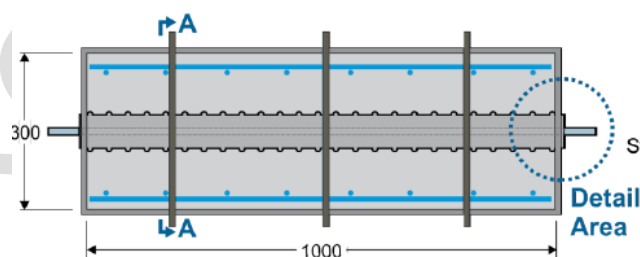
5.2.4 EIT performance of duct system

The objective of this test described in appendix B.2 in [13] is to demonstrate that the polymer duct system components can achieve sufficient electrical resistance to meet the EIT requirements for PL3 on site. Three different types of specimens are tested (with a length of 1.1 m):

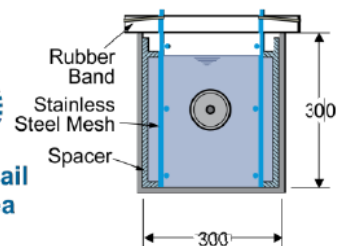
- Duct only
- Duct with connector placed in the center
- Duct with connector and vent placed in the center

All specimens contain a steel rod, are filled with water, and are sealed at both ends. They are then immersed in a water basin of given geometry (

a) PLAN VIEW



b) SECTION A-A



c) DETAIL

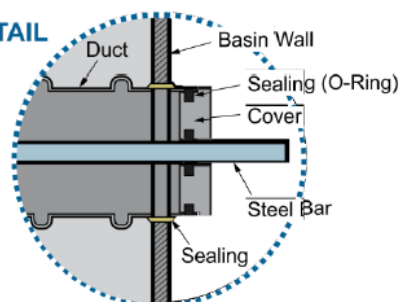


Figure 16) and kept immersed for two weeks. AC impedance measurements are then performed with an LCR meter (at a frequency of 1 kHz). The requirement for all three specimens is that the measured resistance is higher than 2000 kOhm.

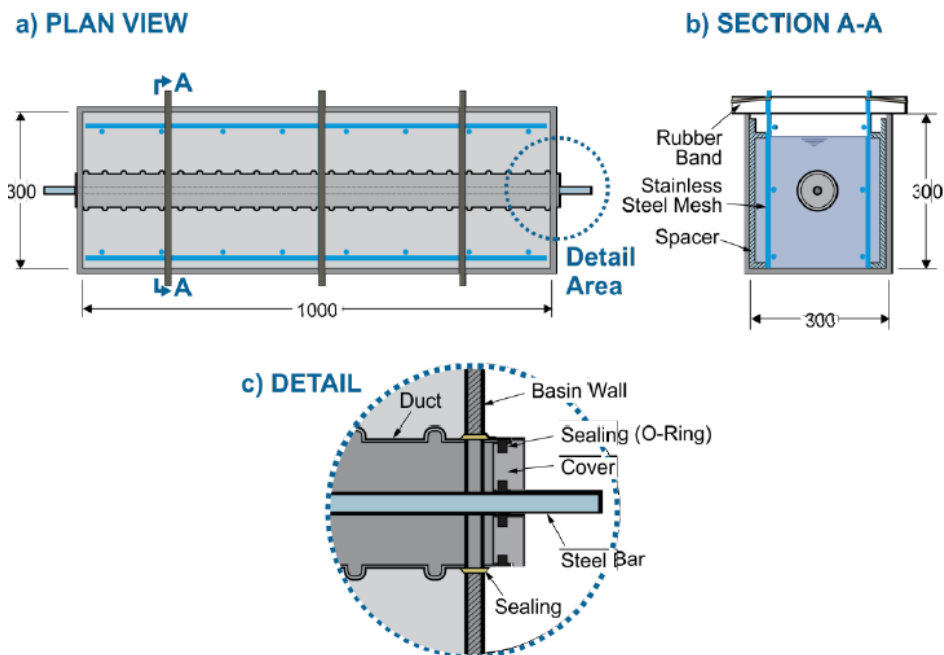


Figure 16. Test setup for EIT performance of duct system testing [13]

5.2.5 EIT performance of anchorage-duct assembly

This test has been developed by the Swiss Society for Corrosion Protection in collaboration with pre-stressing companies and is described Ref. [10]. The test may in principle be used for testing various components of an EIT system. So far, it has, however, primarily been used for anchorages. The reason is that anchorages have been found to be a particularly critical element, where the electrical isolation of EIT can be impaired. In the recently issued *fib* bulletin no. 75 [13], this test is described in appendix B.3 for testing the EIT performance of anchorage-duct assembly.

The objective is to confirm that the electrical resistance of the anchorage-duct assembly is sufficiently high to be used for tendons of PL3. Another important aspect is to verify that the materials involved in the anchorage-duct assembly are long-term stable in alkaline environments. This concerns particularly eventual coatings on metallic surfaces of anchorage members.

The test specimen is an assembly of a piece of duct (>300 mm in length), trumpet / transition to anchorage, anchorage (bearing plate, anchor head and cap), connector between duct and trumpet with vent as applicable, any other component forming part of the anchorage-duct assembly or needed to provide electrical isolation. A steel rod is then installed and the nominal pre-compression between anchor head and bearing plate (1 kN total force or higher) is applied. The anchorage duct assembly is mounted upside down in a test frame and in a container (Figure 17).

Both the container and the inside of the anchorage-duct assembly are filled with an alkaline solution, namely buffered / saturated calcium hydroxide solution. During 28 days, the electrical resistance between the steel rod and the steel test frame is measured with an LCR

PTI/ASBI M50.3-12 [7] contains a few approval specifications. However, these were not intended for the EIT technology. Recommendations for approval testing are made in appendix B of this report.

Revised Draft

6 Detailing

Durability of post-tensioning systems is significantly affected by design, detailing, and quality of execution on-site. The main focus of this chapter is to outline good detailing practices that promote achieving complete encapsulation (electrical isolation) of the prestressing steel in EIT. Further details on good construction practice for durable post-tensioning tendons can be found in the literature, e.g. in *fib* bulletin no. 33 [5] and in *fib* bulletin no. 75 [13] and the references cited therein.

6.1 Detailing of EIT and PT components

6.1.1 Geometry

There are a few general aspects concerning the length of tendons:

- Long or coupled tendons are more difficult to monitor because they have inherently a lower electrical impedance than shorter tendons and thus, it is more difficult to detect ingress of moisture or chlorides at a defect (less pronounced decrease in resistance).
- Long or coupled tendons have a higher probability for defects (arising from handling on-site and applying the tensile force or from the coupling), particularly if they have numerous high or low points or other locations of high curvature.
- Long or coupled tendons are more susceptible to stray-current induced corrosion. The reason for this is that the probability for a sufficiently high potential gradient across a structure, leading to relevant stray current induced corrosion, increases with the length of the structure [11].

Proper detailing of the required tangent length in the tendon profile behind the anchorage is important. High curvatures or abrupt changes in curvature of the tendon (kink) should be avoided as these are locations of potential damage to the duct. Problems could arise at the anchorage head, for instance if the formwork is not perpendicular to the axis of the tendon, as schematically illustrated in Figure 19.

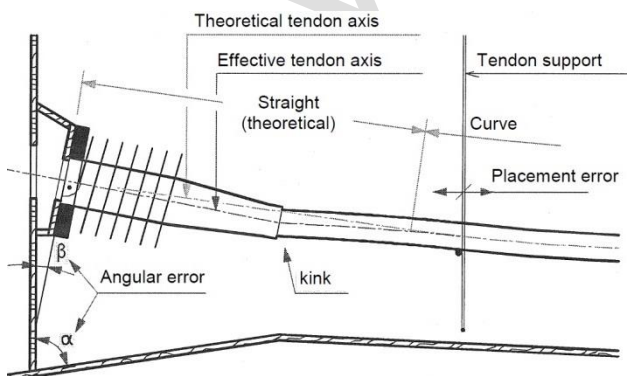


Figure 19. Example of unfavorable geometry: formwork not perpendicular to tendon axis leading to abrupt tendon curvature [3, 4].

Other examples are conflicts between reinforcing steel and tendon, such as when the tendon needs to pass around rebars. If such situations are not taken into account in the design/detailing stage, there is a risk that during execution on-site, the tendon is adapted, e.g. bent sharply around the reinforcing steel bars, which leads to locally high curvatures and thus a high risk of local damage of the duct during tensioning. It is thus important to ensure during detailing that the tendon axis is not in conflict with any reinforcing steel bars. In exceptional cases, this may be avoided by bending the rebars as shown in Figure 20.

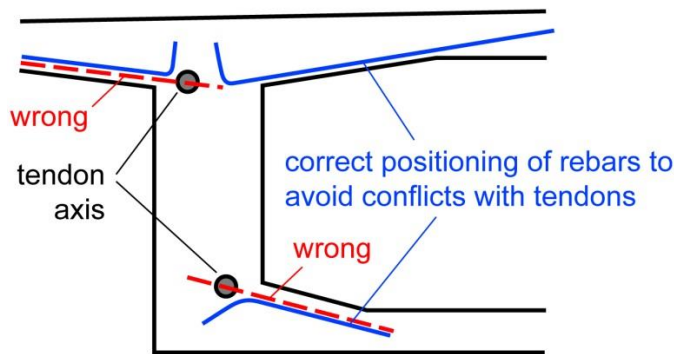


Figure 20. Example of unfavorable geometry: conflict between tendon and rebars (red dashed lines) and proper detailing (blue lines) [3, 4].

6.1.2 Duct

When installing tendons, particularly when applying the tension force, ducts may be indented at locations of high curvature on duct support bars. At such locations, it is necessary to place half-shells between the duct and tendon supports in order to protect the duct (Figure 21). In the Swiss guideline [3, 4], metal half-shells and steel tying wires are not allowed for PL2 and PL3.

The required number of protective half-shells depends on the duct type and the curvature. As a rule of thumb, one may consider that within curvatures with a radius up to twice the minimum radius of curvature of a certain tendon protective half-shells must be installed at every tendon support.

a)



b)



Figure 21. Protecting half shells to support the duct at high curvatures; a) metal half-shell and steel tying wires, b), plastic half-shell and plastic tying wires. Note that for PL2 and PL3, metal half-shells and steel tying wires are not allowed [3, 4].

6.1.3 Segmental duct coupler

When applying post-tensioning tendons in precast segmental bridge construction the match cast joint presents a zone of particular risk of corrosion for the tendon. Even if the match-casting technique is used – where segments are during prefabrication cast against the previous one so that the end face of one segment will be an imprint of the neighbor segment, thus claimed to ensure a perfect match –, and even if the joints are sealed with epoxy, the match cast joint may offer a preferential route for ingress of aggressive substance. The EIT technology offers thus particularly for this type of construction a major advantage. To guarantee the electrical isolation, special duct couplers have by various suppliers been developed for the joints. Figure 22 details examples available in the market.

Special tests for system approval have been devised in order to assess the quality of these important components of an electrically isolated PT system (see chapter 5.2). The Swiss Society of Corrosion Protection has experience, e.g. with a bridge in Geneva/CH passed by a DC powered tram and thus a concern of stray-current induced corrosion, where segmental duct couplers were applied and where this concept did not have significantly increased failures in meeting the requirements.

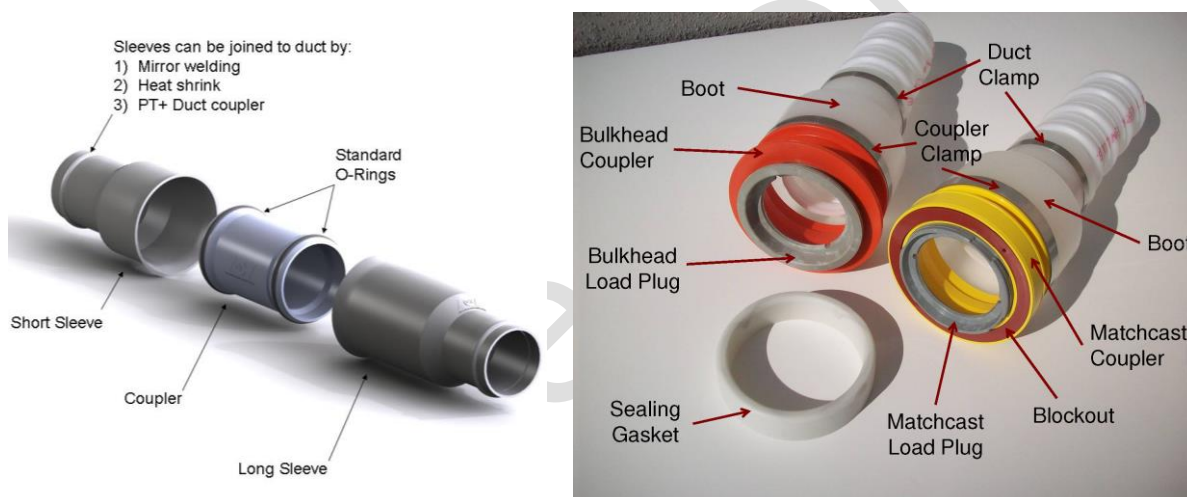


Figure 22. Left: Example of a segmental duct coupler (type 76, marketed by VSL); Right: example of a duct coupler made leak tight by a compressed seal in the joint (GTI Precast Segmental Duct Coupler).

6.1.4 Anchorage

To ensure complete isolation, the entire tendon anchorage must be isolated. This requires the isolation system to be integrated into the anchorage system, which is typically proprietary. Figure 23 shows an example of one such system, where a multi-strand tendon (3) is fixed in the anchor head (10) by wedges. The load from the anchor head is transferred to the cast-iron anchorage body (4) via an electrically isolating plate (5), typically made from fiber-reinforced plastic. Note that this crucial part ensures that the load is transferred to the anchorage body, which then transfers the load to the concrete, but at the same time, the anchor head (10) is electrically separated from the anchorage body (5). To ensure full encapsulation, the anchor head is also surrounded by a plastic protection cap (6). The cap is normally grouted to ensure corrosion protection. Also, the trumpet (2) continues inside the anchorage body (4) up to the isolating plate (5) to electrically isolate the strands from the

anchorage body. As an alternative to the cast iron anchorage body (4) shown in this example, it is also common to have a simple bearing plate.

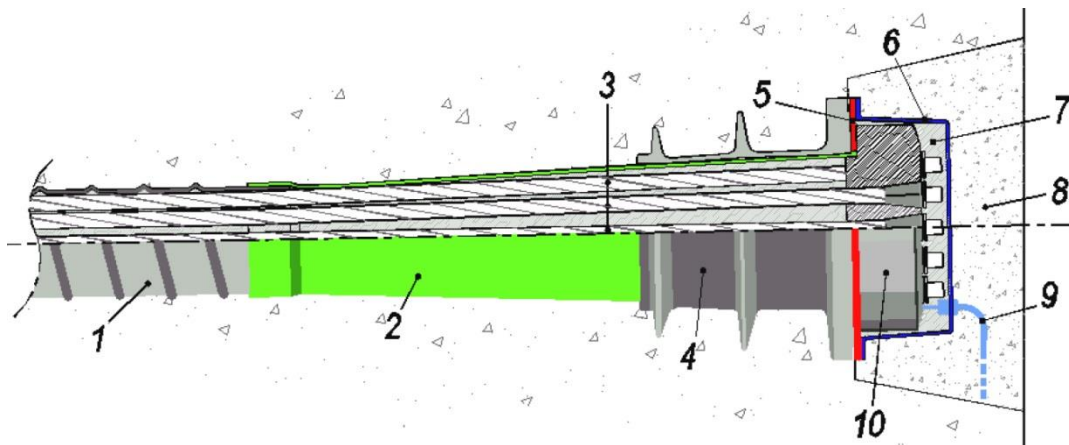


Figure 23. Schematic detail of the anchorage of EIT [14]. 1) plastic duct, 2) plastic trumpet (green), 3) strands, 4) cast iron anchorage body transferring the load from the anchor head to the concrete, 5) mechanically resistant, electrically isolating plate (red), 6) electrically isolating protection cap (blue), 7) grout in cap, 8) concrete, 9) measuring cable, 10) steel anchor head.

6.1.5 Remarks on transverse and vertical tendons

Most of the experience summarized in this report addresses longitudinal tendons. The EIT technology is, however, also applicable to transverse and vertical tendons. One difference, in some cases, may be that the installation of the measuring cables and junction boxes needs more attention or that the positioning of these to guarantee access in the future may be more difficult. With respect to possible stray current interference the shorter length of transverse and vertical cables typically reduces the risk stray-current induced corrosion. In short, all the beneficial effects associated with EIT apply also to transverse and vertical cables.

6.2 Installations for Electrical Resistance Measurements of EIT

To perform the measurement illustrated in Figure 9, electrical connections are required to both the prestressing steel in the tendon and the reinforcing steel in the concrete surrounding the tendon. The electrical connection to the tendon is typically made through one or both of the anchorages and to the reinforcing steel in a convenient location near the anchorage. In the following subsections, suggestions for EIT detailing and selection of materials as described in the Swiss guidelines [3, 4] are given.

6.2.1 Connections and measuring contacts for different situations

Ideally, a junction box with electrical terminals should be installed at both anchorages as illustrated in Figure 24. Electrical measurements can then be made independently from either anchorage. This ensures redundancy, for instance if one of the connections fails over time. In addition, having the possibility to electrically connect the tendon from both ends facilitates localizing defects in the duct (compare section 8.4).

If only one anchorage is to be connected with a cable, it is recommended that two anchorage cables be installed as shown in Figure 25, providing redundancy, should one of the two connections fail. For the reinforcing steel, redundant connections are considered less critical because it is comparatively easy to establish electrical connections to the reinforcing steel later (which is not anymore possible to the prestressing steel in EIT).

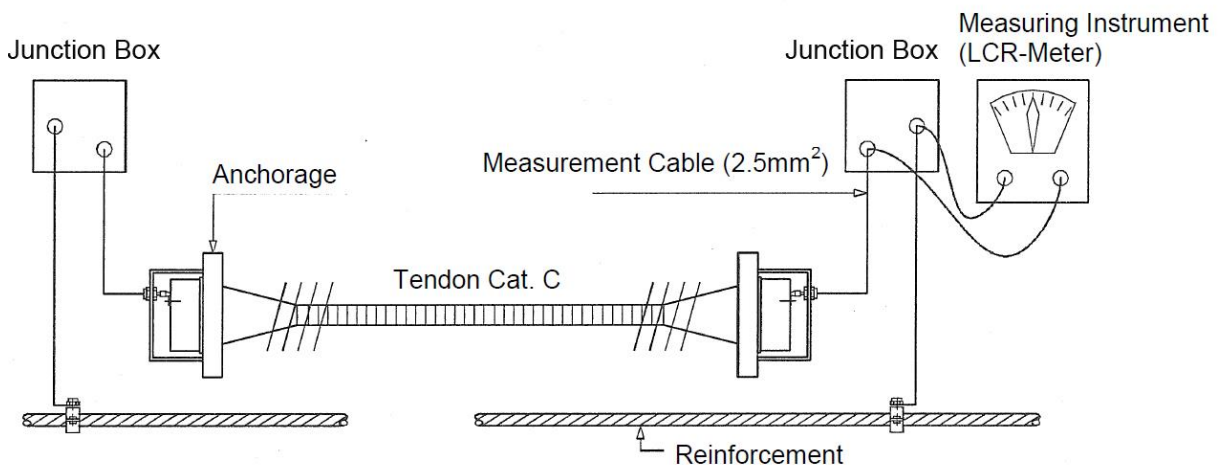


Figure 24. Electrical connections to the tendon at both ends [3, 4]

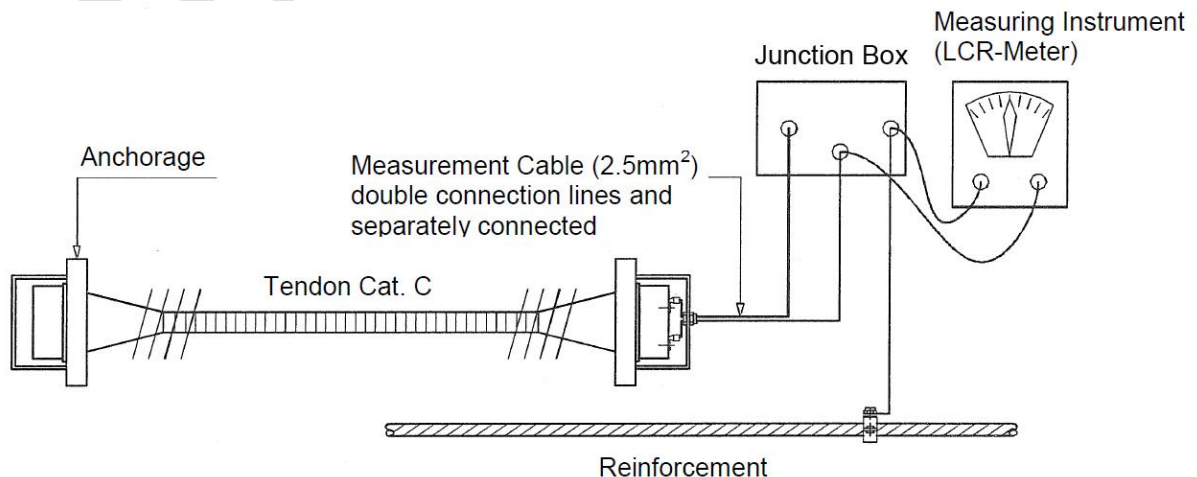


Figure 25. Electrical connections to the tendon at only one end [3, 4]

6.2.2 Special issues for stray-current induced corrosion

In conditions where stray-current induced corrosion is possible, the Swiss guidelines [3, 4] require a few additional provisions. Connections and installations shall be provided that allow connecting the tendon *at both ends* to the reinforcing steel, in case the EIT criteria (threshold values) are not fulfilled during quality control (see chapter 8). This minimizes the adverse effects of stray-currents, while maintaining the ability to perform electrical resistance measurements of the tendon.

Figure 26 shows a diagrammatic view of this requirement. It is also recommended to install so-called "longitudinal main conductors" in the bridge in order to guarantee longitudinal electrical continuity of the reinforcing steel mesh. It is recommended to have at least two of the "longitudinal main conductors" and to connect them to each other at least at both ends with help of "transverse main conductors"; additionally, they must be connected to the reinforcing steel. These longitudinal and transverse main conductors are usually reinforcing bars with large cross section (e.g. 40 mm in diameter). Finally, the "longitudinal main conductors" must at both ends be connected to the prestressing steel.

Connection boxes should be placed to minimize the length of the cable connected to the longitudinal main conductor. Electrical connections from the tendon to the connection box shall also be provided at both ends. To permit measurements, the cables coming from the tendon and from the longitudinal main conductor should at one end of the tendon also be connected with a junction box for measurements as shown in Figure 26. To prevent ohmic potential drops, increased cross sectional areas for the wiring is recommended [3, 4] (Figure 26).

If the measured electrical resistances are below the threshold, stray current induced corrosion can be minimized by *permanently* grounding the tendon to the longitudinal main conductor *at both ends*. During AC impedance measurements, however, this connection should be temporarily removed.

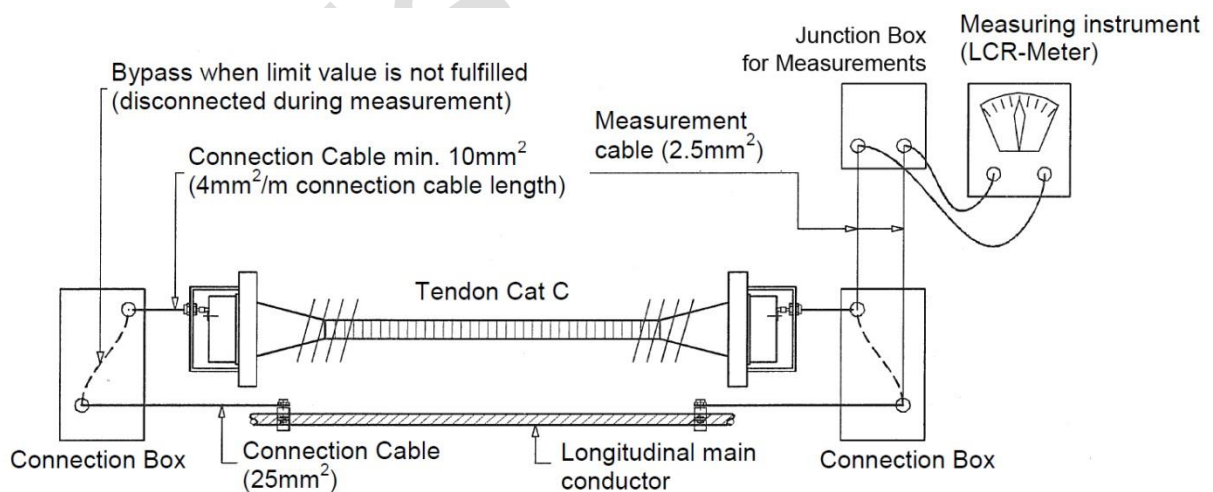


Figure 26. Electrical connections to the tendon and installations in the case of a risk of stray-current induced corrosion [3, 4]

6.2.3 Cables and electrical connections

All cables used for the electrical measurements should be copper cables with a minimum cross sectional area of 2.5 mm^2 [3, 4]. Cables used to ground stray-currents should have a larger cross section, as indicated in Figure 26. All cables should have a water-proof insulation. When embedded in concrete, they must also be able to resist the alkaline environment. Alternatively, the cables may be placed in non-conductive electrical conduits (plastic tubes). Guidelines [3, 4] do not specify the type of copper cables. However, particularly with respect to the resistance against alkaline environment, we suggest to preferably use solid wires rather than multistrand cables.

The recommended method of establishing electrical contact to a tendon is at the anchorage by means of bolted cable strap [3, 4]. For the electrical connection, galvanized conductors and contact bolts should not be used. It is important that the connection is made between bare metallic surfaces and that no rust layers are present; any eventually present rust layers need thus to be removed prior to establishing the connections.

After installation of connections and cables, the electrical connections shall be checked for continuity by appropriate electrical measurements.

6.2.4 Junction box for measurements

The purpose of the junction box is to collect all measuring cables in one place that is easily accessible to personnel performing the measurements for monitoring during the service life of the structure. The box also serves as protection of all connections from weather and mechanical damage. The junction box must be provided with an air ventilation opening protected with anti-insect mesh at the lowest position of the box.

The measuring cables should be soldered to the socket and sealed permanently with heat shrink tubes. All connection sockets must be adequately labeled in the junction box with a reference to which tendon the measurement cables are connected to [3, 4].

7 Execution

7.1 Transport and storage

Metallic components

Materials prone to corrosion damage – prestressing steel, steel ducts, anchorage components, couplers, etc. – should be protected from corrosive influences during transport and storage, and also for the time when placed in the structure prior to permanent protection. Depending on the exposure environment and the duration of these stages, it may be needed to apply temporary protection measures. In this respect, application of suitable water soluble oils is recommended [5].

Plastic ducts

Plastic ducts are an important part of EIT as they ensure the leak-tight encapsulation of the tendon over its length. They are particularly susceptible to damage during transport, storage and handling (Figure 27). Plastic ducts and other components of the encapsulation must thus be carefully handled and stored in clean environments in order to avoid damage [13].

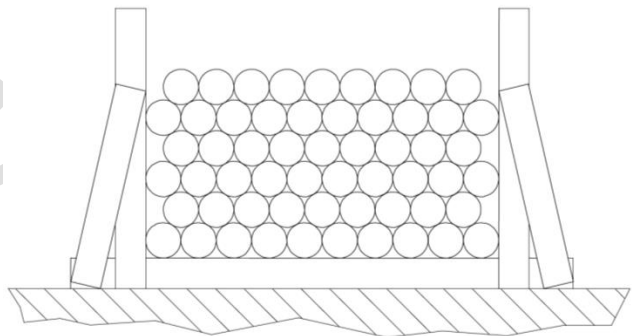


Figure 27. Left: Example of improper storage of plastic ducts leading to defects [3, 4]; right: sketch of proper storage of ducts [15].

7.2 Installation on-site

The quality of the execution on-site is absolutely crucial for the technology of EIT to be successful. Hence, post-tensioning systems should be installed only by specialized companies that are capable of documenting corresponding experience and have suitably trained (eventually certified) personnel. These companies should have a quality plan, adapted to the size and importance of the project, which describes all key processes such as duct placing, tendon installation, stressing, and application of the permanent protection. During execution, these processes should be supervised by a qualified supervisor. Installation on-site must be done in accordance with the general procedures defined by the system supplier.

Fib bulletin no. 75 [13] suggests a meeting between all parties involved in the construction before starting installation of PL2 and in particular PL3 tendons to ensure that all relevant information is shared with all parties and all interfaces are well covered.

Installation of tendons

Post-tensioning tendons and components should be placed (and secured) in accordance with the general instructions by the system supplier, the quality plan for the actual project, and the shop drawings based on proper detailing (see chapter 6). Special attention should be paid to locations of high duct curvature, where protective plastic half-shells are installed in order to avoid damage of the duct due to indentation at reinforcing steel bars (Figure 21). As a rule of thumb, one may consider that within curvatures with a radius up to twice the minimum radius of curvature of a certain tendon protective half-shells must be installed at every tendon support. A sufficient number of vents should be provided, i.e. at both duct ends and at any locations where accumulation of water/air is expected. These vents should be properly marked. During construction, the vents should be sealed to avoid penetration of moisture.

Note that leaving prestressing steel inside ducts without temporary or permanent corrosion protection for extended time has been reported to potentially lead to durability problems [5]. The time should thus be kept as short as possible. If longer exposure times cannot be avoided, application of temporary corrosion protection (e.g. water soluble oils or blowing of dry air) should be considered.

Once polymer ducts are installed and fixed in the reinforcement steel cage, exposure to sunlight and UV radiation may cause damage [13]. If subjected to high daily temperature variations (enhanced by sunlight- and UV radiation-related heating of ducts, particularly of dark color) the confined expansion/contraction can impair the leak-tightness of the system. Attachments of the ducts to the supports, connections and couplers in segmented ducts and at the anchorages need to be able to resist expansion and contraction without failure.

Injection of tendons (grouting)

The injection of tendons with cementitious grout is an important process in order to achieve a durable post-tensioning system. Thus, it should be under the responsibility of experienced and trained (certified) grouting personnel.

Before grouting, the position of vents should be checked. Typically, grouting is done from one tendon end until grout leaves the duct at the first vent. The vent is then closed and grouting continued, etc. until the last vent and finally the inlet are closed. Note that after grouting, inlets and vents can potentially create an electrolytic connection to the concrete and thus decrease the electrical resistance of EIT. To avoid this, inlets and vents must be

properly sealed with leak-tight plastic caps (Figure 28). Vacuum-assisted injection may be used to reduce the number of vents.

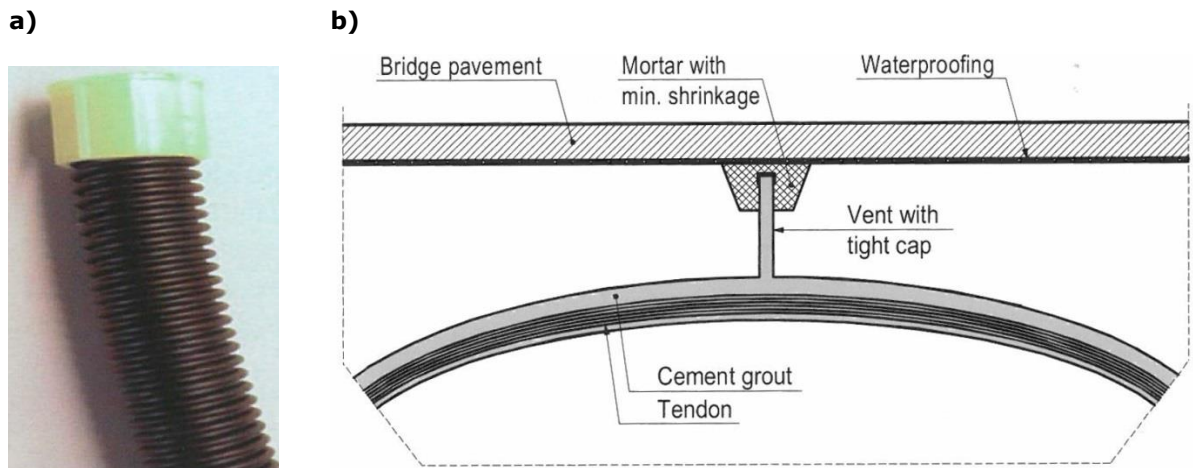


Figure 28. Details at vents (from [5]): a) plastic hose with leak-tight plastic cap; b) schematic illustration of durable sealing of a vent at a high point.

8 Quality Assurance and Control – Initial EIT Measurement and Long-Term Monitoring

The durability of the electrically isolated post-tensioning system is significantly affected by detailing, design, and the quality of the execution on-site. It is thus an important advantage of EIT that their quality can be checked and that their condition can be monitored with non-destructive measurement methods (see section 3.2.3).

The necessary measurements need to be specified by the owner both

- in the quality plan, used during the construction phase
- in the surveillance plan, used for the service life of the structure.

Both the quality plan and the surveillance plan should be adapted to the size and importance of the project. These plans should describe the measurement methods, test equipment, measuring points, and acceptance criteria to meet the project requirements.

As mentioned earlier, to simplify matters, the AC impedance measurements will be referred to as “electrical resistance measurements”, which is also the common term in Refs. [2-5]. This may be justified by the fact that the ohmic resistance is the main component of interest of the measured AC impedance.

8.1 Results of AC Impedance Measurements of EIT

The principle of the measurements that can be performed on EIT was briefly explained in section 3.2.3. Details about the measuring instrumentation can be found in the appendix.

8.1.1 Basic Parameters

When performing AC impedance measurements on an EIT, a measuring instrument (appendix) will typically display ohmic resistance R , capacitance C , and loss factor D . These have the following meaning:

- Resistance R

Resistance R is defined as the ohmic resistance between the prestressing steel and the reinforcing steel in the surrounding concrete. This gives an indication of the number and size of defects in the duct (Figure 10b). Measurements in well-controlled experimental research have shown that defect-free plastic ducts (\varnothing 59 mm, 1 m long, embedded in concrete) have extremely high ohmic resistances (>2.3 M Ω), even at welded or coupled joints. A single 2-mm diameter perforation, however, will cause a decrease in R to values below 100 k Ω [9, 16].

In practice, where the tendon length is variable, it has to be considered that the measured resistance R decreases also with increasing length of a duct (directly proportional relationship). Thus, the length of a tendon is an important parameter. Low values of R may not always indicate the presence of perforations, but may also arise from high tendon lengths.

- **Capacitance C**

Capacitance C is understood as the capacitance of the plastic duct. The capacitance is significantly affected by dielectric properties, diameter, and wall thickness of the duct. For a duct of length L, the capacitance may be computed as follows:

$$C = 2\pi L \varepsilon_0 \varepsilon / \ln(r_o/r_i) \quad (1)$$

Here, ε_0 is the permittivity of free space, ε is the dielectric constant of the duct material, and r_o and r_i are the outer and inner duct radii, respectively. Thus, C decreases with increasing wall thickness, and for a given wall thickness, C increases with increasing duct diameter.

However, the capacitance is virtually unaffected by the absence or presence of duct perforations.

In practice, where the tendon length is variable, it has to be considered that the capacitance of a given duct type increases proportionally with the duct length.

- **Loss factor D**

Loss factor D is defined as the ratio of the real and imaginary component of the impedance:

$$D = \frac{Re(Z)}{Im(Z)} = \frac{|Z|\cos\varphi}{|Z|\sin\varphi} = \frac{1}{\tan\varphi} \quad (2)$$

Here, φ is the phase angle between the voltage and the current signal, and $|Z|$ is the magnitude of the impedance (Ω). In a parallel equivalent circuit of R and C, the real and imaginary parts of the impedance are:

$$Re(Z) = \frac{R}{1+(\omega RC)^2} \quad (3)$$

$$Im(Z) = -\frac{\omega RC}{1+(\omega RC)^2} \quad (4)$$

Here, ω is the angular frequency. Thus, the loss factor can be written as:

$$D = \frac{Re(Z)}{Im(Z)} = -\frac{1}{\omega RC} \quad (5)$$

The loss factor D has no unit and it is independent of the length of the tendon. However, D depends on the number of defects in the duct, i.e. the magnitude of D increases with increasing number of defects. This is because the presence of defects has a negligible effect on the capacitance of the duct, but strongly decreases R. For a given frequency, a decrease in R while C remains constant yields an increase in D (compare eq. (5)).

8.1.2 Influencing Factors

Influence of tendon length

Since R and C are influenced by the tendon length, L , it must be taken into account by computing specific values:

Specific resistance (per unit length) $R_l = R \cdot L$ (unit Ωm)

Specific capacitance (per unit length) $C_l = C/L$ (unit F/m)

These specific values will finally be those compared to specified limiting values as discussed in sections 8.2 and 8.3.

Influence of EIT components

The measured impedance is the result of all components present in the system. The resulting electrical resistance may be regarded as the resistance of an equivalent electrical circuit similar to those shown in Figure 10. The following influences must thus be considered when interpreting electrical resistance measurements:

- The **duct type** affects the capacitance of the duct. As is apparent from eq. (1), the duct diameter, the wall thickness and the dielectric properties affect the capacitance of a certain duct (per unit length). Thus, no unique criteria for C can be given.
- **Anchorage**s have inherently a limited electrical resistance. This affects the measured resistance primarily at short tendon lengths.
- Also **duct couplers** and **tendon couplers** have usually a lower electrical resistance than a part of the tendon without these coupling devices. The extent to which a duct coupler decreases the electrical resistance typically correlates to the duct diameter, because the welding seam (or similar) presenting a potential weak zone is longer on larger ducts.
- **Injection inlets** and **vents** may, if not properly sealed, decrease the electrical resistance of the EIT. In addition, parts of the tendon with vents have typically a higher capacitance than uncoupled parts of the tendon.

Influence of defects

- The number and size of **duct perforations** have mainly an influence on the electrical resistance, but not on the capacitance. The larger the size of perforations and the higher their number, the lower becomes the measured resistance.
- **Metallic contacts** at perforations (reinforcing steel in contact with prestressing steel) strongly depress the electrical resistance. Values of R (not related to the tendon length) lower than approx. 10 or 20 Ω have been found to indicate the presence of such a metallic contact [2-5].

Effect of cementitious materials and exposure conditions

The specific electrical resistance of the grout in the duct and of the concrete surrounding the tendon also affect the measured electrical resistance. These depend on material properties

(e.g. type of cement, w/c ratio, mix proportions), on the degree of hydration or on the age, and on exposure related conditions such as the degree of saturation, temperature, etc.

Electrical resistance measurements are typically performed at 28 days after grouting, but if they are performed at a different age, the time effect needs to be taken into account. This is because the cement hydration continuously increases the electrical resistivity of the grout. The following equation has been proposed for converting the resistance R_t , measured at time t (age of the grout in days = time after grouting), to R at 28 days [3, 4, 10]:

$$R = R_t \cdot \sqrt{28/t} \quad (6)$$

As an example, to convert the resistance measured after 14 days to the age of 28 days, the measured value is to be multiplied by a factor of $\sqrt{28/14} = \sqrt{2}$.

Temperature strongly affects the resistivity of mortar and concrete, and suggestions are made in the literature to correct resistance measurements performed at a certain temperature to a reference temperature, e.g. Refs. [9, 17].

Nevertheless, in practice, the local temperature inside the concrete of a structural member is often unknown. It is also likely spatially variable, e.g. over the tendon length. In recognition of these difficulties for temperature corrections, the approach suggested in the Swiss guideline [3, 4] is thus not to correct any temperature effects. To reduce the error, it is recommended to perform measurements only within a pragmatic range of ambient temperatures. In a range of 10 to 30 °C, for instance, the temperature can induce deviations for resistance measurements of up to 30%. A possible strategy to reduce temperature effects may be to carry out the measurements always during the same season and/or the same time of the day.

8.2 Quality Assurance and Quality Control

During construction, electrical resistance measurements can serve as quality assurance and control measure. It is a useful tool for owners and contractors to check whether the needed quality is achieved or not.

The extent and the sequence of the measurements for the execution phase has to be defined in advance.

There are primarily two stages in the process of installing EIT, where electrical resistance measurements are performed:

- Immediately after post-tensioning, but before grouting.
- 28 days after grouting.

8.2.1 Before Grouting

During post-tensioning, the strands move relative to the plastic duct, which can gouge the inside of the ducts (wear damage). If not properly installed the duct may be damaged at locations of high curvature (e.g. high or low points) severely enough such that the prestressing steel is in direct contact with reinforcing steel. Metallic contacts may also arise at the anchorages, e.g. due to improper installation of the anchorage head.

Such direct contacts tendon/anchorage-reinforcing steel can easily be detected by performing electrical resistance measurements after tensioning, but before grouting. The reason is that such metallic contacts strongly depresses the electrical resistance and that the absence of grout does not yet blur the results. Values of R (not related to the tendon length) lower than approx. 10 or 20 Ω have been found to indicate the presence of such a metallic contact [2-5].

In order to check the effect of the tensioning process, one may also perform electrical resistance measurements prior to the first and after the last step of applying the tension force.

Electrical contacts or short circuits identified at this stage can be located (if necessary) [2-5]. For a description of the methodology it is referred to section 8.4. Some defects may be tolerable, e.g. when the failure rate is below a specified threshold value. Repair of defects is not typically recommended because repair work may cause additional damage and further decrease the durability of the structure. Nevertheless, identifying and locating the defect position may be relevant for later assessment of the structure.

Note that the parameters C (capacitance) and D (loss factor) have at this stage no meaning, because there is no grout yet in the duct. It may also be worth mentioning that due to the absence of grout in the duct, it is virtually impossible to detect perforations in the duct, where no metallic contact between prestressing steel and reinforcing steel is present. This is only possible after grouting.

8.2.2 After Grouting

In Switzerland, the electrical resistance measurements must be performed after grouting, preferably 28 days after injecting grout. At this stage, the measurement allows assessment of the leak-tightness of the tendon encapsulation, and thus the quality of the installation. If no measurements were performed prior to grouting, it will also be possible to detect metallic contacts as described above (i.e. if $R < \text{ca. } 20 \Omega$). However, if such metallic short circuits are present, they will completely dominate the results and no other imperfections,

such as perforations in the duct where no metallic contact of the tendon and the reinforcing steel occur, can be detected. This would only be possible after the metallic contact / short circuit has been eliminated (compare previous section).

Assuming that no metallic contacts between prestressing steel and reinforcing steel are present, the AC impedance measurement can be used to assess the quality. In the latest Swiss guideline [3, 4], the threshold values shown in Table 2 have been stipulated.

Note that only threshold values for the resistance R are given in [3, 4], but that no values were given for C (capacitance) and D (loss factor). The reason for this is that C and D are influenced by the type of the duct (different for different products from different suppliers). However, if the requirements of R are not met, parameters C and D may give useful information for the interpretation of the measurements and indicate possible measures. It is Swiss practice to declare the actual values of C and D of a specific polymer duct system in the PT system documentation.

As a side comment, it may be worth pointing out that in the first version of the Swiss guideline [2], issued in 2001, limiting values were also tabulated for C and D (accordingly, such a table can also be found in *fib* bulletin no. 33 [5]). These values, however, were valid only for a certain duct type ("PT-PLUS"). At that time, this was the only commercial product for which the values had been experimentally determined [9]. Applications in Switzerland and northern Italy have shown that the values specified in the first version of the Swiss guideline [2] can be achieved in practice. For instance, during quality control of the EIT installed in the Piacenza viaduct on the Milano-Bologna high-speed railway line, the average measured capacitances were >70 nF/m for ducts of diameter 76 mm and 100 mm, and thus clearly above the specified values 2.2 nF/m ($\varnothing 76$ mm) and 2.3 nF/m ($\varnothing 100$ mm) [16, 18]. Nevertheless, the revised version of the Swiss guideline [3, 4] does not contain specific limiting values for C and D anymore due to the reasons given above.

Table 2. Threshold values for EIT, applicable 28 days after grouting (according to the Swiss guidelines [3, 4]).

Duct \varnothing	Main criterion		
	Monitoring	Fatigue	Stray current ²
	Specific resistance ¹ $R_I = R \cdot L$	Resistance R	Specific resistance ¹ $R_I = R \cdot L$
60 mm	>50 k Ω m	>20 Ω	>250 k Ω m
75 mm	>50 k Ω m	>20 Ω	>200 k Ω m
100 mm	>50 k Ω m	>20 Ω	>150 k Ω m
130 mm	>50 k Ω m	>20 Ω	>125 k Ω m
Max. tolerable failure rate	10%	0% ³	20%

¹ To convert the measured resistance R to R_I , R needs to be multiplied with the tendon length L , where the value used for L must be at least 25 m.

² In the case of a risk of stray current induced corrosion, in addition a National guideline issued by the Swiss Society for Corrosion Protection [11] needs to be considered.

³ At sections where the fatigue loading is critical, the acceptable failure rate is zero.

The different scenarios *monitoring, fatigue, and stray currents*

Table 2 differentiates between three situations, i.e. *fatigue*, *monitoring*, and *stray currents*. Note that the differentiation between these three scenarios in the Swiss approach has proven useful for the specific conditions in Switzerland, but obviously, in other countries, other scenarios may be more appropriate for quality assurance and quality control in the corresponding situation of construction practice. The threshold values given in Table 2 are the result of a consensus reached between the different interest groups involved in preparing the Swiss guidelines. It is again pointed out that for other countries, differences in construction practices (e.g. segmental bridge construction, which is uncommon in Switzerland) and policies (e.g. risk considerations) may justify devising different threshold values.

According to the Swiss guidelines [3, 4], if *fatigue* is the primary concern, the absolute resistance is considered and the threshold values apparent from Table 2 indicate that the main goal of the measurement is to check that there are no metallic contacts between prestressing steel and tendon support bars or reinforcing steel of structure. Accordingly, the threshold value is independent of the tendon length.

However, when the main criterion is *monitoring* and *stray current*, the threshold values take into account the length of the tendon.

Concerning *monitoring*, the main idea is to follow the electrical resistance of ducts with defects. The criteria given in Table 2, given that they are met, ensure a minimum quality of the encapsulation, but at the same time tolerate some minor defects or imperfections. Additionally, by requesting a certain minimum specific resistance per unit length at the time of construction, it will be easier to detect potential risks caused by ingress of moisture or chlorides through a defect in the duct at later stages in the service life. This is because a relatively high initial resistance will later be depressed more significantly upon arrival of moisture or chlorides than an already initially low electrical resistance.

With respect to a *stray current-induced corrosion* risk, even more strict requirements are defined in the Swiss guideline [3, 4] (Table 2). In order to minimize the risk of *stray current-induced corrosion*, it is imperative to have as few as possible defects in the duct, because each of them presents a pathway for the *stray current* to enter/leave the tendon and cause damage. Additionally, the risk of *stray current-induced corrosion* can be further minimised by using short rather than long tendons or coupled tendons (compare section 6).

8.2.3 Acceptable Failure Rate

In order to ensure smooth progress and to avoid problems, it is recommended to define the acceptable failure in advance, and also to clearly define the consequences of not meeting the specified threshold values and acceptable failure rates. The latter may include the need to localize the defects (compare 8.4) in order to decide whether these are a systematic problem (e.g. always at high points, couplers, etc.), whether the location of a defect is particularly critical (e.g. a metallic contact at a section of critical fatigue loading), etc.

Experience in Switzerland has shown that it is not practical to require 100% of the tendons to fulfil the requirements. Based on the experience with anchors a value of 90% was introduced, i.e. 10% acceptable failure rate for the scenario *monitoring* (Table 2). It has to be considered that an EIT with lower insulation values still shows significant benefits with respect to corrosion protection compared to non electrically insulated tendons (see chapter 3.2).

The acceptable failure rate may also be affected by the purpose of the tendon. An example are cantilever post-tensioning tendons that are excessive due to the construction method and the actual in-service requirements are reduced. Another example are tendons where the scenario stray-current induced corrosion is of concern. In this case, a higher failure rate may be acceptable, because the risk of stray-current induced corrosion can be minimized by connecting the tendon *at both ends* to the reinforcing steel (see section 6.2.2).

8.2.4 Applicability of the Swiss Criteria to Other Regions

The threshold values summarized in Table 2 were defined based on experience made in central Europe, primarily Switzerland and Northern Italy. The ambient temperature lies typically in the range of 0–30 °C and the relative humidity is around 60–80%. For structures in other regions in the world, particularly in much warmer and drier climates, the Swiss threshold values may need to be adjusted (probably more strict requirements) in order to permit detecting perforations in the duct. The range of possible temperatures is in the United States larger than in central Europe and thus, it may also be necessary to take the temperature explicitly into account for measurements and acceptance criteria. This could mean to give guidance on how to correct for temperature differences, e.g. back calculating to a certain reference temperature, or to define different acceptance criteria for different temperature regimes.

Structures in marine environment may also need different threshold values. Finally, structural members in partial or continuous immersion are also expected to exhibit electrical impedance values on a markedly different level than structures in Switzerland.

8.2.5 Other approaches for quality assurance/control

The Swiss Society for Corrosion Protection (SGK) has developed a sensor [19] that can be embedded in the grout inside a tendon at critical locations (such as highpoints, inclined sections of the tendon, and anchorages). The system detects insufficient alkalinity and chloride contamination of the grout during the filling process with in a very short measuring time (ca. 20 s). Moreover, it allows the detection of bleeding water (e.g. in the case of segregation of the grout). Hence, controlling the presence of grout with sufficient passivating properties is possible in critical sections of the tendon, allowing for maximum quality control during installation. This system may also be applied if problems related to “soft grout” are suspected.

The approach is to apply first a current of -2.5 mA/cm^2 to a small carbon steel surface. This current causes a shift of the sensor potential in cathodic direction, the reduction of oxygen, the evolution of hydrogen, and the removal of any residual passive film on the sensor surface. This first step creates well defined starting conditions and eliminates the previous history of the sensor. Subsequently, a current of $+2.5 \text{ mA/cm}^2$ is applied to the sensor for another 10 s, which forces the formation of a passive film on the sensor surface. After about 3 seconds passivation is complete and oxygen evolution occurs. If the pH is too low and/or if the chloride concentration in the grout is too high, passivation and oxygen evolution is not reachable, which permits identifying critical conditions.

Measuring the kinetics of the potential increase during anodic polarization, once the grout has hardened, further allows distinguishing between a situation where convection is possible (bleed water in contact with the sensor surface) and a situation where convection is restricted (solid, porous grout in contact with the sensor surface). Thus, the presence of solid grout or simply alkaline bleed water at the sensor surface can be detected and permits identifying possible problems due to segregation/separation of the grout.

The sensor system is described in detail in Ref. [19].

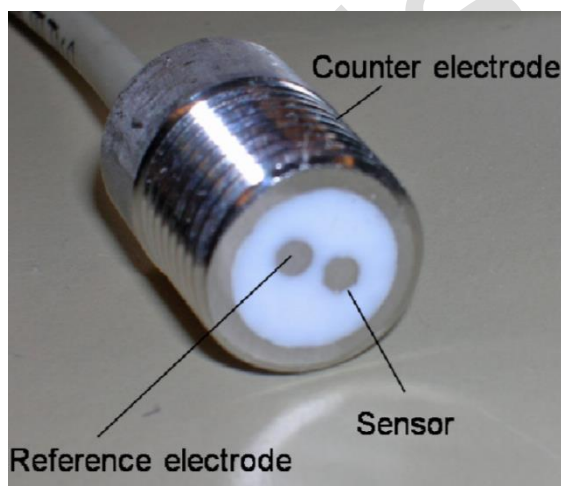


Figure 29. Sensor developed by SGK to non-destructively assess the quality of the grout filling inside a duct [19]. See text for explanations.

8.3 Long-Term Monitoring

The main goal of long-term monitoring during the life of a structure is to detect ingress of moisture or chlorides through defects in the encapsulation into the tendon early, i.e. before they can cause any damage to the prestressing steel. This is possible by performing electrical resistance measurements over time and evaluating the change in measurement rather than the absolute value.

In principle, the ohmic resistance of a tendon with perforations should increase over time due to continuing cement hydration of the grout and the concrete surrounding the duct. An example of field data that illustrates this is shown in Figure 30a. While the six measured tendons show a certain scatter, the overall trend is an increase in resistance with time. When the logarithm of the resistance is plotted vs. the logarithm of time, this corresponds to a straight line with slope 0.5 (unit decade/decade). This result may be interpreted as all six tendons being well encapsulated and protected, i.e. no ingress of humidity or chlorides into the tendon encapsulation or neighborhood of defects in the encapsulation.

Figure 30b shows another example of field data of long-term monitoring of EIT. In this case, due to the larger scatter between the individual tendons (among other reasons because of the differences in duct diameter), the results were normalized with respect to the value measured at 28 days after grouting. Again, there is a trend with a slope close to 0.5 in the plot logarithm of the resistance vs. the logarithm of time for most of the tendons. For one tendon, however, the resistance starts decreasing after ca. 1 year, which indicates the ingress of water or chlorides at the defect, which may potentially harm the prestressing steel by inducing corrosion (see section 3.2.1). It has to be mentioned, however, that a sudden decrease in electrical resistance after a certain time may also be related to causes other than ingress of moisture/chlorides through an existing perforation. Examples in this regard are infiltration of moisture into measuring cables or creep of the plastic duct under high local loads such as at tendon supports, leading to a perforation after extended time.

Nevertheless, long-term monitoring of the electrical impedance of EIT is an early warning system to detect a corrosion risk. Once such a risk is detected (as in the example shown in Figure 30b), an owner can initiate additional investigations to assess the risk for the structure given the specific conditions and to plan eventual rehabilitation measures.

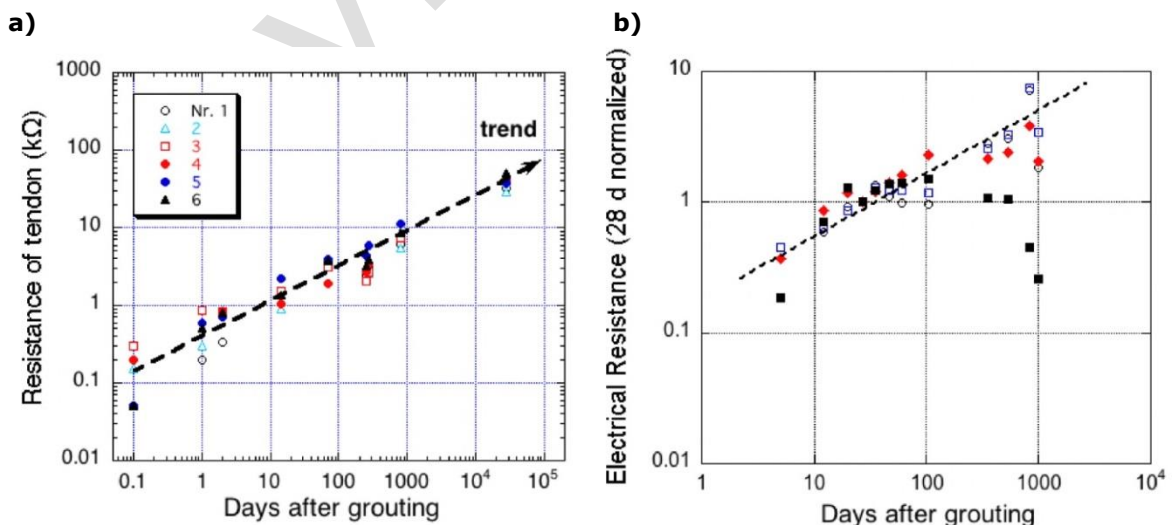


Figure 30. Electrical resistance of EIT over time [10, 16], a) measurements for 6 EIT in the bridge "Pré du Mariage" in Switzerland, duct diameter 76 mm, tendon length 49.3 m; b) measurements for 4 EIT in the bridge "Muhen" in Switzerland, duct diameter variable, tendon length 23 m.

8.4 Localizing Defects

8.4.1 Incomplete filling of the duct (grout voids)

AC impedance measurements

In a laboratory study performed at ETH Zurich, Switzerland, different situations of incomplete duct filling by grout were investigated [10, 20]. The aim of the work was to study whether it is possible to detect grout voids based on AC impedance measurements. This would be beneficial because, AC impedance measurements are part of the quality control and monitoring of EIT.

Plastic ducts (of 1 m length) were either only filled over 50% of their length or 50% of their cross section (only lower half of the duct cross section), respectively, and compared with completely filled ducts. The partial grouting resulting in a lower surface area of the duct being in contact with grout. A reduction in area directly affects the capacitance. Thus, for both studied situations of only 50% of the duct volume filled with grout, a reduction of the capacitance by 50% was expected in comparison to the completely grouted duct. This was indeed confirmed by the AC impedance measurements.

While it was concluded that capacitance measurements allow in principle distinguishing between completely and incompletely grouted plastic ducts, the following concerns were highlighted for practical applications:

- Due to the direct proportional relationship between the capacitance and the inner surface area of the duct in contact with grout, small ungrouted fractions of the duct surface lead to small reductions in capacitance (compared with a fully grouted duct). As an example, a void of 1 m length in a duct of 100 m length, decreases the capacitance by only 1%. Considering the limitations of measurement precision, this is too small to permit reliable detection of voids under practical conditions.
- The capacitance is an integral result, thus it does not permit distinguishing between a situation with one large void and situations with several smaller voids (given that the sum of ungrouted duct surface area is the same in all these situations). Furthermore, the AC impedance measurements do not permit determining the location of grout voids.

Thus, detecting and localizing grout voids as part of the AC impedance measurements routinely used on EIT, seems not possible in practice.

Other methods

Alternative methods are available, but these require specialized equipment and access to concrete surfaces of the bridge where measurements are of interest. Thus, although, such methods are non-destructive, their application implies relatively high costs. They are thus not suitable for routine quality control, but are commonly applied in the context of condition assessment of existing, aged structures.

Positive experience in localizing grouting defects have been reported particularly for ultrasonic or impact-echo methods, primarily from Germany [21, 22]. In addition, also radiographic methods are known (commonly termed "gammagraphy"), but these obviously demand strict application of radiation protection and safety procedures. For a more detailed description of these alternative methods, which are not directly related to the technology of EIT, but applicable for post-tensioned structures in general, it is referred to the literature. An overview can be found in Ref. [23].

8.4.2 Perforations in the Duct

The methodology of localizing perforations in the duct is described in detail in Ref. [10]. Here, the technique is only briefly summarized.

Using the electrical connections provided for the impedance measurements, an AC voltage can be imposed between the prestressing steel and the reinforcing steel (Figure 31a). This results in an AC current flow through the system and in a magnetic field. To minimize the energy, the AC current will attempt to keep the loop as small as possible, thus the current will leave the tendon through the first defect and return through the reinforcing steel cage back to the location where the AC signal is fed into the system. Due to the strongly confined AC current flow in the tendon, a relatively well-defined magnetic field is established around the tendon (Figure 31b). At a defect, such as a metallic contact between prestressing and reinforcing steel, the AC current loop is closed and in the further part of the tendon, no AC current is present (Figure 31a). Ideally, the magnetic flux completely vanishes at the defect. Measuring this magnetic flux along the tendon thus permits locating the defect. It is required to also consider the variable distance between the device measuring the magnetic flux and the tendon axis – due to the geometry of the tendon (high points, low points, accessibility, etc.) – because this affects the magnitude of the magnetic flux.

Note that a limitation of this method is that in principle, only one perforation can be localized, namely the one with the smallest impedance. The reason is that after this, the magnetic flux vanishes and the remaining part of the tendon cannot be assessed with this measuring method. The situation can be improved if the tendon can be electrically contacted at both its ends (compare section 6.2), thus the AC signal can be injected from both ends. In this case, localizing defects can be done from both tendon ends, which improves the detection rate of the method.

In some cases, the magnetic flux does not completely vanish at a defect, but is only reduced. Based on this, an assessment of at least part of the remaining tendon length can be done.

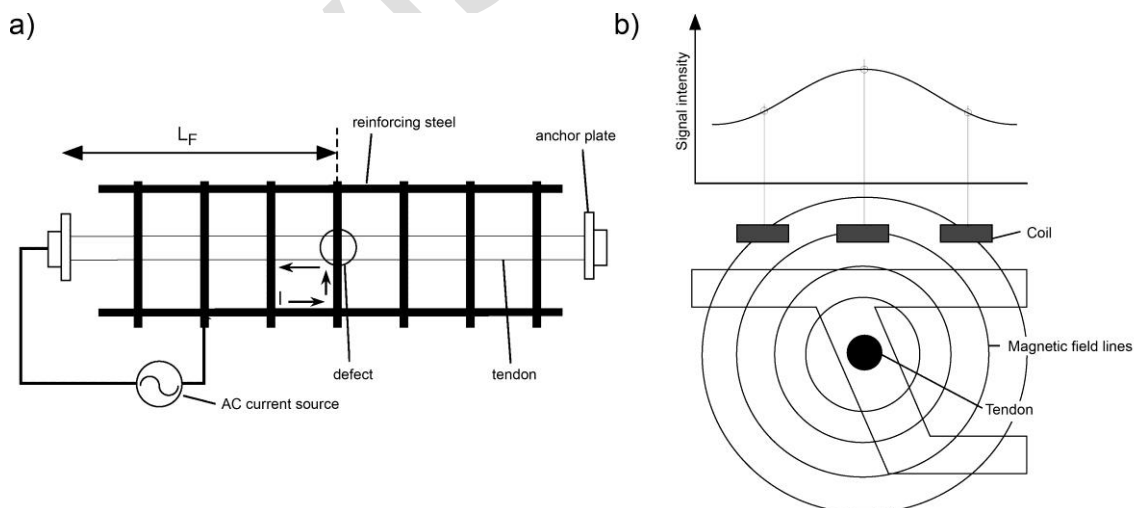


Figure 31. Localizing defects such as metallic contacts or duct perforations by means of magnetic flux measurements of an induced AC current; a) schematic illustration of measurement setup with AC signal fed from the left side and the closed current loop at the defect; b) sectional view showing the concentric magnetic field arising around the tendon axis [10].

The practical experience has shown that this method is reliable in identifying the location of the metallic contact between the tendon and the reinforcing steel or perforations in the duct providing an electrolytic path that results in decreased isolation quality. However, practical experience in the past years has shown that repairing these defects is often not easily possible. Reasons are the typically high concrete cover and the vicinity of several tendons in parallel. Hence, the repair work bears an increased risk for damage to the structure. Nevertheless it was found that locating the isolation defect (perforation, metallic contact) provides useful information in the case of decreasing electrical resistance values, as for instance shown in Figure 30. Knowing the location of the defect can help in these cases in the further assessment of the damage risk of the structure or the relevance of the resistance change on the durability and structural behaviour of the structure.

9 Safety

In principle, long and electrically isolated metallic components such as EIT may act as antenna in the presence of nearby magnetic fields and thus pick up an AC voltage. This may theoretically present a potential safety issue for measuring personnel when touching the electrical connections to the tendon and the reinforcing steel of a structure, as AC voltages may be present between these two connections. However, experience in Switzerland and Europe has shown that this is in practice not a severe issue. The reasons are that typically arising magnetic fields are not high enough to induce relevant AC voltages in EIT, and secondly, that tendons are normally shielded from the magnetic field by the presence of the reinforcing steel cage. Special considerations may be required if high voltage transmission lines are installed on the bridge.

Revised Draft

10 Further Research

This section summarizes possible areas for future research to further improve the EIT technology.

10.1 Potential Measurements

We believe that EIT offer a unique opportunity to perform potential measurements. Given that a tendon is electrically isolated from all other metallic components of a reinforced / prestressed concrete structure, the electrochemical potential of the tendon can be measured vs. a reference electrode placed on the concrete surface without the direct interfering action of corroding or non-corroding reinforcing steel present in the same structural element. In combination with the non-destructive method of localizing perforations in the duct, it is possible to measure the tendon potential at the perforation and thus to assess its corrosion state at such weak points. We propose to investigate this, particularly with respect to the interpretation of the results under consideration of the strongly limited access of oxygen at the tendon surface.

10.2 Measurement of Faradaic Rectification

To assess the corrosion state, measurement methods are commonly based on external polarization of the tendon or reinforcing steel. These methods exhibit major shortcomings such as the unknown steel surface area which is polarized or the lack of applicability of the method due to the localized nature of the phenomenon under investigation (e.g. Ref. [24]). This applies to galvanostatic pulse measurements or potentiodynamic linear polarization measurements that are frequently used to determine the corrosion state of steel in concrete. In order to avoid these severe fundamental limitations, we propose to investigate the effect of faradaic rectification as an alternative approach in more detail. Faradaic rectification occurs in the presence of an applied AC voltage (between the tendon or reinforcing steel and a counter electrode), where the asymmetry of the current-potential characteristic of a corroding/passive electrode in concrete leads to a partial rectification of the imposed AC current. This manifests as a shift in the DC potential, which can be measured and which gives direct information about the corrosion state of the polarized electrode. The major benefit for the interpretation of this is that it is independent of the polarized area.

11 Conclusions

The technology of electrically isolated tendons (EIT) is a concept to protect and monitor tendons against corrosion attack from the outside of the tendon. Additionally, the EIT technology and the related measurements are the most established methodology for monitoring post-tensioning systems with respect to their durability performance. The practical experience of the application of EIT in the last 15 years based on the Swiss guideline has demonstrated its applicability and led to the following conclusions:

- Attempting to achieve electrical isolation of tendons has significantly increased the quality of workmanship and the durability of prestressed structures, by raising the awareness for quality in the entire production chain, viz. from detailing, product supplying to execution on-site.
- The ability to identify and localize individual duct perforations and to monitor them over time provides key information for the assessment of the current status of structures and to follow up on their development.

Despite these key advantages it must be clearly stated that the technology has certain limitations.

- Insufficient grouting or poor grouting quality cannot be detected by means of a resistance measurement. The application of EIT must be accompanied by additional measures that assure that the specified grout performance characteristics are met as for any other type of tendon. Such measures include in particular inspection of grout filling and quality at all anchorage caps and all vents along the tendon immediately after grout setting. Appropriate corrective measures can thus be taken immediately if any problem with grout quality (soft grout) or incomplete filling is found.
- The possibility to check for isolation quality raises questions for responsibility. This implies correction measures, costs, and liability.

The concept of the EIT technology, including performance testing and monitoring procedures, are also applicable to the conditions in the United States. Based on the experiences made in Europe, this is expected to increase the durability of pre-stressed structures. Threshold values and acceptance criteria reviewed in this report stem from the experience made in Switzerland over the last two decades, given the specific conditions of Swiss engineering and construction practices. For other countries, differences in construction practices, climatic conditions, and owner policies may require devising different criteria (different scenarios and different threshold values). This refers particularly to segmental bridge construction (by using the match-casting technique), the use of epoxy-coated steel reinforcement, or applications of EIT in the case of internal unbonded tendons and external tendons; all of these are not common in Switzerland and there exists no or very little experience.

12 References

1. Schupack, M. and Suarez, M.G., *Patent no. 4348844, "Electrically isolated reinforcing tendon assembly and method"*. 1982.
2. ASTRA/SBB AG, *Richtlinie "Massnahmen zur Gewährleistung der Dauerhaftigkeit von Spanngliedern in Kunstbauten" (in German, 1st edition)*. 2001: Berne, Switzerland.
3. ASTRA/SBB AG, *Richtlinie "Massnahmen zur Gewährleistung der Dauerhaftigkeit von Spanngliedern in Kunstbauten" (in German, 2nd edition)*. 2007: Berne, Switzerland.
4. ASTRA/SBB AG, *Guideline "Measures to Ensure Durability of Post-Tensioning Tendons in Structures" (English translation of 2nd edition)*. 2007: Berne, Switzerland.
5. fib (Fédération internationale du béton), *fib Bulletin no. 33 "Durability of post-tensioning tendons"*. 2005.
6. EOTA (European Organisation for Technical Approvals), *ETAG 013 "Guideline for European technical Approval of post-tensioning kits for prestressing of structures"*. 2002: Brussels.
7. Post-Tensioning Institute (PTI) and American Segmental Bridge Institute (ASBI), *PTI/ASBI M50.3-12 "Guide Specification for Grouted Post-Tensioning"*. 2012.
8. von Matt, U., *20 years experience with electrically isolated ground anchors (in German)*, in *VSV Tagung "Dauerhaftigkeit von vorgespannten Kabeln und Ankern"*, Zurich, Switzerland. 2004. p. 1-8.
9. Elsener, B., Toller, L., Voûte, C.H., et al., *Überprüfen des Korrosionsschutzes von Spanngliedern mit Kunststoffhüllrohren, research report ASTRA/AGB 1998/105 (in German)*. 2002, Swiss Federal Roads Administration.
10. Elsener, B. and Büchler, M., *Quality control and monitoring of electrically isolated post-tensioning tendons, research report ASTRA/AGB 2004/010*. 2011, Swiss Federal Roads Administration.
11. Swiss Society for Corrosion Protection (SGK), *Guideline "C3. Recommendations for the protection from corrosion caused by DC stray currents" (in German)*. 2011: Zurich, Switzerland.
12. European Organisation for Technical Assessment (EOTA). Available from: <http://www.eota.eu>.
13. fib (Fédération internationale du béton), *fib Bulletin no. 75 "Polymer duct-systems for internal bonded post-tensioning"*. 2014.
14. Vedova, M.D. and Elsener, B., *Enhanced Durability, Quality Control and Monitoring of Electrically Isolated Tendons*, in *fib 2nd Int. Congress*. 2006: Naples, Italy.
15. Zulassungsstelle für Bauprodukte, *VSL bonded and unbonded post-tensioning systems, Swiss Technical Approval of post-tensioning kits for prestressing of structures with internal, bonded tendons and bonded and unbonded slab tendons consisting of strands (STA-01/007 E2) (in German)*. 2014.
16. Elsener, B., *Monitoring of electrically isolated post-tensioning tendons*, in *Taylor made concrete structures*, J. Walraven and D. Stoelhorst, Editors. 2008, Taylor & Francis Group: London. p. 231-236.
17. Bürchler, D., *Der Elektrische Widerstand von zementösen Werkstoffen (in German)*. 1996, ETH Dissertation Nr. 11876.
18. Vedova, M.D., Elsener, B., and Evangelista, L. *Corrosion protection and monitoring of electrically isolated post-tensioning tendons*. in *Proc. Third European conference*

- on structural control, 3ECSC. 2004. Vienna, Austria: Vienna University of Technology.
19. Büchler, M., Brem, M., and Ganz, H.-R., *Quality control of tendons: Control of the filling with grout with passivating properties during installation*, in *4th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-4)*. 2009: Zurich, Switzerland.
 20. Nicollier, V., *Monitoring of electrically isolated tendons with impedance measurements (in German); master thesis at Institute for Building Materials, ETH Zurich, Switzerland*. 2005.
 21. Krause, M., Mayer, K., Friese, M., et al., *Progress in ultrasonic tendon duct imaging*, in *NDTCE'09, Non-destructive testing in civil engineering*. 2009: Nantes, France.
 22. Taffe, A. and Wiggenhauser, H., *Zerstörungsfreie Zustandsermittlung und Qualitätssicherung in der Betoninstandsetzung (in German)*. *Beton- und Stahlbetonbau*, 2008. 103, p. 1-13.
 23. Breysse, D., ed. *Non-Destructive Assessment of Concrete Structures: Reliability and Limits of Single and Combined Techniques (State-of-the-Art Report of the RILEM Technical Committee 207-INR)*. 2012, Springer.
 24. Angst, U. and Büchler, M., *On the applicability of the Stern-Geary relationship to determine instantaneous corrosion rates in macro-cell corrosion*. *Materials and Corrosion*, (in press).

Appendix A – Requirements for Measuring Instruments

In order to measure the AC impedance of a tendon in a concrete structure, and to separate the ohmic and capacitive component, the measuring device needs to fulfill a few requirements. As a pragmatic solution, relatively simple handheld instruments were recommended in the Swiss guideline [2-4], namely LCR meters. Figure 32 shows an example of a product frequently used in Switzerland.

These simple LCR meters measure the magnitude of the AC impedance by applying a given AC voltage at a determined frequency (that can normally be selected by the operator). The devices also determine the phase angle between the voltage and current signals. By assuming an equivalent circuit, the ohmic resistance and the capacitance can be computed and displayed. Generally, when determining resistance and capacitance, these commercial devices automatically assume a parallel circuit of R and C. This corresponds well to the situation of a capacitor (plastic duct) with a leaky dielectric (defect in the duct).

The specific requirements for measuring instruments defined in the Swiss guideline [2-4] were as follows (also adopted in *fib* bulletin no. 33 [5]):

Measuring voltage amplitude:	min. 0.5 V alternating voltage
Measuring frequency:	1 kHz
Measuring range:	digital display for <ul style="list-style-type: none">- Ohmic resistance R: 0.1 Ω - 10 MΩ (with a resolution of 0.1 Ω at the lower end of the range)- Capacitance C: 0.1 nF - 100 μF- Loss factor D: 0.001 - 10

Note that no requirements were made with respect to the shape of the AC voltage signal. The device used in Switzerland employs a square wave signal of amplitude ca. 0.9 V.



Figure 32. Example of a handheld instrument as a pragmatic solution for performing the AC impedance measurements of EIT (ESCORT ELC-131D).

Appendix B – EIT Specification Language

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