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Quality Control and Monitoring of electrically isolated post-tensioning tendons in bridges

Qualitätsprüfung und Ueberwachung elektrisch isolierter Spannglieder in Brücken

Contrôle de la qualité e surveillance des câbles de précontrainte isolés électriquement dans les ponts

ETH Zurich, Institute of Building Materials, Zurich
Prof. Dr. Bernhard Elsener

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Forschungsauftrag AGB 2004/010 auf Antrag der Arbeitsgruppe Brückenforschung (AGB)

Juli 2011 **647**

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Preface

Tendons contribute decisively to the serviceability, safety and durability of pre-stressed concrete structures. Despite a generally good long-term behaviour, some corrosion problems and rare collapses are documented; thus industry, designers and owners were looking for a more durable solution. Electrically isolated tendons (EIT) with plastic ducts for internal grouted post-tensioning were developed about 20 years ago. The first guideline for the use and application of the EIT systems was elaborated and published in 2001 jointly by the Swiss Federal Highways and Railways "Measures to ensure the durability of post-tensioning tendons in bridges".

The present research report is based partly on previous laboratory studies of the authors and results from structures used as pilot-objects with a long track record. These results contrasted with part of the experience in practice where more difficulties were encountered, especially in reaching the acceptance value specified in the Swiss guideline from 2001. The guideline had to be revised and the present research project was undertaken. The specific objectives were to establish whether anchor heads are systematic defects or not, to check if capacitance measurements could indicate the non-grouted areas, to extend the time of measurement from a fixed value 28 days after grouting to a period from some days to 2 month and to test the possibility of locating defects with magnetic flux measurements from the concrete surface.

The authors thank the task group "revision of the Swiss guideline" for providing valuable cases from practical application, the Begleitkommission for interesting discussion and critical review of the report and especially the working group 2 "Electrically isolated tendons" in the framework of the European collaboration COST 534 that provided access to the results of an application of EIT on viaducts of the Italian high-speed train network. Several parts of the research report were integrated in the revision of the "Swiss guideline". In addition the authors hope that this research report will contribute to a broad application of electrically isolated tendons allowing quality control and long-term monitoring.

Prof. Dr. Bernhard Elsener

Summary

Tendons contribute decisively to the serviceability, safety and durability of pre-stressed concrete structures. Despite a generally good long-term behaviour, some corrosion problems and rare collapses are documented; thus industry, designers and owners were looking for a more durable solution. Electrically isolated tendons with plastic ducts for internal grouted post-tensioning were developed about 20 years ago. The progress achieved in the meantime and the implementation of this new approach into the framework of *fib* recommendation is also based on previous research reports and the first Swiss guideline “Measures to ensure the durability of post-tensioning tendons in bridges”.

Since 1995 an increasing number of bridges, flyovers and viaducts have been constructed with electrically isolated tendons (EIT) according to the *fib* protection level 3 (PL3). Quality control and long-term monitoring is performed with electrical resistance measurements between tendon and reinforcement. Experience with practical application showed some difficulties in reaching the acceptance value specified in the guideline, further the time of measurement of 28 days was found not to be adequate for practice. Together with the revision of the Swiss guideline the present research project was undertaken.

The research report establishes the scientific and technical background for the revision of the guideline, especially with regard to the limit of the electrical resistance specified and its evolution with time after grouting. The project shows that the anchor head might not be “a priori” a systematic defect in the electrical isolation, problems can arise in application on site. Larger defects or short-circuits in the electrical isolation can be located with magnetic flux measurements from the concrete surface.

Finally the research report documents some typical application of electrically isolated tendons on bridges and viaducts in Switzerland. Thanks to the international collaboration in the framework of COST 534 a large number of results from prefabricated segments of viaducts of the new high-speed lines of the Italian railways are available. Both type of structures show the importance of a careful quality control system, including the design process, material specification and training of the workers on site. The most important conclusion for practice is that also tendons that did not reach the 28-day acceptance criteria can be considered as better protected against corrosion and can be included in the long-term monitoring strategy.

Zusammenfassung

Spannglieder im Verbund leisten einen ausschlaggebenden Beitrag zur Tragsicherheit und Dauerhaftigkeit von Tragwerken. Dennoch sind Korrosionsschäden und vereinzelt Einstürze dokumentiert. Als dauerhaftere Lösung wurden vor etwa 20 Jahren elektrisch isolierte Spannglieder mit Kunststoffhüllrohren entwickelt. Der seither erzielte Fortschritt und die Aufnahme dieses neuen Systems in die fib Richtlinien basiert auch auf früheren Forschungsarbeiten der Forschungsstelle und der wegweisenden Schweizer Richtlinie „Massnahmen zur Gewährleistung der Dauerhaftigkeit von Spanngliedern in Kunstbauten".

Seit 1995 wurden eine zunehmende Anzahl von Brücken, Ueberführungen und Viadukten mit elektrisch isolierten Spanngliedern (Kategorie c oder Schutzgrad PL3) gebaut. Die Erfahrung aus der Praxis zeigte aber einige Schwierigkeit beim Erreichen des in der Richtlinie geforderten Grenzwerts des elektrischen Widerstands, zudem wurde der Zeitpunkt der Messung – 28 Tage nach der Injektion – häufig als nicht praxisgerecht beurteilt.

Der Forschungsbericht bildet den wissenschaftlichen und technischen Hintergrund für die Revision der Richtlinie, speziell im Hinblick auf die Grenzwerte für die elektrische Widerstandsmessung und der Entwicklung des Widerstands mit der Zeit. Der Bericht zeigt weiter, dass die Ankerköpfe nicht „a priori" eine Schwachstelle in der elektrischen Isolation darstellen, in der Praxis aber Verletzungen nicht ausgeschlossen werden können. Grössere Defekte im Hüllrohr oder Kurzschlüsse können mittels Messungen des magnetischen Flusses von der Betonoberfläche her geortet werden.

Der Forschungsbericht dokumentiert auch einige typische Anwendungen der elektrisch isolierten Spannglieder an Brücken in der Schweiz. Dank der internationalen Zusammenarbeit im Rahmen des europäischen Forschungsprojekts COST 534 sind auch Resultate einer grossen Zahl von vorfabrizierten Elementen des Viadukts Piacenza der neuen Hochgeschwindigkeitslinie Mailand – Bologna der Italienischen Staatsbahnen enthalten. Beide Bauweisen, sowohl Brücken in Ortsbeton als auch vorfabrizierte Elemente für Viadukte in Segmentbauweise zeigen die Bedeutung eines sorgfältig aufgebauten Qualitätssicherungssystems, welches Projektierung, Materialspezifikation, Einbau und vor allem die Ausbildung des Personals auf der Baustelle beinhaltet. Dies wurde in der überarbeiteten Richtlinie aufgenommen. Die für die Praxis wichtigste Schlussfolgerung lautet: auch diejenigen elektrisch isolierten Spannglieder, welche den Grenzwert nicht erreichen, können als besser korrosionsgeschützt betrachtet und über die gesamte Nutzungsdauer überwacht werden.

Résumé

La contribution des câbles de précontrainte est déterminante pour la sécurité structurale, pour l'aptitude au service et pour la durabilité des structures en béton précontrainte. Dans l'ensemble, cette technique de construction a fait ses preuves et s'est avérée très fiable. Néanmoins, un certain nombre de dégradations plus ou moins graves dues à la corrosion sur des câbles de précontrainte sont apparues. Industrie, ingénieurs et propriétaires ont cherché pour une solution plus durable. D'après Il y a environ 20 ans que les des câbles de précontrainte isolés électriquement avec une gaine en matières synthétiques ont été développés. Les progrès réalisés depuis et l'intégration de ce nouveau système dans les directives *fib* (fédération international du béton) sont basés aussi sur des recherches antérieures des auteurs et su la première directive suisse de l'office fédérale des routes (OFR) et CFF «Dispositions pour garantir la durabilité des câbles de précontrainte dans les ouvrages d'art » édition 2001.

Depuis 1995, un nombre croissant de ponts, viaducs et passage supérieurs avec des câbles isolés électriquement (catégorie C ou de degré de protection PL3 selon *fib*) ont été construits. Le contrôle de qualité et la surveillance à long terme sont réalisés avec des mesures de résistance électrique entre le câble et les armatures. L'expérience acquise dans la pratique a montré quelques difficultés à atteindre les valeur limites spécifiés dans la directive, de plus le temps de mesure de 28 jours ne s'est pas révélé adéquat dans la pratique. Conjointement avec la révision de la directive suisse, le présent projet de recherche a été entrepris.

Ce rapport de recherche établit le contexte scientifique et technique pour la révision de la directive, en particulier en ce qui concerne la limite de la résistance électrique spécifiée et son évolution temporelle après l'injection des gaines. Le projet montre que la tête d'ancrage ne semble pas être "a priori" un défaut systématique dans l'isolation électrique, des problèmes peuvent néanmoins se manifester lors de l'application en site. Des défauts pas trop minces ou des courts-circuits dans l'isolation électrique peuvent être localisés avec des mesures de flux magnétique à la surface du béton.

Enfin, ce rapport de recherche présente quelques applications typiques des câbles de précontrainte électriquement isolées sur des ponts et viaducs en Suisse. Grâce à la collaboration internationale dans le cadre de COST 534, un grand nombre de résultats de voussoirs préfabriqués des viaducs de la nouvelle ligne à grande vitesse des chemins de fer italiens sont inclus. Les deux types de structures montrent l'importance d'un système de contrôle de qualité rigoureux, y compris le processus de conception, spécification du matériel et la formation des travailleurs sur le site. La conclusion la plus importante pour la pratique est qu'également les tendons qui n'ont pas atteint les critères d'acceptation à 28 jours peuvent être considérés comme mieux protégés contre la corrosion et peuvent être inclus dans la stratégie de surveillance.

1 Introduction

Tendons contribute decisively to the serviceability, safety and durability of prestressed concrete bridges. Optimum corrosion protection of post-tensioning tendons has been a priority since the beginning of this technology [1]. The UK temporary ban of grouted post-tensioning tendons, from 1992 to 1996, has initiated a review of all aspects related to durability of post-tensioning tendons [2]. Traditionally, ducts for bonded post-tensioning tendons have been made from steel stripes with a special corrugation. A long experience and generally good „track record“ with these tendons is available from many different applications. Their overwhelming use has allowed the creation of national and international standards. Despite a generally good long-term behaviour, some corrosion problems are documented that rose concern about the durability of post-tensioning tendons. An overview on corrosion damages of pre-stressing steel in Germany has been published [3], the situation in North America, Europe and Japan is summarized in papers presented at the fib/IABSE workshops „Durability of post-tensioning tendons“ in 2001 [4] and 2004 [5]. Recently, the situation in Switzerland was analyzed [6]. From 143 structures approximately half showed small to significant corrosion damage of the pre-stressing steel. From 27 sufficiently documented bridge case studies, 12 bridges were dismantled of which 9 for traffic reasons and only 3 due to lack of serviceability, structural safety and durability. In this group of dismantled bridges (where a much better tendon inspection is possible) significant damage with corrosion of the pre-stressing steel was found in 2 bridges. The reason was chloride-containing water penetrating at „weak points“ such as expansion joints, drainage systems etc. to the steel duct [6]. A typical scenario of deterioration of a pre-stressed box girder is shown in figure 1.

Plastic ducts have been used for many years in pre-stressing technology for various applications such as monostrands, ground anchors, stay-cables and external tendons, mostly in the form of smooth pipes. An early example is the Schillersteg in Stuttgart completed in 1961; after 13 years of exposure to the environment no particular changes in the properties of the polyethylene have been observed [7]. Corrugated plastic ducts have been used for ground anchors in the bond length. Between 1968 and 1974 about 300'000 m of thin wall corrugated black polyethylene ducts have been installed in Switzerland for bonded post-tensioning (simply because the material at that time was cheaper than steel ducts). Nowadays some of these bridges were demolished [6], the analysis of these thin-walled polyethylene ducts after up to 30 years in use showed no deterioration and the steel strands did not present crevice corrosion. A renewed interest for plastic ducts occurred after 1980 when the phenomenon of fretting fatigue in bonded tendons was discovered and investigated [8, 9].

At the beginning of the 1990’s a new generation of thick-walled corrugate polymer ducts for bonded, internal tendons was developed and gradually introduced in the market. These ducts were specifically designed for use with bonded tendons. The research work and development of thick-walled polymer ducts for post-tensioning and the performance in practice is well documented in literature [11, 12], a *fib* report [13] summarizes the actual knowledge and presents a recommended specification for corrugated plastic ducts for bonded post-tensioning. Corrugated polymer ducts have been developed and introduced for these main reasons:

- reduced friction losses during stressing of the tendon
- increased fretting fatigue resistance of the tendon [10]
- improved corrosion protection, especially in the case of DC stray currents, which is a vital aspect for bridges with DC current (e.g. tramways)
- feasibility for electrical monitoring of the tendon

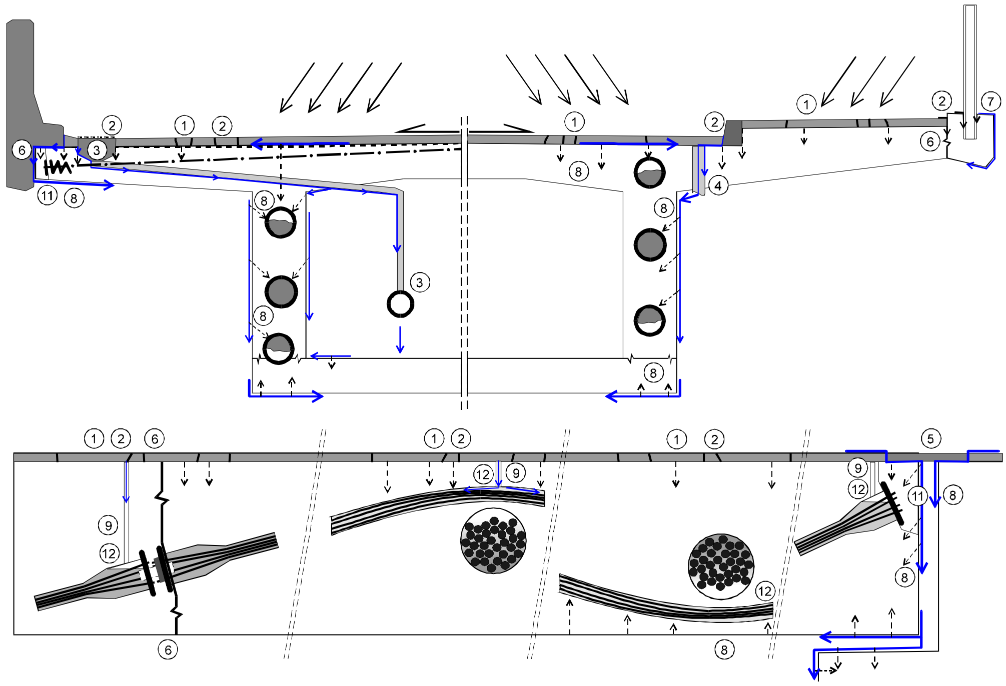


Figure 1: Hazard scenarios for pre-stressing steel in a typical box girder bridge. Indication of potentially "weak points" where water (possibly contaminated with chlorides) can gain access to the tendons and cause corrosion. 1: Defective pavement (e.g. cracks), 2: Missing or defective waterproofing membrane incl. edge areas, 3: Defective drainage intakes and pipes, 4: Wrongly placed outlets for the drainage of wearing course and waterproofing, 5: Leaking expansion joint, 6: Cracked and leaking construction or element joint, 7: Inserts (e.g. for electricity) [6]

These polymer ducts can provide complete encapsulation to protect the tendon against ingress of aggressive media from the outside, if properly designed, manufactured and installed. The use of thick-walled polymer ducts combined with suitable details in the anchorage zone may provide electrical isolation of the tendons from the reinforcement of the structure. Such electrically isolated tendons (EIT) protect from the harmful effects of stray currents. Electrically isolated tendons also permit monitoring of the quality of the encapsulation of the tendons - thus for the first time a quality control and long-term monitoring of the tendons, the important load-bearing parts of a structure, became possible.

Also problems or disadvantages of the new technology have to be mentioned, as e.g. the possibility of poor adhesion between the polymer duct and concrete, the formation of holes and defects during placing on-site, pressure of the high-strength steel at curvatures onto the polymer duct, formation of defects in the electrical isolation plate during stressing. It is generally accepted that quality of workmanship must be higher compared to post-tensioning structures with traditional metal ducts.

A pioneering work important for the future application of electrically isolated tendons was the Swiss Guideline *Measures to ensure the durability of post-tensioning tendons in bridges* published jointly by the Swiss Federal Railways (SBB) and the Swiss Federal Roads Authority (ASTRA) in 2001 [14]. The guideline proposed three categories for post-tensioning tendons in terms of corrosion protection: tendons of category a) are in traditional corrugated steel duct. Category b) specifies corrugated polymer ducts for enhanced protection. Tendons of category c) shall be electrically isolated. The main difference between tendons of category b) and c) is the complete electrical isolation at the anchor head to avoid stray currents and to allow monitoring the integrity of tendon encapsulation. The guideline gives indications for the choice of the tendon category, measuring instructions, limits of the electrical resistance and hints for the interpretation of results. The guideline was presented at the second workshop on durability of post-tensioning tendons in 2004 at ETH Zurich. In the discussions the three categories were transformed to three protection levels (PL) and as such the guideline was at the base of the *fib* recommendation *durability of post-tensioning tendons* [15] following a multi-layer protection approach.

Since 1995 an increasing number of bridges, flyovers and viaducts have been constructed with electrically isolated tendons according to protection level 3 (PL3), mainly in Switzerland [12, 16]. Similar systems have been applied for the first time in Italy for the design and construction of several bridges and viaducts of the new high-speed lines [17, 18] on simply supported spans realised with partial or total pre-casting of the decks. Quality control and long-term monitoring is performed according to the guideline [14] with electrical resistance measurements between tendon and reinforcement. Experience with the practical application revealed difficulties in reaching the limits of the electrical resistance specified in the guideline. Further the fixed time of 28 days defined for the quality control (acceptance) was found not to be adequate (too late) for practice.

As the Swiss guideline had to be renewed in 2006, the present research project was undertaken. Goal of the project was to establish the scientific and technical background for the revision, especially with regard to the limiting values of the electrical resistance specified. Several “case studies” of EIT application were analyzed in detail. The project further intended to study the anchor head as possible location of defects in the isolation, the evolution of the grout resistance with time in order to be able to perform the measurements at any time after grouting, and a more detailed analysis of the capacitance values with the intention of detecting voids in the grout.

2 Previous laboratory measurements

Laboratory tests were performed on concrete blocks with embedded 1 m segments of grouted tendons with plastic ducts [16]. Several ducts contained intentionally produced defects such as holes of different size, grouting vents etc. The impedance of the tendon in the duct was measured.

2.1 Impedance measurements

The impedance measurements are performed between the steel strands in the grouted ducts and the normal reinforcement in concrete (figure 2a). The measuring system thus includes the grout in the duct, the duct (with pores and defects) and the concrete surrounding the duct. Grout and concrete are (at least in the range of measuring frequencies between 100 and 1000 Hz) pure resistances, whereas the polymer duct is essentially a capacitance in parallel with a very high resistance (figure 2b). Any system related imperfection (e.g. not fully closed grout vents) and/or defect in the duct is represented by an ohmic resistance in parallel.

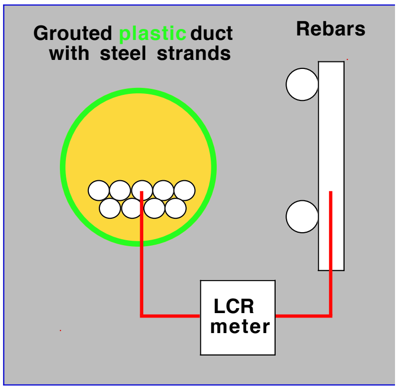


***Fig. 2a:** Principle of measuring the electrical impedance of a tendon with the LCR meter*

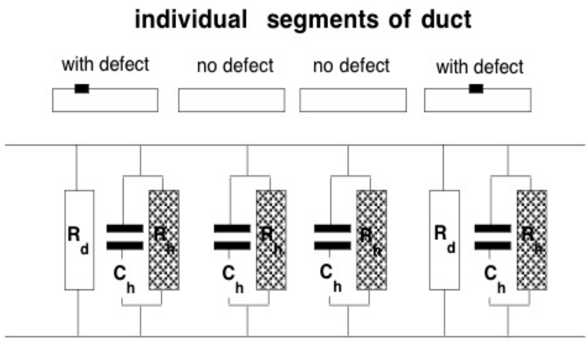


***Fig. 2b**: Electrical equivalent circuit for an electrically isolated tendon with small defects [16]*

2.2 Influence of diameter and length

A polymer duct without any defects is characterized by its geometry (length, diameter, wall thickness) and material properties (specific resistance ρ, dielectric constant ε). For a duct of length L, the capacitance C can be calculated using the formula

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

where L is the length of the duct [m]
r_i the inner radius
r_a the outer radius of the duct
ε_0 the vacuum constant
ε the dielectric constant of the polymer

From laboratory results on 1 m long plastic ducts of 59 mm diameter [16], a specific capacitance C of 2.34 ± 0.03 nF/m was obtained. From eq. (1), using the nominal geometrical values for the duct radius and wall thickness, a dielectric constant ε = 7.5 results. This value is relatively high compared to literature values for dry polypropylene (ε = 3), but can be explained by a slight water uptake (ε = 81) during the long time embedded in concrete. The capacitance C of the duct according to eq. (1) increases proportional to the length L of the duct.

This capacitance C gives rise to a frequency dependant capacitive impedance Z_c that decreases with measuring frequency f and with the length L (according to eq. (1)) of the duct.

$$Z_c = 1 / 2*\pi*f*C \qquad (2)$$

where f is the frequency of the measuring AC signal [Hz]
C value of the capacitance that depends on length and diameter

2.3 Detect defects in the duct

In order to test the sensitivity of the impedance measurements in locating defects of the duct, 1 m long ducts of 59 mm diameter with holes (ø 2, 20 and 40 mm), grout vents, duct couplers and welding joints were prepared and cast into concrete blocks [16].

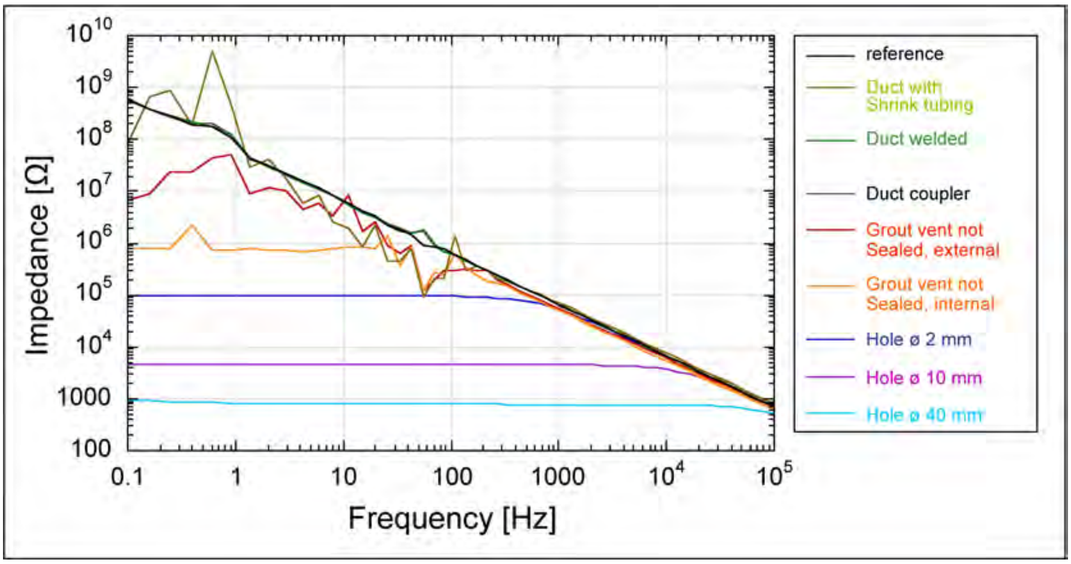


***Fig. 3**.: Impedance spectra (Bode plot) of the grouted ducts with different defects in concrete. Amplitude 10 mV. From ref. [16, 28].*

The impedance spectra of the ducts with different defects are shown in figure 3. The general trend in the Bode plot is a straight line with slope -1 (representing the capacitance according to eq. 2). In these laboratory tests the capacitance values of all the ducts – irrespective if a defect is present or not – are identical, a value of 2.34 ± 0.04 nF was measured. A defect in the duct is represented by a resistance (horizontal line in the plot). As can be seen, a low resistance indicates a very severe defect (e.g. hole of 40 mm). The results of the ducts with the different defects are given in table 1. Note that the direct current (DC) resistance of ducts without defects is nearly infinite.

As can be seen from table 1, ducts that are intact (reference), welded or coupled have a very high resistance value (> 2.3 MΩ) and very low loss factors D (< 0.034), thus they behave essentially as capacitance. Ducts with a hole show very low resistance values (< 100 kΩ) and the resistance drops to less than 1 kΩ for bigger holes. The loss factor is very high, thus at 1 kHz these systems behave as resistance. An open grout vent that ends in the concrete (thus a very small electrolytic contact is possible) has a resistance of 573 kΩ and a loss factor of 0.098. As a not perfectly closed grout vent represents a “defect” for the impedance measurement but not directly a loss in durability, this situation was chosen as borderline between acceptable and not acceptable defect. The acceptance criteria thus was defined as R = 500 kΩm, the control value D < 0.1.

***Table 1**: Results of laboratory measurements of grouted ducts (length 1 m, diameter 59 mm) in concrete after 146 d. Frequency 1 kHz [16].*

Type of duct / defect	Resistance R [kΩ]	loss factor D [-]
hole of diameter 40 mm	0.814	n.d.
hole of diameter 20 mm	4.71	14.0
hole of diameter 2 mm	98.7	0.669
grout vent not sealed, end in concrete	573	0.098
grout vent not sealed, out of concrete	1150	0.052
duct coupler, sealed	2380	0.034
duct coupler as from system supplier	3000	0.022
duct welded	3700	0.018
duct (reference)	3800	0.017

2.4 Acceptance criteria

From these laboratory measurements and pilot objects with electrically isolated tendons the acceptance criteria, essentially the specific ohmic resistance R (length of the tendon * measured resistance R) have been defined (table 2) and published in the Swiss guideline [14]. The specific capacitance values and the loss factor are given as control values. In practice, especially the specific capacitance is of importance, because it allows checking materials properties, length and diameter of the tendons. The loss factor D is the only parameter that is independent on length of the tendon.

***Table 2**: Limits of the specific electrical resistance and control values for electrically isolated tendons with ducts of the type PT-PLUS for grouted ducts in concrete measured 28 days after grouting (1 kHz) as given in the Swiss guideline edition 2001 [14].*

type of duct	**limit**	**control value**	
	specific resistance ρ*	specific capacitance C**	loss factor D***
Ø 59 mm	> 500 kΩm	< 2.35 nF/m	< 0.1
Ø 76 mm	> 400 kΩm	< 3.05 nF/m	< 0.1
Ø 100 mm	> 300 kΩm	< 3.35 nF/m	< 0.1
Ø 130 mm	> 250 kΩm	< 4.30 nF/m	< 0.1

* The experimentally measured values of the ohmic resistance R have to be multiplied by the length of the tendon L before comparing with the limits given in the table. For tendons with a duct of Ø 59 mm and 100 m length an experimental value of R > 5000 Ω has to be measured in order to reach the limit.

** The experimentally measured values of the capacitance C have to be divided by the length of the tendon L before comparing with the control values. For tendons with a duct of Ø 59 mm and 100 m length experimental values of C = 234 ± 4 nF should be measured. Lower capacitance values are obtained for higher wall thickness of the ducts and are thus no problem. Note: the capacitance values are not sensitive to the presence of small defects in the duct.

*** The loss factor D is the only measured value that is independent on the length of the tendons. This value allows a rapid control and evaluation of the overall state of the tendon.

2.5 Practical experience

These acceptance criteria and the control values defined in the Swiss guideline edition 2001 [14] were applied in practice – frequently with problems. Quite a lot of structures built with the new technology "electrically isolated tendons" gave rise to discussions because the acceptance criteria (table 2) were not reached due to manifold reasons. As the guideline had to be revised anyway after five years (end of 2006), this research work was proposed in collaboration with the commission with the following goals:

- try to identify possible systematic failures, e.g. in the electrically isolated anchorage head
- evaluate if and to what extent grout voids can be detected by measuring the capacitance value C of a tendon
- study the evolution of the electrical resistance of grouts with time in order not to be limited to a fixed time after grouting (today 28 days).
- apply the new technique for locating defects in the ducts on structures
- collect data from structures in order to learn from good practice or mistakes

3 Electrically isolated anchorages

Electrically isolated anchor heads were originally developed in the context of the requirement of electrically isolated permanent ground anchors for the railway station Stadelhofen, Zurich, in 1985. As the station is located in the city centre and close to one of the rectifiers of the DC powered tramways it was necessary to provide the permanent ground anchors with suitable protection against the risk of stray currents. Electrically isolated tendons are based on the use of electrically isolated anchor heads and corrugated plastic ducts. This new system allows reaching the highest level of protection (PL3) of bonded post-tensioning tendons [14, 15] and is the only one that allows electrical resistance measurements for quality control after construction and continuous monitoring of the degree of protection during the whole service life.

3.1 Design of anchorages

Anchoring of seven-wire pre-stressing strands using threaded wedges is a well-proven technology. Detailing is most important near the anchorages (Fig. 4) in order to guarantee complete encapsulation and electrical isolation. Between the steel anchor head (item 10) with the wedges that block the strands (items 3) and the cast iron bearing plate (item 4), a mechanically resistant insulation plate (item 5) is placed in order to electrically isolate the tendon from the normal rebar network. Inside the anchorages a plastic trumpet (item 2) tightly connected to the duct (item 1) isolates the strands from the cast-iron bearing anchorage.

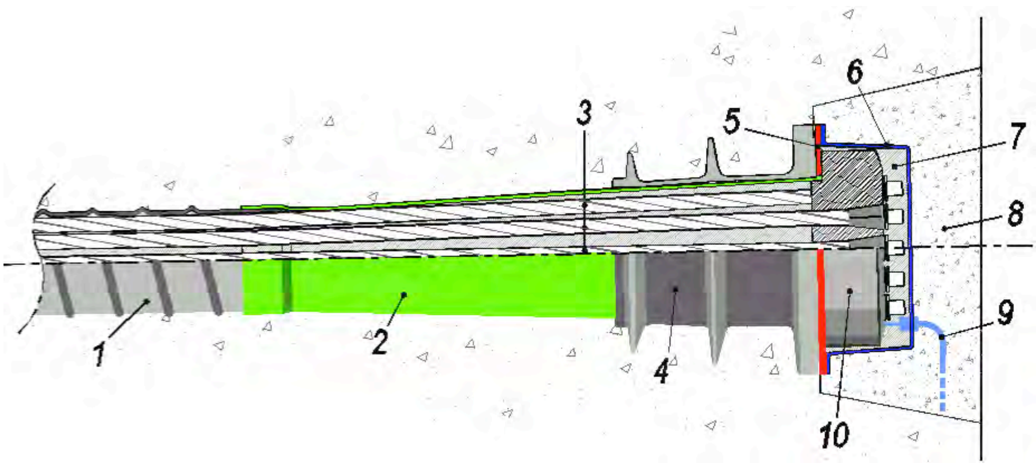


Figure 4. *Principle of electrically isolated anchorage (description of the numbered items in the text).*

According to the Swiss guideline [14], the anchor heads are protected by plastic caps (item 6) and fully grouted (item 7). An electrical terminal (item 9) is drawn out from the head anchorage for impedance measurements. Minimum cross-section area of the electric terminal shall be 6 mm^2 for railway bridges with alternating current traction, 1 mm^2 in other cases. The anchorage shall be in accessible position (even if covered with second step casting for further protection) and the box collecting all electric terminals of a single deck shall be in areas easily accessible for inspection and maintenance personnel.

3.2 Tests on different electrically isolated anchorages

The tendons with a specific type of anchor head in several short and quite simple post-tensioned bridges did not reach the acceptance criteria for the specific resistance as defined in the guideline [14]. One possible explanation could be an insufficient electrical isolation in the anchor heads. For this reason tests were performed on anchors used from different pre-stressing companies operating in Switzerland.

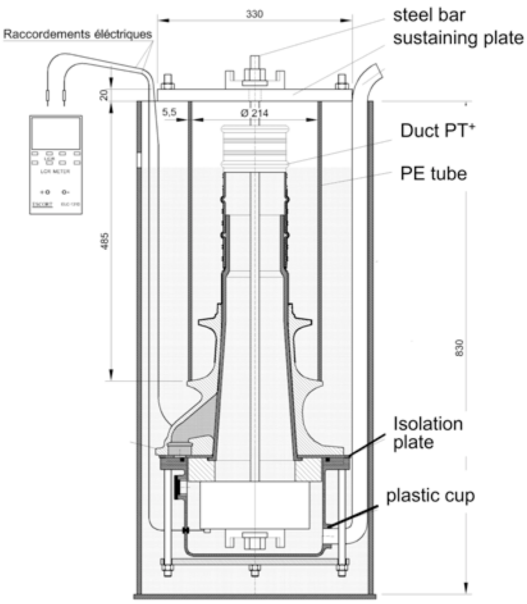


Figure 5*: Test rig for the electrical resistance testing of electrically isolated anchorages*

Test procedure

In collaboration with the pre-stressing companies a test rig was designed and prepared for the tests of this anchor type. An example is shown in figure 5. The container was filled with 180 l of potable water, adjusted to pH 12.5 by adding $Ca(OH)_2$.

Results

The pH of the test solution remained constant at pH > 12 over the testing period of 3 month. The electrical resistance measured between the central steel bar and the anchor head was constant at 200 ± 5 kΩ over the testing period of 3 month (figure 6).

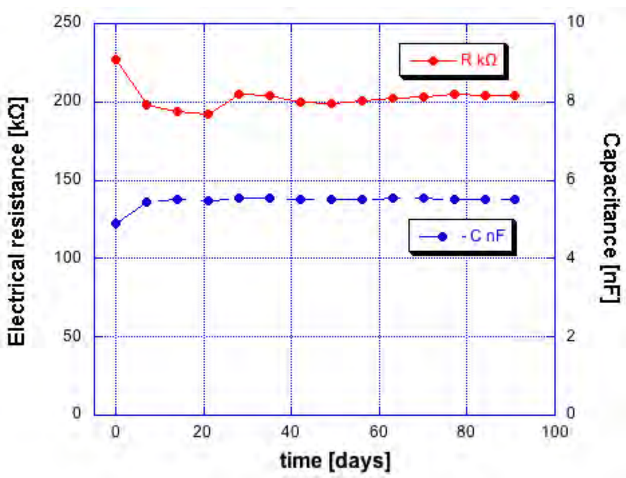


Figure 6: *Evolution of electrical resistance and capacitance with time*

Despite some scatter in the electrical resistance (quality of electrical isolation) of the anchor heads, the laboratory experiments showed that the electrical resistance of this type of anchors was found high enough in order to exclude a design problem. This good behaviour in the laboratory test might not be automatically transferred to practice. The stressing procedure on-site might – due to limited space, deviations from the perpendicular angle respect to the anchor plate, fragility of the isolation plate – be more difficult. If the anchors cannot be correctly mounted and stressed on site the anchor heads can become a defect in the electrical isolation. Magnetic flux measurements to locate the defects on site did not reveal systematic defects at anchor heads [24].

3.3 Possibilities for further improvement

Several improvements can be proposed based on the experience with the prefabricated decks for the Italian railway company.

- The use of a *transparent cap* on the anchor head allows to check visually the grouting execution of the caps at the end of the grouting (figure 7) and, if necessary, re-grout from an additional inlet at the highest point of the caps before covering them permanently.
- Actually, the Swiss guideline leaves to the designers the choice to cover the anchorage caps with concrete or not. As a means of further protection the anchorages should be completely surrounded by concrete.

***Figure 7**: Transparent cap of the anchor head used in the prefabricated elements of the segments of Piacenza Viaduct (Foto V. Nicollier [19])*

4 Detecting grout voids based on capacitance measurements

A frequent problem in post-tensioning tendons is the presence of voids in the grout in the ducts where the high-strength steel is not surrounded by a protective alkaline environment and is prone to corrosion. Detecting grout voids is difficult, non-destructive techniques that in principle can locate voids are presented in ref. [20]. The measurement of the impedance of the tendon gives as result the electrical resistance and the capacitance. In principle from the capacitance value information on voids in the grout could be obtained. The research project investigated this possibility.

4.1 Measurement setup

The tests were performed in the measurement setup shown below [16]. In a water-filled basin of 1 x 0.3 x 0.3 m polymer ducts of 59 mm diameter and length 1 m were placed (figure 9). The ducts with a central steel reinforcement of diameter 12 mm were filled with grout in three different ways (fig. 8):

a) half diameter grouted
b) half length grouted
c) fully grouted

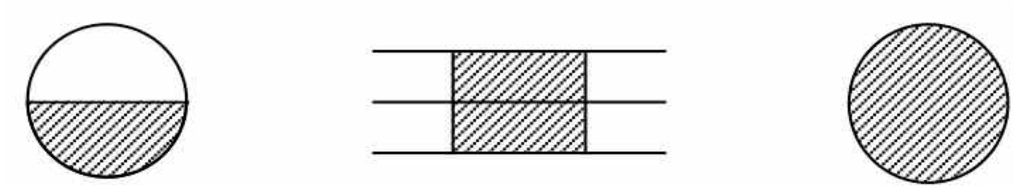


***Figure 8**: Principle of the grouting of the 1 m long polymer ducts ø 59 mm*

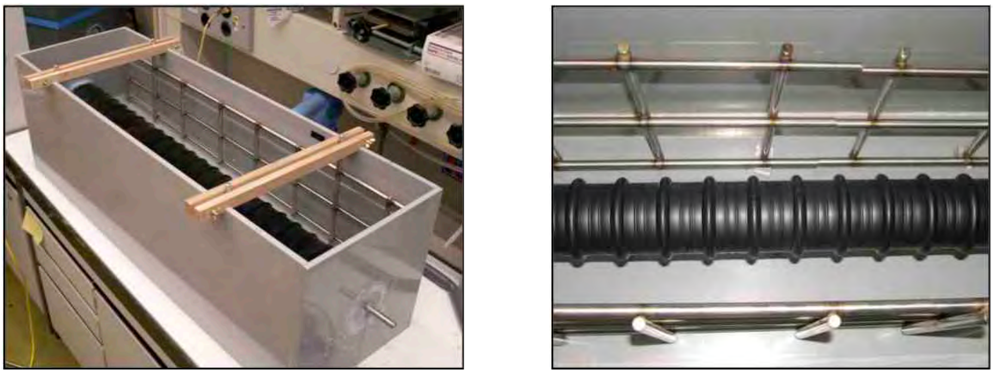


***Figure 9**: Experimental setup for the impedance measurements on the polymer ducts [19]. Note the stainless steel grid used as counter electrodes*

The grout mixtures had to be prepared with a high mixing rate in order to avoid bleeding of the grout. Details of the preparation of the fully and partially grouted ducts are given in the Master Thesis of Vanessa Nicollier [19].

The impedance was measured with a LCR meter (6451 LCR databridge) at frequencies of 0.1, 1 and 10 kHz between the reinforcement in the duct and the stainless steel counter electrodes placed in the basin (Figure 9). The measurements were performed 28 days after grouting.

4.2 Results

The results of the impedance measurements on the three samples with different grouting are shown in figure 10. The results of resistance R, capacitance C and loss factor D are shown in table 3. The phase angles are very close to 90 degrees and the impedance values decrease by a factor of 10 per decade frequency, thus indicating the typical behaviour of a capacitance. The fully grouted polymer duct shows the lowest impedance.

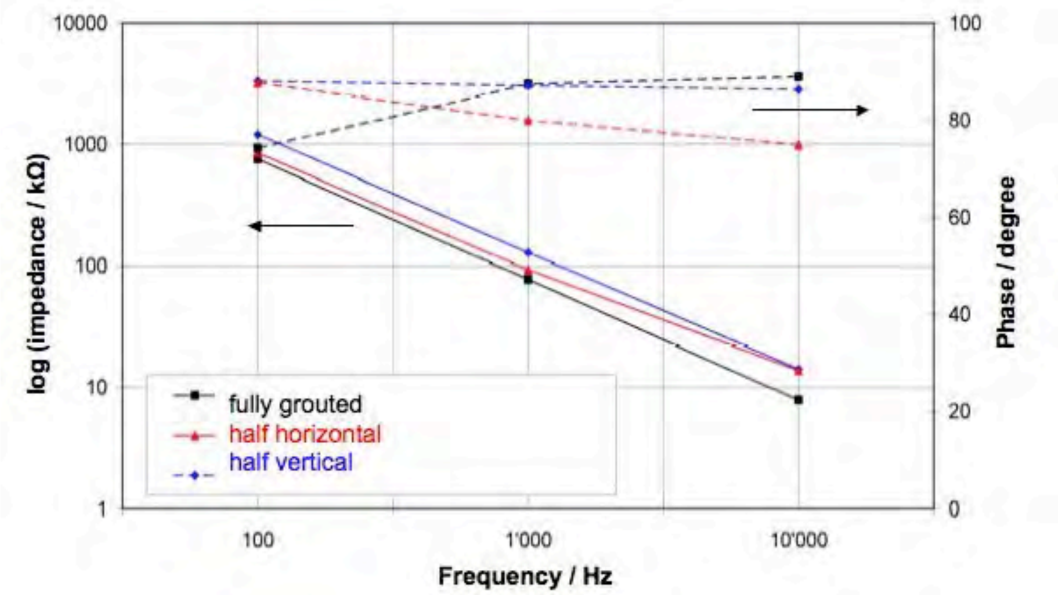
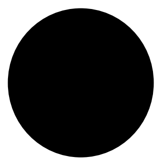


***Figure 10**: Impedance spectra in the frequency range from 100 to 10'000 Hz for the three differently grouted polymer ducts (see figure 8). Measurements performed after 28 days with LCR meter (6451 LCR databridge) [19].*

***Table 3**: Results of resistance R, capacitance C and loss factor D for the differently grouted polymer ducts*

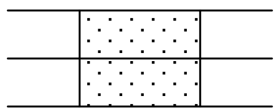
Fully grouted

Frequency	Resistance	Capacitane	Loss Factor
100 Hz	*2.668 MΩ*	*2.107 nF*	*0.283*
1 kHz	*1.731 MΩ*	*2.057 nF*	*0.045*
10 kHz	*0.442 MΩ*	*2.023 nF*	*0.018*



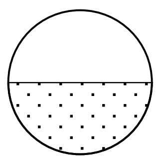
Half length grouted

Frequency	Resistance	Capacitane	Loss Factor
100 Hz	*35.4 MΩ*	*1.294 nF*	*0.034*
1 kHz	*2.58 MΩ*	*1.223 nF*	*0.05*
10 kHz	*222.7 kΩ*	*1.124 nF*	*0.064*



Half section grouted

Frequency	Resistance	Capacitane	Loss Factor
100 Hz	*21.2 MΩ*	*1.875 nF*	*0.04*
1 kHz	*535.7 kΩ*	*1.687 nF*	*0.176*
10 kHz	*53.21 kΩ*	*1.108 nF*	*0.27*



Evolution with time
For the fully grouted polymer duct of length 1 m the evolution of resistance and capacitance was followed over time from 3 days after grouting to 28 days after grouting.

Resistance: The resistance R at the frequency of 100 Hz decreased from 550 to 2.67 MΩ, the drop in resistance occurred between 4 and 15 days. At times longer 20 days after grouting the resistance remained constant and is in good agreement with earlier measurements [16].

Capacitance: The capacitance C of the fully grouted 1 m long polymer duct at the frequency of 100 Hz increased gradually from 2.02 nF to 2.107 nF. From 20 days onward the values were constant.

The results can be interpreted by a slight water uptake into the polymeric material, resulting in a lower specific resistance and a slightly higher specific capacitance, where the dielectric constant e slightly increased.

4.3 Interpretation

The goal of this series of experiments was to verify if and to what extent voids in a not fully grouted duct could be detected. As is expected and shown in table 3 the differently grouted ducts showed difference capacitance values.

The capacitance C can be calculated according to

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \quad [F] \quad \text{with} \quad \varepsilon_0 = 8.85 \cdot 10^{-12} \quad \left[\frac{C}{Vm}\right] \quad \text{eq. (3)}$$

The capacitance C of a duct corresponds to a condenser in cylindrical form and can be calculated according to

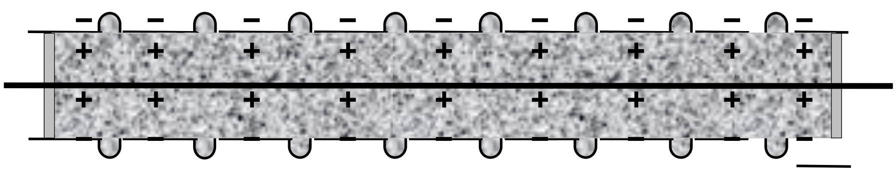
$$C = \frac{2\pi l \varepsilon_0 \varepsilon_r}{\ln\left(\frac{r_a}{r_i}\right)} \quad \text{eq. (4) with}$$

l = length of the duct [m]
ε_0 = dielectric constant of the vacuum = 8.85 * 10^{-12} [C/(Vm)]
ε_r = dielectric constant of the duct material [-]
r_a = external diameter of the duct [m]
r_i = internal diameter of the duct [m]

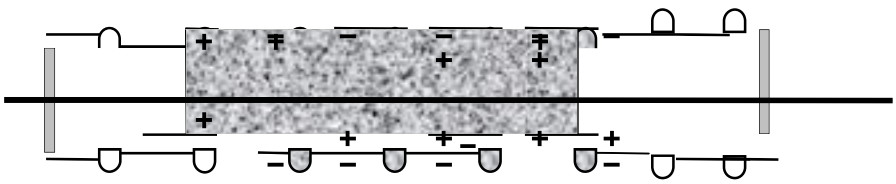
The specific ducts used (VSL PT-PLUS system) ø 59 mm show external diameter r_a of 63 mm und internal diameter r_i von 58 mm. The dielectric constant of Polypropylene ε_r was found to be ca. 3. With the formula above the capacitance of a 1 m long fully grouted duct is 2.02 nF in good agreement with the measured values.

Comparing the different geometries of the fully and half grouted ducts it is obvious that the area A of the capacitance for the half grouted ducts is only half of the fully grouted duct.

Fully grouted duct



Half grouted duct (50% of the length)

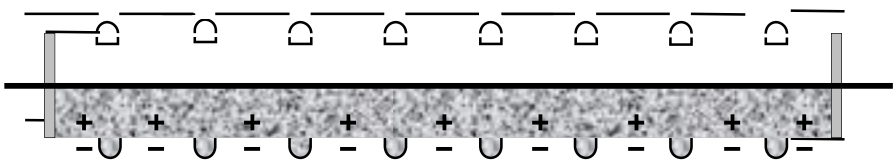


As only the area changes the capacitance of the half grouted duct (LS) should be half of the fully grouted duct (RF)

$$C_{LS} = \varepsilon_0 \varepsilon_r \frac{A/2}{d} \Rightarrow C_{LS} = \frac{1}{2} C_{RF} \qquad \text{eq. (5)}$$

As can be seen from table 3 the ratio is found between 0.61 (100 Hz) and 0.56 (10’000 Hz). These differences can be explained by experimental difficulties: the actual length of the fully grouted duct was only 0.95 m and the length of the grouted zone was slightly longer then 0.5 m. With these uncertainties the value 0.56 is in good agreement with the theoretical ratio of 0.5.

Half grouted duct (50% of cross section).



Also in this case the area of the capacitance is only half of the fully grouted duct and the capacitance ratio should be 0.5, too. The results (table 3) range from 0.89 at 100 Hz to 0.56 at 10'000 Hz. This slight deviation can be explained by the grouting procedure; it was difficult to control exactly 50% of grout filling.

4.4 Conclusions for practice

The results show that grout voids can – in principle – be detected by capacitance measurements. The voids considered were model situations that might not be found in practice, the detection becomes more difficult. In any case for a (completely empty) void of 1 m length in a 100 m long duct the variation of the capacitance would be only 1%. This variation is too small compared to the precision and scatter of the measurements. For practical situations where voids are partially grouted the detection might be even more difficult. In addition the capacitance measurement provides an integral result that does not allow locating the place of the voids.

5 Evolution of grout resistance with time

The Swiss guideline from 2001 [14] required the measurement of the electrical resistance at 28 days after grouting. This quite rigid requirement was found to be problematic in practice:

- it was frequently difficult to measure exactly after 28 days
- 28 days are a long time, owner and contractor often prefer to get the results of the acceptance measurements and the fulfilment of the criteria earlier.

Thus a second research topic was to study the evolution of the electrical resistance of grout mixtures at times ranging from 3 to 28 days after grouting in the laboratory.

5.1 Measurement setup

For the measurement of the evolution of the electrical resistance of grout mixtures 12 samples with dimensions of 160 x 40 x 40 mm were cast (figure 11a). In the samples stainless steel measuring pins (ø 4 mm) were mounted before grouting.

***Figure 11**: Samples of grout mixture for measuring the evolution of the electrical resistance with time. a) moulds after filling with grout on the vibration table.*

The mixtures studied were made of CEM II /A-L 42.5 R and 6.5 weight% of additive Flowcable (Rheomac GF320, Master Builders Technologies). They were stored in constant temperature and relative humidity cabinets at 10, 20 and 30 °C and 85% and 95% relative humidity for 28 days.

5.2 Measurement principle

The 4-point measurement according to Wenner uses a 40 V 107 Hz AC signal. At the outer pins the current I enters into the sample, at the inner pins the voltage drop U is measured.

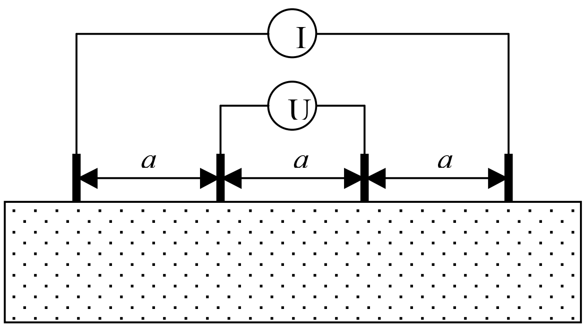


***Figure 12**: Principle of the electrical resistance measurement according to Wenner*

Assuming a homogeneous isotropic grout material, the specific electrical resistance ρ of the grout can be calculated according to

$$\rho = \frac{2 \cdot \pi \cdot a \cdot U}{I} \quad [\Omega m] \quad \text{eq. (6)} \quad \text{with}$$

a : Distance between the electrodes $[m]$
U : measured voltage $[V]$
I : impressed current $[A]$

Measurements were performed with a four-point electrical resistance meter GEOHM (figure 13) at a frequency of 107 Hz to avoid interference with 16 2/3 Hz and 50 Hz AC line signals.

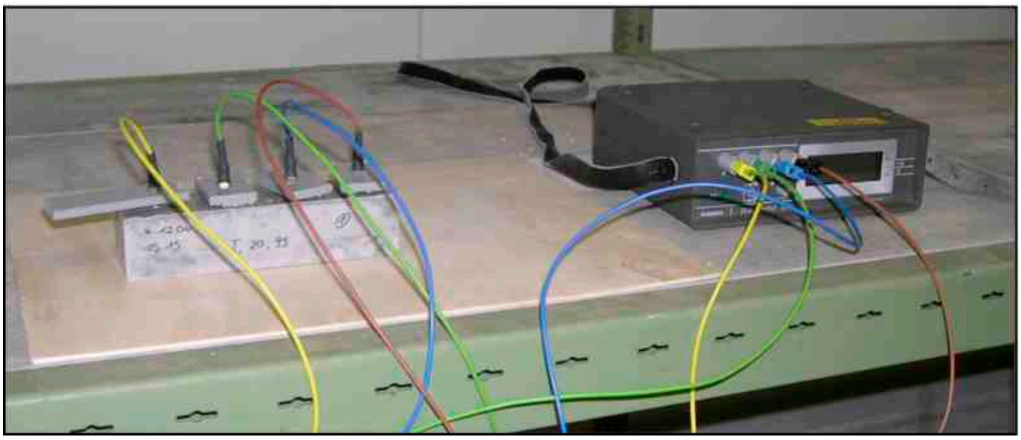


***Figure 13**: Measurement setup for the electrical resistance measurements*

5.3 Results

The evolution of the specific resistance (average over three samples each, standard deviation < 8%) of the grout mix for the different temperatures (10, 20 and 30 °C) and relative humidities (85%, 95%) with time is shown in figure 14 [19].

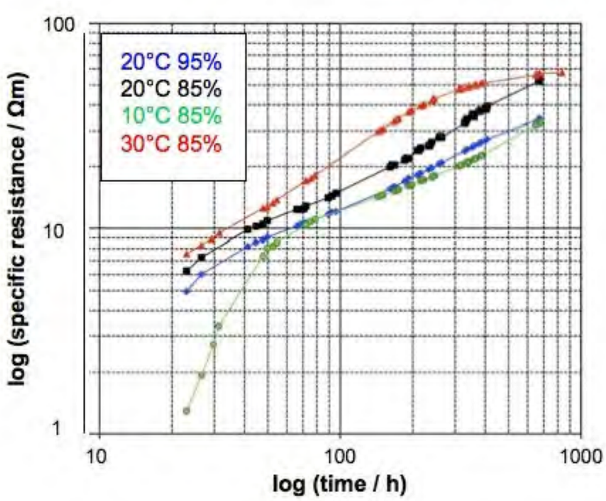


***Figure 14**: Evolution of the specific electrical resistance ρ for cement grout mixture at different temperatures and relative humidities (10 – 30 °C, 85% and 95% RH) [19].*

After an initial phase (20 – 50 h, probably due to the hardening of the grout) the specific electrical resistance increases according to the expected square root law (represented by a straight line in a log ρ vs log t plot with slope of ca. 0.5). The slope, thus the hydration rate, increases with increasing temperature. The relative humidity in the range 85 to 95% has a minor effect.

5.4 Interpretation

Cements are fine mineral powders that, when they are mixed with water, form paste that sets and hardens due to hydration reactions. In the presence of water, the compounds of the cement form colloidal hydrated products of very low solubility. Hydration of cement in concrete, mortar or grouts is a time dependant process and the electrical resistance of mortar or concrete [21] and grouts increases with time [22] similar to the strength development of concrete. This process can continue for several years.

5.5 Conclusions for practice

The results have shown that hydration of cement based grouts is accompanied by an increase of the electrical resistance of the grout material with approximately a square root time function. This allows establishing a conversion function that can transform the specific electrical resistance ρ_t measured at any time t (t > 2 days for normal ambient temperature, longer for low temperatures) into the specific electrical resistance ρ_{28d} used as criteria in the revised guideline for electrically isolated tendons (EIT):

$$\rho_{28d} = \rho_t * (28 / t)^{0.5} \qquad \text{eq. (7)}$$

As an example: the specific resistance measured after 7 days has to be multiplied by $(28/7)^{0.5}$, thus a factor of two. The same information is given in the graphical representation in figure 15. These conversion formula and graph have been included in the revised Swiss Guideline [25].

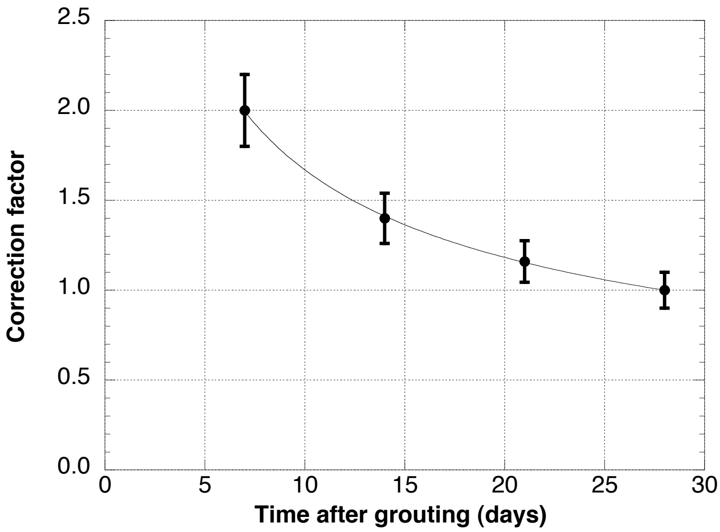


***Figure 15**: Graphical representation of eq. (7)*

6 Quality control of EIT systems in practice

System approval and quality control is decisive for the success of new technologies such as electrically isolated tendons (EIT), but detailing and the construction process as well as the quality of workmanship are equally important.

6.1 Component and system approval test

The requirements, test methods and acceptance criteria for the individual components of the EIT system are given in international regulations [13]. Any new pre-stressing system with plastic ducts has to pass a System Approval Testing according to the Guideline for European Technical Approval of Post-tensioning Kits for Prestressing of Structures (ETAG 013). Additional specifications and requirements for system approval can be specified nationally. In Switzerland, the approval procedure of a new post-tensioning system is based on extensive laboratory tests and continuous quality control of the components. Three systems are approved so far (updated information on the web site www.empa.ch/zulassungsstelle).

The Italian Railways have applied System Approval Testing to new post-tensioning system proposed by Italian construction companies; so far only one electrically isolated system has been approved and widely used on site. The System Approval Testing – apart from chemical and mechanical tests on the post-tensioning system components – has to be performed on the prefabrication site before starting the construction, for every first application of a pre-stressing system with post-tensioning tendons, because personnel skills and experience, and available instruments in the construction site have decisive influence on system performance. The measurement of the electrical impedance to test the electrical isolation is only one of several tests that compose the System Approval Testing. These other tests should always be performed on site even when systems with corrugated plastic ducts without electrically isolated anchorages (EIT) are adopted. System approval includes a test beam representative of the structure or the prefabricated segments [23]. Stressing has to take place in the worst condition expected from design: it means the minimum number of days from casting, with the lowest concrete compressive strength and comparable pressure and relative displacements of pre-stressing steel during stressing. Grouting operations have to be performed on the tendons in the test beam as it is expected on real decks; for the post-tensioning tendons of PC railway bridge deck, injection with vacuum technique was always prescribed [23].

6.2 Quality control

6.2.1 Impedance measurements

The measurements of the electrical isolation between the strand and the reinforcement require a sound electrical connection (item 9 in fig. 4) to each individual tendon (preferably mounted to both of the end anchorages) and another connection to the reinforcement. All the connection wires (area 1 mm^2 apart from the case of AC railway bridges where it is 6 mm^2) are concentrated in a box easily accessible. Monitoring of the electrically isolated tendons is performed with AC impedance measurements at a frequency of 1 kHz with portable LCR meters.

The instrument measures the impedance Z that includes (over the whole tendon length) the grout in the duct, the duct (with couplers, vents, pores and defects) and the concrete surrounding the duct (Fig. 2). Grout and concrete are (at 1 kHz) pure resistances, the intact polymer duct is a pure capacitance and “defects” are represented by parallel ohmic resistances (fig. 2). The instrument calculates and displays the ohmic resistance R, the capacitance C and the loss factor D.

The capacitance C is constant for a specific tendon length, diameter and material of the duct; it increases proportionally to the length of the tendon. The capacitance C can thus be used as a first control value to check the tendon integrity. The ohmic resistance R for a given tendon decreases with its length L. For a good electrical isolation the specific value ρ = R*L (Ωm) should be as high as possible, limiting values based on laboratory studies and field experience have been defined (table 2). The measurements of R, C and D allow assessing the degree of electrical isolation (and thus of the tightness of the duct on its whole length) at any time after grouting. This can be used both for quality control and for long-term monitoring of the corrosion protection of post-tensioning tendons.

6.2.2 Impedance measurements before grouting

Impedance measurements are recommended in [25] also after stressing the tendons but before grouting. The electrical measuring circuit (fig. 2) is due to the lack of grout not closed, thus usually very high and unstable values are obtained. These measurements can reveal short circuits or unexpected very low impedance between high-strength pre-stressing steel and the normal reinforcement. Reasons might be defects in the anchor head (for example, non perfect junction between insulation plate and plastic trumpet), damaged ducts due to insufficient wear resistance, too low stiffness or too long distance between supports. These electrical impedance measurements provide information that cannot be obtained otherwise. In combination with techniques to locate a short circuit repairs may be possible before grouting.

6.2.3 Impedance measurements after grouting

In tendons for which electrical insulation is measured after stressing, a drop of impedance is measured just after grouting due to filling of the whole length of the duct with an electrolyte. From that time on, impedance starts to increase with hydration and later slow drying of the grout (and partially also of the concrete). This is the reason that the limiting value for sufficient electrical isolation referred to a fixed period of time after grouting (according to [14], 28 days). According to the revised guideline [25] the measurements can be performed between 2 days and 28 days after grouting and converted to the 28 day value (see chapter 5, figure 15).

6.3 Acceptance criteria in practice

6.3.1 Experience with segmented slabs (Piacenza Viaduct)

In the Italian high speed network the Piacenza viaduct (Fig. 16, 17) on the Milano-Bologna line is an example for full-span pre-casting of 151 simply supported pre-cast pre-stressed concrete decks composed by a monolithic box girder with two cells, spanning 33.1 m and weighting about 1000 tons. The design of the elements and of the viaduct has been reported previously [18, 23]. Data have been collected from the first 71 decks of the Piacenza viaduct (fig. 17), each containing 9 cables with 12 strands, duct ø 76 mm (in the lower slab) and 15 cables with 19 strands, duct ø 100 mm (in the webs).

Figure 16: *Piacenza viaduct anchorages and transparent cap [18].*

Figure 17: *Piacenza viaduct full span precast deck in stocking area [23]*

The values of the capacitance C (table 4) allow a first control on the execution quality.

The values of the capacitance are Gaussian distributed and show a very small standard deviation, indicating a high and stable quality in the prefabrication process. The mean value is higher for ducts with higher diameter, the specific capacitance (per meter length) is well below the control values specified in [14, 25]. This indicates that the duct wall thicknesses are higher than specified.

Table 4:
Mean values and standard deviation of the capacitance values of the tendons tested

	Piacenza Viaduct				Marchiazza Viaduct				[14]
Type	C_{mean} [nF]	Std dev [nF]	Length [m]	C_{spec} [nF/m]	C_{mean} [nF]	Std dev [nF]	Length [m]	C_{spec} [nF/m]	C_{lim} [nF/m]
Ø 76	70.3	2.3	32.1	2.2	166.5	2.0	72.0	2.3	3.05
	73.5	2.2	32.1	2.3					3.35

The statistical analysis of the measured resistance R on more then 1000 tendons is more complicated because the values – despite the constant length of the tendons – do not show a gaussian distribution. The analysis is thus performed with the cumulative probability plot (figure 18, 19). For the tendons with ø 100 mm from the segments of the Piacenza viaduct (figure 18), less then 1% of all values are below 10 Ω, thus cables with a short circuit (electrical contact between tendon and normal reinforcement). The minimum of the specific resistance ρ = 300 kΩ*m according to [14] results in a lower limit of the electrical resistance R = 9 kΩ for the tendon with length 32.1 m.

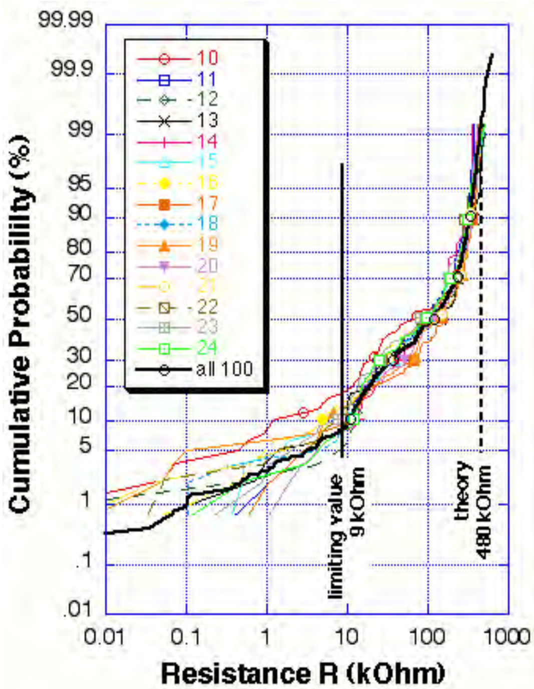


Figure 18: *Cumulative probability distribution of the resistance R, measured for 19 strands E.I. cables in 71 Piacenza viaduct decks.*

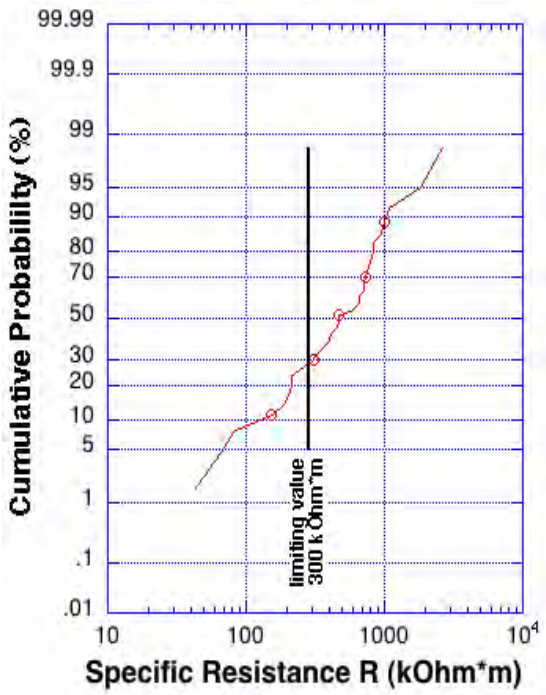


Figure 19: *Cumulative probability distribution of the specific resistance ρ, measured for 19 strands E.I. cables in 33 Marchiazza viaduct decks.*

As can be seen from figure 18 the limiting value is not reached by about 9% of the tendons. For the tendons with duct ø 76 mm the limiting value was not reached by 20%. The cumulative probability plot shows further that there is no specific tendon position (indicated by numbers 10 – 24 in fig. 18) that is more difficult to install then others because all cumulative plots are very similar. In addition, it can be noted that for each tendon position about 5% of all segments were produced with perfect isolation (reaching the theoretical value of a completely tight plastic duct). The broad distribution of resistance values measured shows that there is a strong influence of the human factor, as written procedures, approved material and components, deck formwork, reinforcement and pre-stressing were always the same.

6.3.2 Results from continuous slab bridges (Marchiazza Viaduct)

In the Italian high-speed network the Marchiazza viaduct is an example of a three span (22-28-22 m) continuous slab bridge along the Torino-Milano railway line, with height of the slab of 2.70 m. It is cast and pre-stressed on site in formworks scaffolding from the ground; it has 33 19-strand tendons with a length of 72 m and high points of duct profiles over central piers.
The measured capacitance values C (table 4) show a very narrow Gaussian distribution (standard deviation only 2 nF). This indicates a good and stable construction process as material and geometry of the duct are the same. The specific resistance values (cumulative probability plot fig. 19) are for about 75% of all tendons above the limiting value of 300 kΩm [14]. In contrast to the data from the Piacenza viaduct, no tendon reached the theoretical maximum value. As the pre-stressing company and the details of the isolation of the anchor head were the same as in the Piacenza viaduct, one would expect similar results as in the Piacenza viaduct. However, the construction company was different, thus all the experience and the personnel training was different.

6.3.3 Results from continuous slab bridges - Switzerland

The flyover “P.S. du Milieu” near Avenches is about 100 m long and consists of six spans with five columns. The anchorage zone is constructed with robust plastic ducts and plastic sleeve and electrically isolated anchorages. Six electrically isolated tendons (length 100 m, PT PLUS duct diameter 59 mm) were measured in order to control the integrity of the duct after construction. The temperature during measurements was 11 °C, there was no rainfall several days before the measurements. Table 5 presents the results of the impedance measurements at 1 kHz. As can be observed, the ohmic resistance R is high or very high for five of the six tendons (nr. 1 – 5), tendon nr. 6 shows a very low value, indicating a short circuit between steel strand in the duct and reinforcement. The capacitance values C are nearly constant (234.8 ± 2 nF). The loss factor D varies between 0.023 and 0.093.

***Table 5**: Experimental and calculated specific values of the ohmic resistance R, the capacitance C and the loss factor D from the flyover “P.S. du Milieu” (length 100 m)*

tendon Nr	experimental values			Specific values		
	R (kΩ)	C (nF)	D (-)	R (kΩm)	C (nF/m)	D (-)
1	7.234	234.0	0.093	723	2.34	0.093
2	13.70	233.0	0.048	1370	2.33	0.048
3	20.87	235.0	0.032	2087	2.35	0.032
4	17.81	237.2	0.037	1781	2.37	0.037
5	28.25	234.7	0.023	2825	2.35	0.023
6	0.006	-	-	Short circuit		

The old Swiss Guideline [14] defined a lower limit of 500 kΩm as acceptance criteria for the integrity of the duct (59 mm). Thus all the tendons of the flyover P.S. du Milieu (table 5) show a good to perfect electrical isolation with no defects present (otherwise the electrical resistance should be much lower). An additional confirmation can be obtained from the (length independent) loss factor D that was found to be always < 0.1 (table 5).

The increasing number of PC structures constructed with EIT tendons in Switzerland allowed to gain more practical experience, unfortunately only partially available and published [12, 24]. Since the construction of the first flyovers (pilot-projects) [12, 16] about 100 structures (both railway and highway bridges or flyovers) were built with electrically isolated tendons. Often contractors and owners complained about the difficulty or even impossibility to reach the acceptance criteria fixed in the Swiss guideline [14].

Wiesebrücke Basel

This flyover constructed for a highway link with about 60 EIT tendons of different length showed that the capacitance values of the individual tendons are proportional to the tendon length L as expected (Figure 20). From the slope of the diagram a value of C = 2.35 nF/m was obtained in good agreement with laboratory results. The results of the resistance values R (multiplied by the length of the tendons) showed values from 10 to 1800 kΩm. In the cumulative probability plot (Figure 21) clearly two distributions (lines) could be observed: the one at high R values was associated with "good" tendons (acceptance criteria fulfilled). However, ca. 50% of the tendons did not reach the acceptance criteria.

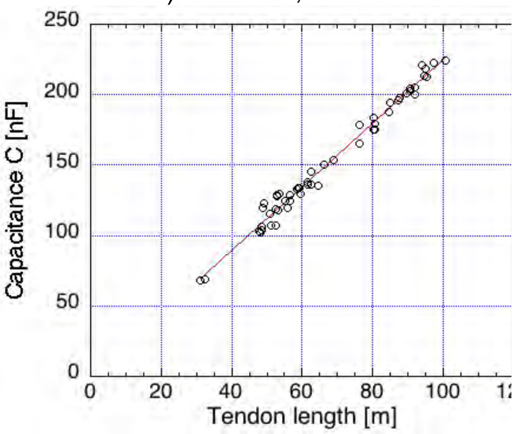


Figure 20: Capacitance C of the individual EIT tendons in a flyover near Basel as a function of the tendon length. Diameter of plastic duct 59 mm

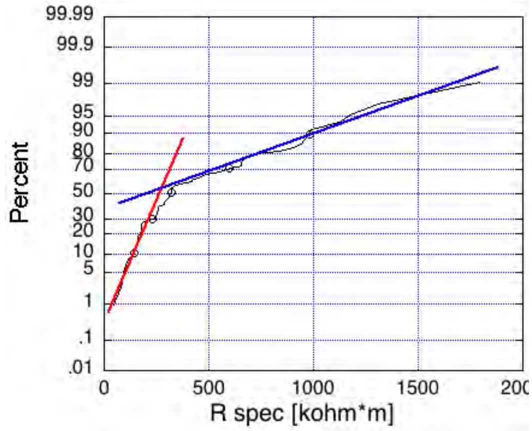


Figure 21: Cumulative probability plot of the resistance values measured for EIT tendons in a flyover near Basel. Diameter of plastic duct 59 mm.

Glattal viaduct

This series of viaducts near Zurich airport were built for the new tramway connection. Electrically isolated tendons were mandatory due to the expected stray currents (DC current for the trajection). Measurements on one viaduct with about 45 EIT tendons of different length between 37 and 150 m confirmed that the capacitance values of the individual tendons are proportional to the tendon length L as expected (Figure 22).

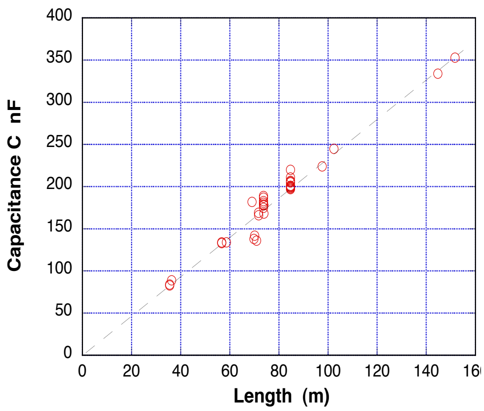


Figure 22: Capacitance C of the individual EIT tendons in a viaduct near Zurich airport as a function of the tendon length. Ø 59 mm

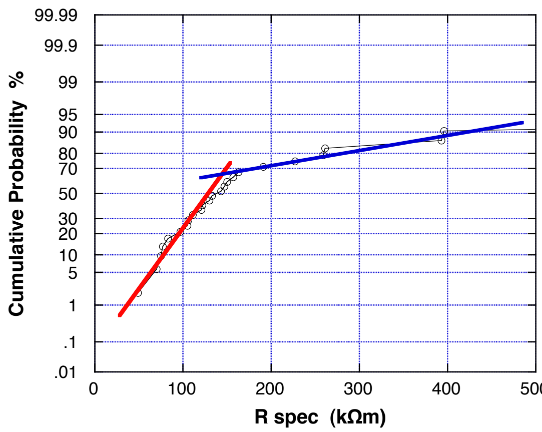


Figure 23: Cumulative probability plot of the resistance values measured for EIT tendons in a viaduct near Zurich airport. Ø 59 mm

The measured resistance values, converted to specific resistance by multiplying with the tendon length, showed two distributions as well (Figure 23). Particularly surprising was at first the very low level of the specific resistance of all the tendons (all values below the acceptance criteria of 500 kΩm). This fact could be explained by the special atmospheric conditions in the bridge: due to an occluded situation (no air convection) very frequently condensation of the humidity on the concrete occurred, so drying out as usually expected could not occur and the specific resistance of the concrete remained low and even decreased with time. In this specific case the criteria established in the Swiss guideline [14, 25] could not be applied.

Overall the percentage of success in different PC structures showed large differences: bridge structures with EIT tendons where 100% were considered as "good", others where only 30% of the tendons fulfilled the acceptance criteria. Many reasons, e.g. the beginning of the transfer of the EIT technology to practice, the length of the cables, the presence of couplers, design or execution problems were discussed:

1) Every structure is "unique" in its design, not all engineers are familiar with the special design requirements when using plastic ducts and electrically isolated anchorages.
2) The system approval test is performed on the components in the laboratory and not on several tendons on site.
3) The construction company often has no specific experience with EIT systems and the personnel working on site frequently changes, thus instruction becomes very difficult
4) Quality control until today is concentrated mainly at the prestressing company – defects often are detected too late.
5) A systematic quality control system operating on-site is lacking.

6.4 Suggestions for practice

Electrically isolated tendons (EIT) are a new system for enhanced corrosion protection of PC tendons. This system allows a rigorous quality control in prefabrication but also on continuous slab bridges. The success of this new system in terms of enhancing the durability depends on several factors:

1) The design process: the engineer has to be aware of the fact that EIT tendons with plastic ducts will be used. Curvature, space for putting the duct between the normal reinforcement and careful placing of half-shells at high- and low points are necessary. The worst results were obtained when changing in the last moment from traditional metallic ducts to EIT tendons.

2) Operators working on site have to be instructed and trained how to work with plastic ducts. E.g. plastic binders should be used, plastic half-shells at support points. The plastic duct should have enough space. Do not walk on the duct.

3) Quality control on the construction site at any time is important. Starting from the delivery, the storage, placement and fixing of the ducts has to be controlled. Before inserting the steel wires into the tendon a leak test (light in the dark, smoke) is recommended. Only at this time a repair is (relatively) easy possible.

4) All partners involved in the construction – from the engineer, the contractors, working people and the owner should agree to achieve together the highest quality possible. It is not only the responsibility of the pre-stressing company to guarantee a good result.

6.5 Revised Swiss Guideline

The Swiss guideline from the year 2001 [14] had to be revised after 5 years in the light of the experience from practice. The following improvements have been included into the new Swiss guideline (2007) [25]:

- The electrical resistance measurements (acceptance criteria) can now be performed not only after 28 days after grouting but at any time (between 7 days and 56 days). The normalization of the measured value to 28 days is performed by taking into account the evolution of the resistance with time (see chapter 5). This gives more flexibility to the contractor and the owner.
- The acceptance criteria have been differentiated according to the main reason for using electrically isolated tendons: if only fretting between normal reinforcement and the high strength steel in the duct has to be prevented, the limiting resistance value has been defined as 20 Ω (no short circuit exists); for long term monitoring purpose the acceptance criteria has been defined as 50 kΩm, and for protection against stray currents the acceptance criteria has been defined as 150 kΩm. In the case of multiple reasons for specifying EIT strands the highest value is the limiting value.
- In an appendix the “good practice” on site is documented with short text and mainly images, showing the most frequent errors in the application and how they should be avoided.

It has to be stated once more: tendons with polymer ducts that did not reach the acceptance criteria are in any case protected much better against corrosion then tendons with metallic ducts. In all cases (except when a short circuit is present) the tendons can be included in the long term monitoring program of the structure (see following chapter).

7 Long term monitoring

One of the main concerns regarding internal bonded post-tensioning tendons is the inability to inspect the tendons visually. Non-destructive techniques to locate the steel strands have made great progress [20], the detection of corrosion is still very difficult. Using electrically isolated tendons with plastic ducts, the evolution of the resistance values over time can be used to control the integrity of the corrosion protection system.

7.1 Bridge inspection system

The measurements require a sound electrical connection to each individual tendon (preferably mounted to both of the end anchorages) and another connection to the reinforcement. All the connection wires usually are concentrated in a box easily accessible (Fig. 24). Monitoring of the electrically isolated tendons was performed with AC impedance measurements at frequency of 120 Hz and 1 kHz. A small portable and battery driven instrument (LCR meter ESCORT 131) measures the real and imaginary part of the impedance of the tendon under test. The instrument calculates and displays the ohmic resistance R, the capacitance C and the loss factor D for the measuring frequency chosen.

Figure 24 *: Measuring box*

After opening of the box with the sockets and connection cables, a visual check of the sockets should be performed; the sockets should be dry and clean. The connection from the instrument to the socket “rebar” and “tendon number“ is established using short laboratory cables with a diameter of 1 mm. The results of measurements should be written down in a form. Each tendon has to be measured twice. Temperature and weather condition must be documented.

7.2 Field tests – long term monitoring

As an example the flyover “Pré du Mariage” (Figure 25) is presented. It is a relatively simple, short box girder structure with only one column in the middle. Six electrically isolated tendons of ø 76 mm and length 49.3 m were used. At “Pré du Mariage” electrical impedance measurements have been performed at frequent intervals since the time of grouting. The evolution of the electrical resistance with time is shown in figure 26. As can be noted, the values for the six individual tendons show a certain scatter, but the overall trend is an increase of the electrical resistance with time. In the log R vs log t plot a straight line with slope 0.5 is found.

***Figure 25**: Flyover "Pré du Mariage" near Avenches (highway A2 Switzerland)*

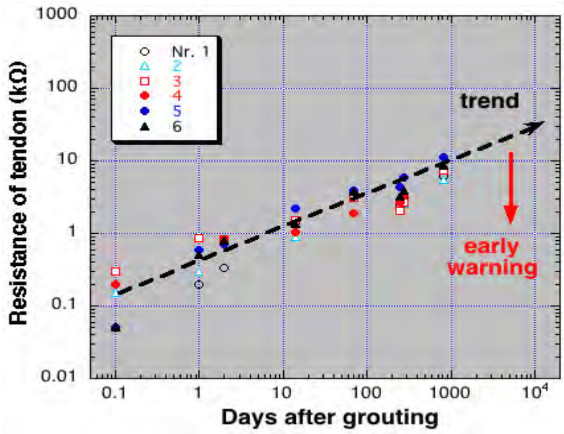


***Figure 26**: Evolution of the electrical resistance of the six tendons of the flyover "Pré du Mariage" with time*

This is equivalent to the normal square root law indicating that the increase in resistance is very rapid at the beginning and slows down after some month. This trend is expected to continue, with some variations due to temperature, for all tendons and for the entire future service life of the structure. Deviations from the expected trend, a decrease in the resistance of one or several tendons, allows detection of the ingress of (chloride containing) water at a very early stage: if water reaches a defect in the duct, the concrete and the grout near the defect get wet and the electrical resistance of this specific tendon will drop [26, 27].

Another example of long term monitoring is a simple one span railway bridge of 23 m length with 12 tendons of 59 / 76 mm diameter near Lenzburg (AG, Switzerland) built in 2003. Measurements of the electrical resistance were performed in regular intervals. As the resistance of the individual tendons varied much more than in the "Pré du Mariage" (Fig. 26), the values were normalized with the value at 28 days. This allows following the evolution with time (Figure 27) much better. As can be seen, three of the four tendons represented follow the trend line with slope 0.5, indicating an asymptotic increase of the electrical resistance with time and no sign of water ingress. Only one tendon shows continuously decreasing values of the normalized resistance, indicating that at least at one of the defects water (and probably also chloride ions) are penetrating into the grout.

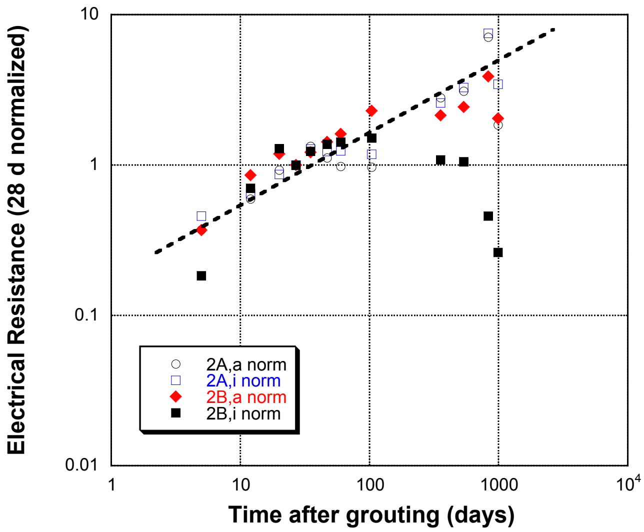


***Figure 27** : Evolution of the normalized electrical resistance of four tendons of the bridge "Muhen" with time*

The measurement of the electrical impedance of the electrically isolated tendons at the normal inspection intervals represents a simple but very effective early warning system to detect a corrosion risk situation (ingress of water) long before corrosion actually starts. Enough time is available to locate the defect with magnetic measurements [24, see chapter 8], to judge the corrosion risk and to plan rehabilitation. An additional advantage is that no sensors (with unknown reliability and long term stability) are needed: the steel strands to be controlled represent the sensors for remote monitoring, thus EIT tendons can be considered as a “smart structure” [26].

7.3 Suggestions for practice

Electrically isolated tendons allow to monitor the corrosion protection of the high-strength steel (tightness of the duct) in grouted tendons over the whole service life with simple measurements of the electrical resistance. Several pilot objects have demonstrated that with good workmanship the acceptance criteria can be fulfilled. In normal construction practice, the degree of success was only 50 – 70 %. However, a tendon that does not fulfil the acceptance criteria can still be monitored over time – only an electrical short circuit makes monitoring impossible. The measured resistance of the tendon should increase with a power law – if for several measurement in sequence the resistance decreases, this specific tendon will have a durability problem (ingress of water at some point).
Note that temperature has a marked effect on the electrical resistance measured, the variations can be up to 30%. It is thus important to record also the temperature at the time of measurement.
Although an electrical connection at both ends of a tendon is slightly more expensive, both ends should be connected. This gives further redundancy (connection broken) and helps in locating possible defects (see chapter 8).

8 Defect location

When short circuits are measured at the time of quality control (acceptance) or insufficient resistance values during service life, the question arises whether the defect can be located in order to estimate its consequences for the durability, to improve the system in upcoming applications, or to repair the defect. As a consequence, techniques for detecting these defects were developed and tested [24].

8.1 Principle

Imposing an AC electric field between the high strength steel and the reinforcement (using the electrical connections provided for the impedance measurements), a current is flowing through the tendon. Measuring the magnetic flux of the resulting AC-current (figure 28) allows determine the areas with current flow and, as a consequence, to locate the preferred sites (short circuits) where the current is leaving the tendon. Hence, this measurement allows detecting the areas with lowest resistivity of the isolation of the tendon. A schematic representation of the experimental setup is shown in figure 28a and b.

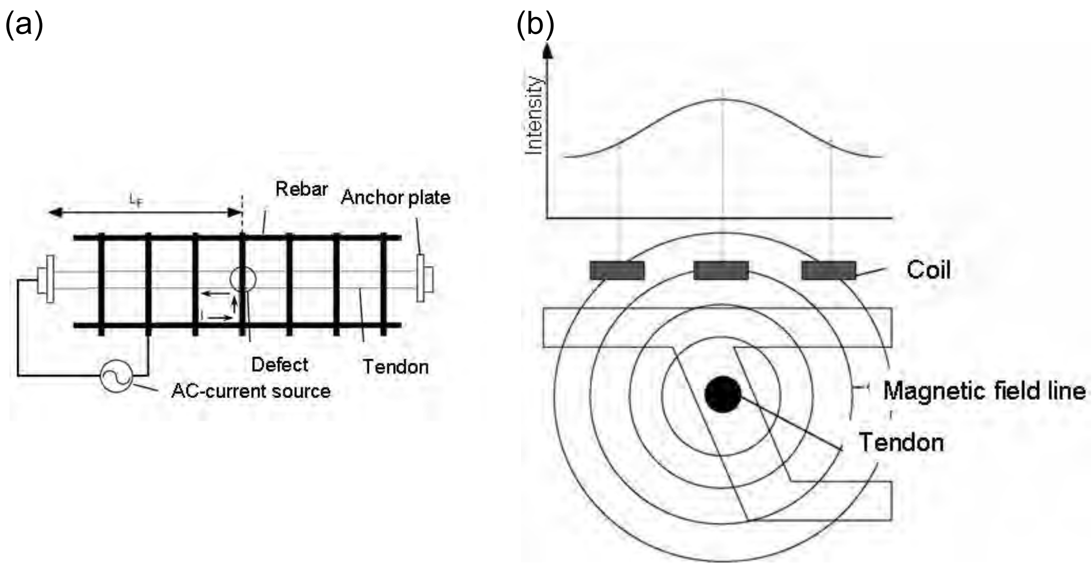


***Figure 28**: Detection of the magnetic flux created by a current in the tendon. a) Experimental setup for the measurement. b) Dependence of the result on the measuring position relative to the tendon.*

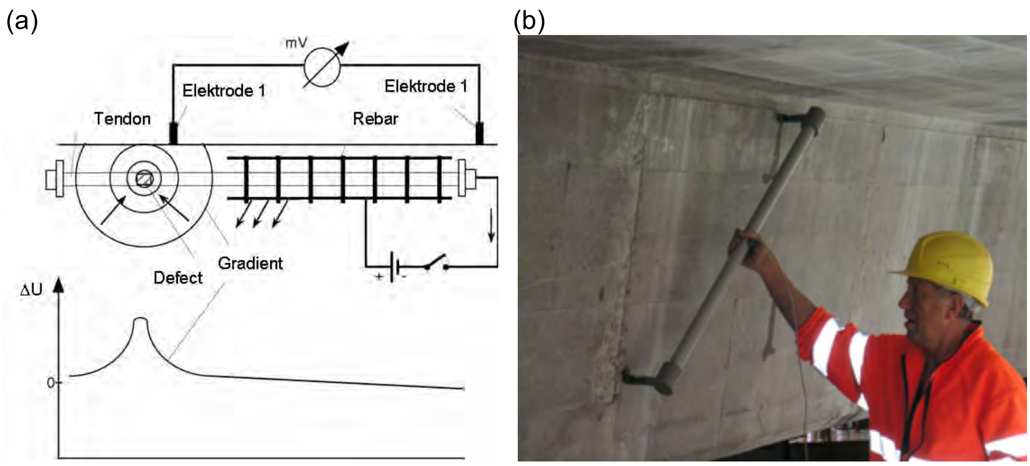


***Figure 29**: Detection of the ohmic potential drop caused by current leaving the defect. a) Experimental setup for the measurement. b) Application in the field.*

In the case of defects in the duct without a metallic contact to the reinforcement, the measurement of the potential drop in the concrete due to an applied current can be used to locate the defect. While the detection of the magnetic flux (see above) does not require a direct contact between the detector and the concrete surface, the use of the potential drop technique is only possible when the concrete surface over the rebar is accessible. The experimental set-up is shown in figure 29a for a DC-current source. The current leaving the tendon results in a ohmic potential drop in the concrete that can be measured (Figure 29b). In the practical application the use of an AC-current turned out to be the most reliable approach.

8.2 Examples, practical experience

In order to calibrate the measurements, simulated defects were introduced in concrete elements for laboratory investigation. Moreover a bridge was equipped with an additional tendon (Figure 30). For the measurements the AC current source and the detector unit CL20 from Baur was used in all measurements. The frequency was 815 Hz in all measurements.

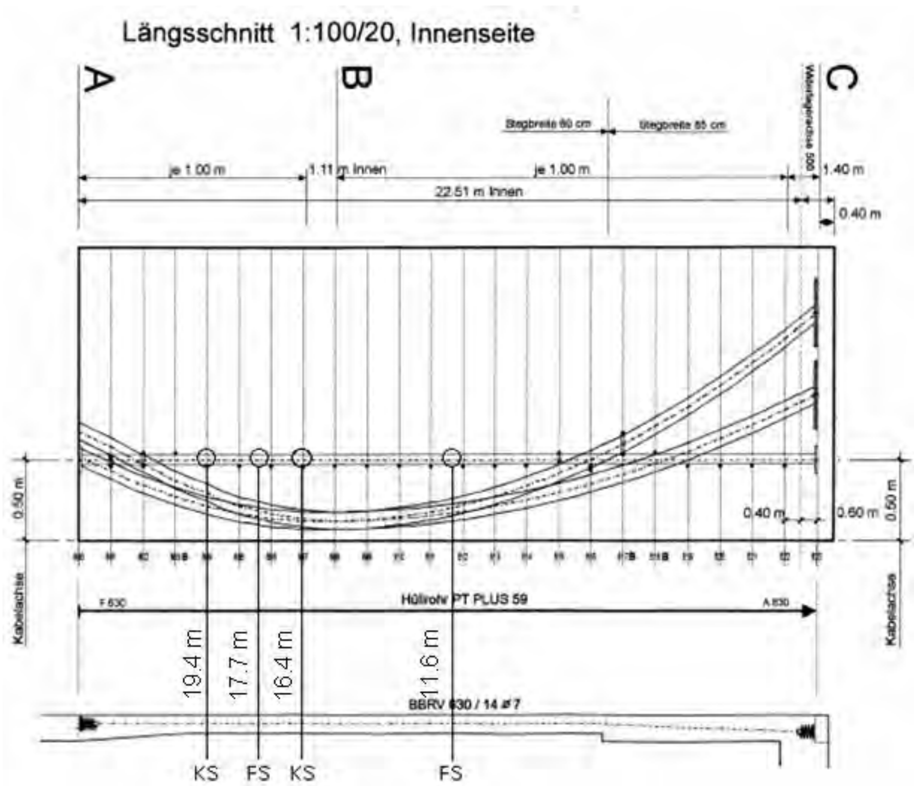


***Figure 30**: Additional horizontal tendon equipped with holes (FS) and contacts to the reinforcement (KS) that can be electrically opened.*

8.2.1 Additional tendon in a bridge with artificial defects

The results of the location of a metallic contact between rebar and tendon on the bridge equipped with a tendon that contains artificial defects are shown in figure 31. The measurement of the magnetic flux B was performed walking over the bridge deck with the detector. Different configurations with only one (front and rear contact) and both contacts were investigated. The reference point of the measurement was the anchor head at the end of the structure. Clearly a decrease of the magnetic flux is found at the location of the contact. This is due to the fact that the current is leaving the tendon at this point. The detection of a single contact is readily possible while in presence of two contacts a reliable detection of both of them is difficult.

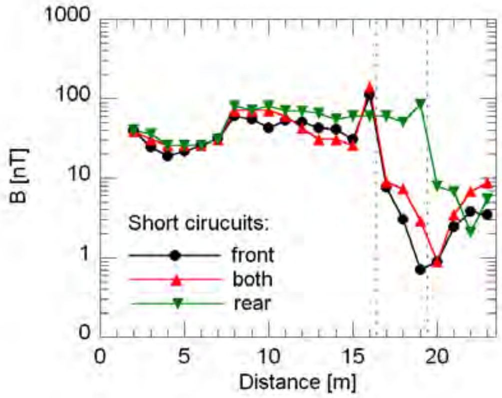


Figure 31: Distribution of the magnetic flux along the tendon installed in a bridge with different metallic contact configurations.

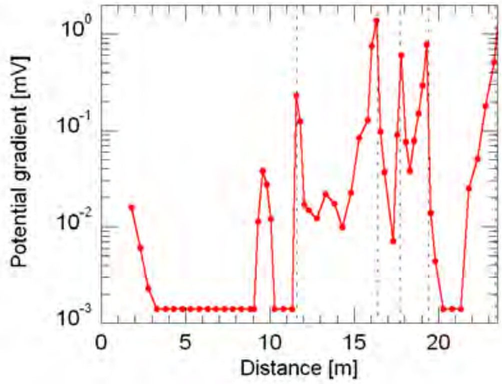


Figure 32: Potential drop on the concrete surface caused by the current flow from the tendon to the rebar. The vertical lines mark the area with the introduced defects (cf. Figure 30).

8.2.2 Defects without short circuits

Defects in the insulation of the tendon can be located only in the absence of a direct metallic contact between the reinforcement and the tendon by measuring the potential drop on the concrete surface along the tendon (Figure 29).

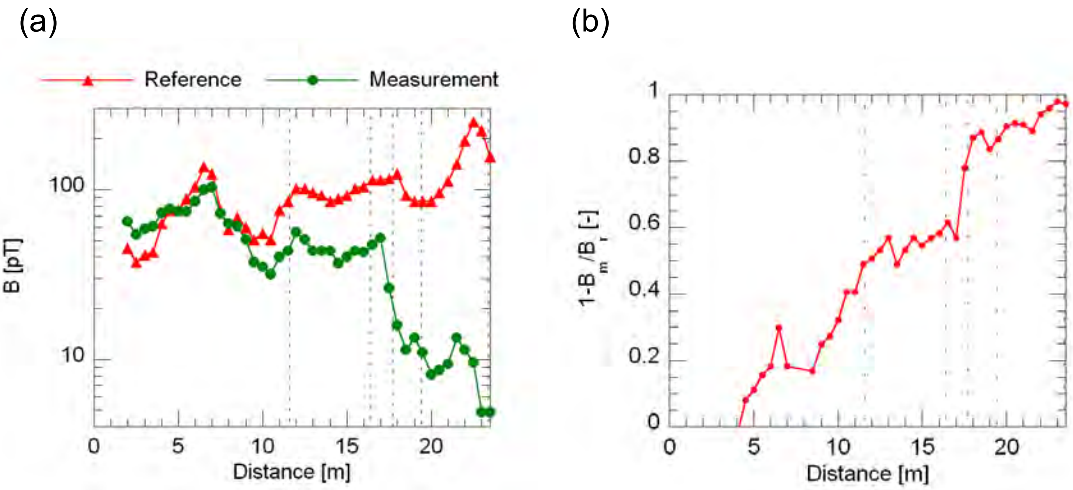


***Figure 33:** Measurement of the magnetic flux along the tendon. a) Results for a reference and the actual measurement without any connections to the rebar. b) Correction of the data in (a).*

This measurement was performed from the inside of the box girder. The two defects artificially introduced at 11.6 m with 5 mm diameter and at 17.7 m with 10 mm diameter show an increasing signal. Surprisingly, also the installations for the metallic contact and the cable connections at the anchors at both ends of the tendon show a signal. Based on this result it must be concluded that the wires connected to the tendon caused some interference with the measurement, since the signal level is very low. Additionally, at 9.8 m a potential drop is observed that cannot be caused with any of the artificially created defects. It can only be explained by a defect created during the construction.

In addition to the potential drop measurement, the magnetic flux distribution on the bridge deck was measured along the tendon in the same configuration as in Fig. 31. The results of the measurement are shown in Fig. 33a. Clearly, the major decrease of the magnetic flux is found at the large defect with a diameter of 10 mm at 17.7 m. Additional variations of the signal cannot be explained with defects in the structure.

Creating an electrical connection between the rebar and the anchor at 23.4 m and applying the same current as the original measurement allowed determining the magnetic flux created by the current flow in the tendon (Fig. 33a). Although the distance between detector and tendon is constant, a significant variation of the signal is observed. This is due to the inductance of the structure. Normalizing the data in Fig. 33a allows for compensating for the inductance of the structure (Fig. 33b). This correction allows a more clear analysis of the data. Still the large defect at 17.7 m can be detected. Additionally, a change of the signal between 8.9 and 11.5 m is observed. This effect can be explained with the defect introduced at 11.6 m with a 5 mm diameter and the defect at 9.8 m created during the construction (cf. Fig. 31). No changes in the signal were found at 17.7 and 19.4 m demonstrating that the signals observed in the potential drop measurement must be attributed to an interference with the connection cable.

Based on the obtained results it can be concluded that the measurement of the magnetic flux is a fast method for detecting the defect with the lowest resistivity in a tendon. The defects with a higher resistivity can only be reliably detected if a reference measurement is performed in order to compensate for the inductance of the structure.
In practical application the potential drop measurement turned out to be difficult to apply, since the access to the concrete surface over the tendon is not readily possible in most cases. Moreover, the concrete cover is often high in critical areas at pylons or anchors resulting in a decreased resolution. As a consequence, the potential drop measurement was only used in practical applications when the defect located with the magnetic flux measurement had to be localized more precisely or confirmed by an alternative measurement.

8.2.3 Detection of defects on a 100 m long tendon

An example for the detection of defects in a practical application is shown in Fig. 34 for four different tendons in a bridge girder. The variation of the magnetic flux B clearly shows the influence of the distance between the detector (concrete surface) and the different tendons. A sharp decrease of the signal allows the location of the defect. Based on the results it can be concluded that especially highpoints at the columns are critical areas. In the case of tendon 3, however, also a defect in the anchor was observed.

***Table 6**: Defects in percent of the corresponding element*

Metallic contact				Defect			
Highpoint	Lowpoint	Anchor	Coupling	Highpoint	Lowpoint	Anchor	Coupling
4.4	2.9	0.8	1.7	1.3	2.9	4.3	0.2

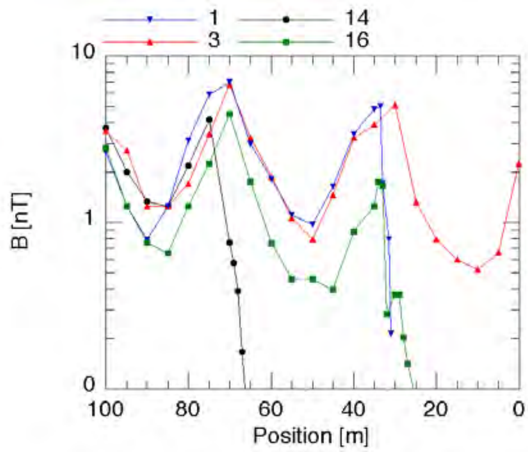


***Figure 34**: Measurement of the magnetic flux along the tendons in a bridge with 100 m length.*

8.3 Limitations of the technique

The results show also the problems associated with the measurement of the magnetic flux. Although the distance between the detector and the tendon was constant, significant changes in the flux are observed. This effect can be explained with the local geometry of the structure (Fig. 30). The increased rebar concentration at the end of the bridge results in a stronger shielding of the magnetic flux.

The technique primarily locates the defect with the lowest resistivity (e.g. metallic contacts between tendon and reinforcement). Such low resistive defects might mask other defects (e.g. holes in the duct). The most reliable location is possible if the tendon is electrically connected from both ends.

Moreover, it is important to note that the magnetic flux does not completely disappear beyond the contact. Instead an increase of the magnetic flux is sometimes observed. This can be explained with the inductance of a current in the other tendons. As these tendons are guided in a plastic duct but do not have insulating anchors, the magnetic flux induces a current that creates a magnetic field, which is interfering with the measurement. Contrary to laboratory investigation the extended dimension and conductor distribution (presence of reinforcement layers) have significant impact on the measurement. Hence the technique requires a detailed knowledge of the structure in order to obtain reliable results.

8.4 Suggestions for practice

The determination of the magnetic flux density around a tendon turned out to be a fast and efficient way of detecting the defects; electrical contacts (short circuits between rebar and tendon) as well as defects in the duct (e.g. holes) can be detected. The measurement of potential gradients on the concrete surface can be used additionally for a more precise location of defects in the duct. The combination of both techniques results in lateral resolution of up to 10 cm. In order to reach this lateral resolution the electrically isolated tendons should be connected from both ends.

A number of systematic sources for defects could be determined on about 170 tendons tested. Critical points are high and low points and all other deviations from the straight line of the tendon. At these points mechanical protection measures such as plastic half-shells are required.

At the anchorage, the damage of the duct, a shift of the insulation plate and a leak in the protection cap of the anchorage can compromise the electrical resistance of the tendon. Special care has to be applied during stressing procedure.

9 Summary and conclusions

Electrically isolated tendons (EIT) are now a proven system to enhance the durability of structures with post-tensioning tendons. The polymer ducts reduce fretting fatigue, they form a tight barrier against the ingress of water and chlorides and the electrical isolation at the anchor head allows quality control during construction and monitoring over the whole service life.

Measurements of the electrical impedance on electrically isolated tendons have shown to be an efficient way for quality control of the tendons. Monitoring over time allows the identification of the penetration of (chloride containing) water at defects in the ducts. Thus for the first time, a simple, cost-effective early warning system for post-tensioning tendons is available.

Magnetic flux measurements allow locating defects (short circuits and holes) in the polymer ducts. For optimum success the tendons should be electrically connected at both ends. The interpretation of the magnetic flux measurements requires a good knowledge of the reinforcement present in the structure.

Also electrically isolated tendons that do not reach the 28 days acceptance criteria according the Swiss guideline are protected better against corrosion then tendons with metallic ducts. Unless there is a short circuit all tendons can be monitored over time and tendons that show ingress of water can be identified.

Main factors for success of electrically isolated tendons are high quality material and components, a detailed design focused on the critical aspects, proper testing, the personnel skills and experience in execution and the respect of well established construction procedures.

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Projektabschluss

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK

Bundesamt für Strassen ASTRA

FORSCHUNG IM STRASSENWESEN DES UVEK — ARAMIS SBT

Formular Nr. 3: Projektabschluss

erstellt / geändert am:	16. Juni 2011

Grunddaten

Projekt-Nr.:	AGB 2004/10
Projekttitel:	Quality Control and Monitoring of electrically isolated post-tensioning tendons in bridges
Enddatum:	Mai 2011

Texte:

Zusammenfassung der Projektresultate:	Der Forschungsbericht bildet den wissenschaftlichen und technischen Hintergrund für die Revision der ASTRA/SBB Richtlinie, speziell im Hinblick auf die Grenzwerte, für die elektrische Widerstandsmessung und der Entwicklung des Widerstands mit der Zeit. Der Forschungsbericht dokumentiert typische Anwendungen der elektrisch isolierten Spannglieder an Brücken in der Schweiz und dank der internationalen Zusammenarbeit im Rahmen des europäischen Forschungsprojekts COST 534 auch aus Italien. Die Bedeutung eines sorgfältig aufgebauten Qualitätssicherungssystems, welches Projektierung, Materialspezifikation, Einbau und vor allem die Ausbildung des Personals auf der Baustelle beinhaltet, wurde unterstrichen. Diese Aspekte wurden in der überarbeiteten Richtlinie aufgenommen.
Zielerreichung:	Die gestellten Ziele wurden erreicht.
Folgerungen und Empfehlungen:	Die für die Praxis wichtigste Schlussfolgerung stellt fest, dass auch diejenigen elektrisch isolierten Spannglieder, welche den erforderlichen Grenzwert nicht erreichen, als besser korrosionsgeschützt betrachtet werden und zudem über die gesamte Nutzungsdauer überwacht werden können.
Publikationen:	Ayats J., Gnägi A., Elsener B., Electrical Isolation as Enhanced Protection for Post-tensioning Tendons in Concrete Structures, *fib* congress Osaka 2002, Vol. 6 pp. 169 – 176, Japan Prestressed Concrete Engineering Association (2002)

Della Vedova M., Elsener B., Evangelista L., Corrosion Protection and Monitoring of Electrically Isolated Post-tensioning Tendons, Proc. Third European Conference on Structural Control, 3ECSC 12-15 July 2004, Vienna

Della Vedova M., Elsener B., Enhanced Durability, Quality Control and Monitoring of Electrically isolated Tendons, Proc. 2nd Int. fib Congress, June 5 – 8, 2006, Naples, Italy. Paper 14-9

Elsener B., Long-term monitoring of electrically isolated post-tensioning tendons, *fib* Journal Structural Concrete 6 (2005) 101 – 106

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Bundesamt für Strassen ASTRA

Beurteilung der Begleitkommission:
Diese Beurteilung der Begleitkommission ersetzt die bisherige separate fachliche Auswertung.

Beurteilung:	Der Forschungsbericht fasst die schweizerischen Ergebnisse von mehreren Forschungsarbeiten der letzten 10 Jahre gut zusammen. Dazu enthält er eine Auswahl repräsentativer Pilot- und Praxisobjekte aus der Schweiz und – dank internationaler Zusammenarbeit - auch aus dem Ausland. Der Bericht gibt dem Bauherrn und projektierenden Ingenieur eine gute Übersicht über den „state of the art“ der elektrisch isolierten Spannglieder. Nach Ansicht der Begleitkommission zeichnet der Bericht für die EIT Technologie und die dazugehörenden Prüfungen ein etwas zu optimistisches Bild. Die hohen Anforderungen an die Unternehmungen beim Einsatz dieser Technologie werden in verschiedenen Kapiteln erwähnt. Der Forschungsbericht stellt eine sehr gute Ergänzung zur Richtlinie ASTRA/SBB "Massnahmen zur Gewährleistung der Dauerhaftigkeit von Spanngliedern in Kunstbauten" dar.
Umsetzung:	Die Umsetzung des Forschungsberichts ist mit der Überarbeitung der ASTRA/SBB Richtlinie bereits weitgehend erfolgt. Die Resultate des Berichts sind für die Spannstahlfirmen, die projektierenden Ingenieure und die Bauherren wichtig. Mit einer Serie von Publikationen wurden die Resultate der interessierten Fachwelt vorgestellt. Eine Publikation im Schweizer Ingenieur und Architekt - tec21 wäre sinnvoll. Die Abfassung in englischer Sprache sowie die Publikation auf dem VSS Server werden die Resultate der Forschungsarbeiten auch einem internationalen Fachpublikum zugänglich machen.
weitergehender Forschungsbedarf:	Die Anwendung der elektrisch isolierten Spannglieder wird dank der einfachen Überwachbarkeit dieser für die Tragsicherheit wichtigsten Teile in Zukunft noch zunehmen. Trotz der in der Schweiz und im Ausland zahlreichen Anwendungen fehlen die Erfahrungen aus der Praxis weitgehend, da diese Informationen nicht systematisch gesammelt werden. Dies und auch die Langzeiterfahrungen mit dieser Technologie sollten in einer zukünftigen Forschungsarbeit zusammengefasst werden; darin sollten auch die Erfahrungen mit der *fib* Empfehlung "Durability of post-tensioning tendons" (fib bulletin 33 2005) eingeschlossen werden.
Einfluss auf Normenwerk:	Der Forschungsbericht hat die wissenschaftlichen Grundlagen für die Revision der ASTRA/SBB Richtlinie erarbeitet. Die entsprechenden Resultate wurden in die Revision eingearbeitet, so zum Beispiel kann die Kontrollmessung neu zwischen 7 und mehr als 28 Tagen durchgeführt werden. Die Grenzwerte für den elektrischen Widerstand wurden nach Anforderungen (Ermüdung, Monitoring, Streuströme) differenziert.

Präsident Begleitkommission:

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Unterschrift Präsident Begleitkommission:

List of previous research reports

Report Nr.	Project Nr.	Titel	Date
601	AGB 2001/472	Remplacement de ponts sous traffic *Brückenersatz unter Verkehr*	2006
602	AGB 2001/485	Laboruntersuchungen an fünf ausgebauten Trägern der Autobahnbrücke "Viadotto delle Cantine" a Capolago *Etude expérimentale de cinq poutres prélevées sur le pont autoroutier "Viadotto delle Cantine" a Capolago*	2006
603	AGB 2002/015	Risiko von Betonabplatzungen infolge Bewehrungskorrosion *Risque d'éclatements du béton dû à la corrosion de l'armature*	2006
604	AGB 2002/003	Luftpermeabilität als Kenngrösse für die Qualität des Überdeckungsbetons von Betonwerken *Perméabilité à l'air en tant que paramètre caractéristique de la qualité du béton d'enrobage des ouvrages en béton*	2006
605	AGB 2000/401	Comportement, Calcul et dimensionnement des tranchées couvertes *Verhalten, Berechnung und Bemessung von Tagbautunneln*	2006
606	AGB 200/486	Résistance à l'effort tranchant des poutres précontraintes à âme mince *Querkraftwiderstand von vorgespannten Trägern mit dünnen Stegen*	2006
607	AGB 2003/017	Evaluation des systèmes existants pour le suivi àlong terme des déformations des ponts *Beurteilung bestehender Messsysteme für die Langzeiterfassung der Verformungen von Brücken*	2006
608	AGB 1998/101	Zustandserfassung von Brücken bei deren Abbruch (ZEBRA) *Evaluation de l'état de ponts pendant leur demolition (ZEBRA)*	2006
610	AGB 2005/025	Instandsetzung von Galerien – Wirkung und Wirksamkeit der ergriffenen Massnahmen *Remise en état de galeries - effet et efficacité desmesures réalisées*	2007
611	AGB 2002/027	Streuung der Betoneigenschaften in Bauwerken *Variabilité des caractéristiques du béton dans les ouvrages*	2006

Report Nr.	Project Nr.	Titel	Date
612	AGB 2001/489	Permanente, vorgespannte Boden- und Felsanker: Fluktuationen des elektrischen Widerstands *Tirants d'ancrage précontraints en sol et en rocher: Fluctuations de la résistance électrique*	2007
613	AGB 1997/06 AGB 2001/480	Experimentelle Untersuchung der Lawinenkräfte auf Galeriedächer *Recherche expérimentale sur les forces d'avalanches agissant sur les galeries de protection*	2007
614	AGB 2002/026	Temporärer Korrosionsschutz von Spanngliedern (TEKplus) – Wissenschaftlich, technische Begleitung der Umsetzung in die Praxis *Protection temporaire des câbles de précontrainte contre la corrosion (TEKplus) – documentation scientifique et technique de la transposition à la pratique*	2007
615	AGB 2002/004	Betoneigenschaften nach SN EN 206-1 *Propriétés de Béton selon SN EN 206-1*	2007
616	AGB 2002/020	Beurteilung von Risiken und Kriterien zur Festlegung akzeptierter Risiken in Folge aussergewöhnlicher Einwirkungen bei Kunstbauten *Appréciation et critères d'acceptation des risques dus aux actions extraordinaires pour les ouvrages d'art*	2009
618	AGB 2005/102	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten: Methodik zur vergleichenden Risikobeurteilung *Bases d'une méthode pour une appréciation comparative des risques*	2009
619	AGB 2005/103	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten: Ermittlung des Netzrisikos *Estimation du risque pour le réseau*	2010
620	AGB 2005/104	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten: Effektivität und Effizienz von Massnahmen *Efficacité et efficience des interventions*	2009
623	AGB 2005/107	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten Tragsicherheit der bestehenden Kunstbauten *Sécurité structurale des ouvrages d'art existants*	2009

Report Nr.	Project Nr.	Titel	Date
624	AGB 2005/108	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten: Risikobeurteilung für Kunstbauten *Appréciation des risques pour les ouvrages d'art*	2010
625	AGB 2005/109	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten: Effektivität und Effizienz von Massnahmen bei Kunstbauten *Efficacité et efficience des interventions sur les ouvrages d'art*	2009
626	AGB 2005/110	Sicherheit des Verkehrssystems Strasse und dessen Kunstbauten: Baustellensicherheit bei Kunstbauten *Sécurité sur les chantiers d'ouvrages d'art*	2009
627	AGB 2002/002	Eigenschaften von normalbreiten und überbreiten Fahrbahnübergängen aus Polymerbitumen nach starker Verkehrsbelastung *Caractéristiques des joints de chaussée en bitume- polymère de largeur normale et de grande largeur après forte sollicitation par le trafic*	2008
628	AGB 2005/026	Massnahmen gegen chloridinduzierte Korrosion und zur Erhöhung der Dauerhaftigkeit *Mesures contre la corrosion induite par les chlorures pour augmenter la durabilité*	2008
629	AGB 2003/001 AGB 2005/019	Integrale Brücken- Sachstandsbericht *Ponts à culée intégrée*	2008
630	AGB 2002/016	Korrosionsinhibitoren für die Instandsetzung chloridverseuchter Stahlbetonbauten *Inhibiteurs de corrosion pour la remise en état des ouvrages en béton armé, contaminés par des chlorures*	2010
631	AGB 2000/555	Applications structurales du Béton Fibré à Ultra-Hautes Performances aux ponts *Anwendungen von Ultra-Hochleistung Faserbeton im Brückenbau*	2008
633	AGB 2002/014	Oberflächenschutzsysteme für Betontragwerke *Systèmes de protection de surface pour les structures en béton*	2008
634	AGB 2002/007	Untersuchungen zur Potentialfeldmessung an Stahlbetonbauten *Recherches relatives à la mesure de potentiel sur des structures en béton armé*	2008
635	AGB 2004/002	Applicabilité de j'enrobé drainant sur les ouvrages d'art du réseau des routes nationales *Anwendbarkeit von offenporigen Asphaltdeckschichten auf Kunstbauten des nationalen Strassennetzes*	2008

Report Nr.	Project Nr.	Titel	Date
636	AGB 2002/028	Dimensionnement et vérification des dalles des roulement des ponts routiers *Bemessung und Nachweis der Fahrbahnplatten von Strassenbrücken*	2009
637	AGB 2005/009	Détermination de la présence de chlorures à l'aide du géoradar *Georadar zur Auffindung von Chloriden*	2009
638	AGB 2003/003	Ursachen der Rissbildung in Stahlbetonbauwerken aus Hochleistungsbetonen *Causes des fissurations dans les structures an béton armées à haute performance*	2008
645	AGB 2005/021	Grundlagen für die Verwendung von Recyclingbeton aus Betongranulat *Bases pour l'utilisation due béton de recyclage engranulats de béton*	2010