Electrically Isolated Tendons in European Transportation Structures

October 2020

FHWA Global Benchmarking Program Report

RPT NO FHWA-PL-20-013

U.S. Department of Transportation
Federal Highway Administration

FOREWORD

Post-tensioning (PT) is a method of reinforcing concrete that has greatly improved our Nation's bridges with its ability to extend span lengths, reduce concrete cracking, connect prefabricated bridge elements, and accelerate construction. Keeping check on tendon condition is vitally important to the load-carrying capacity and durability of PT bridge structures.

Recognizing post-tensioning as an increasingly popular solution for significant improvements in concrete bridge performance, the Federal Highway Administration (FHWA) has undertaken several studies to examine state-of-the-art best practices. One study, completed in 2014, looks at promising non-destructive evaluation (NDE) techniques for post-tensioning systems. One of the technologies from this study that captured FHWA's attention was the use of electrically isolated tendons (EITs) to provide in-service PT tendon durability readings and improve the construction/installation quality. At the time of the 2014 study, research on EITs was not extensive. The 2014 study also revealed that several European countries had had effectively used EITs for several decades with good experiences. To follow-up, FHWA conducted a desk review to investigate worldwide experience with design and operation of EITs. Findings from these efforts led to a Global Benchmarking Program study. As part of the study, technical site visits were made to Italy and Switzerland to better understand how EITs are used to improve durability and construction quality in their bridge structures.

This report, which is part of the Global Benchmarking Program study, includes details about EIT design, construction, and operation based on site visits and interviews with international experts. Investigations revealed that Italy and Switzerland are established world leaders in the use of EITs in bridge structures. What the team learned from visiting several bridge sites and through discussions with owners and installers, was eye-opening. The team hopes that the information shared in this report will inform and improve post-tensioned bridge durability and management approaches.

Notice

This document is disseminated under the sponsorship of the U.S. Department of Transportation (USDOT) in the interest of information exchange. The U.S. Government assumes no liability for the use of the information contained in this document.

The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objective of the document.

Quality Assurance Statement

The Federal Highway Administration (FHWA) provides high quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. FHWA periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-PL-20-013	2. Government Accession No.	3. Recipient’s Catalog No.

4. Title and Subtitle Electrically Isolated Tendons in European Transportation Structures	5. Report Date August 2020
	6. Performing Organization Code:
7. Author(s) Michael C. Brown	8. Performing Organization Report No.
9. Performing Organization Name and Address WSP USA One Penn Plaza, Second Floor New York, NY 10119	10. Work Unit No.
	11. Contract or Grant No. DTFH61-14-D-00048/49/50
12. Sponsoring Agency Name and Address Office of Research, Development, and Technology Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296	13. Type of Report and Period
	14. Sponsoring Agency Code HIBS-10

15. Supplementary Notes
Michael C. Brown
WSP USA
One Penn Plaza, Second Floor
New York, NY 10119

16. Abstract

Post-tensioning (PT) is a method of reinforcing concrete that has greatly improved our Nation’s bridges with its ability to extend span lengths, reduce concrete cracking, connect prefabricated bridge elements, and accelerate construction. Keeping check on tendon condition is vitally important to the load-carrying capacity and durability of PT bridge structures. Currently, the PT state-of-the-practice in the U.S. does not provide the ability to remotely monitor in-service tendon condition and relies upon labor-intensive visual inspection. The Federal Highway Administration, American Association of State Highway and Transportation Officials, and National Cooperative Highway Research Program sponsored a Global Benchmarking Program study to look at electrically isolated post-tensioning systems (EIT) in Italy and Switzerland with a focus on the ability of this technology to improve post-tensioning durability.

Through multiple face-to-face meetings and field visits, the study team found that both Italy and Switzerland use EITs to provide a high level of corrosion protection and provide the ability to monitor PT tendon condition throughout a structure’s intended service life. They emphasized proper installation to ensure that the EIT system provided these benefits.

Team recommendations for U.S. implementation include developing EIT system prequalification testing requirements, researching details to accommodate U.S. construction and inspection practices, and developing an education and outreach program for bridge designers and constructors.

17. Key Words Post-tensioning, durability, electrically isolated tendon	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

Abbreviations and Acronyms

AASHTO	American Association of State Highway and Transportation Officials
AREMA	American Railway Engineering and Maintenance-of-Way Association
ASBI	American Segmental Bridge Institute
ASTRA	*Bundesamt für Strassen* ASTRA [Federal Roads Office FEDRO, Swiss Confederation]
EIT	Electrically Isolated Tendons
ETAG	European Technical Approval Guidelines (ETAGs) established by the European Organisation of Technical Approvals
ETH	*Eidgenössische Technische Hochschule* [Swiss Federal Institute of Technology]
FHWA	Federal Highway Administration
fib	*féderation internationale du béton* [the International Federation for Structural Concrete]
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
GBP	Global Benchmarking Program
LCR	Components of electrical impedance under an alternating current: Inductance (L) – Capacitance (C) – Resistance (R)
NDE	Nondestructive Evaluation
PT	Post-tensioning, or post-tensioning tendons
PTI	Post-Tensioning Institute
RFI	*Rete Ferroviaria Italiana* [Italian Railway Infrastructure Manager]
SBB	*Schweizerische Bundesbahnen-Chemins de fer fédéraux suisses-Ferrovie federali svizzere* (*SBB CFF FFS)* [Swiss Federal Railway]
TFHRC	Turner-Fairbank Highway Research Center (research division of FHWA)
TRB	Transportation Research Board (of the National Academies of Sciences, Engineering, and Medicine)
USDOT	United States Department of Transportation

Table of Contents

List of Figures

List of Tables

Executive Summary

Overview

The Federal Highway Administration (FHWA) Global Benchmarking Program (GBP) serves as a tool for accessing, evaluating, and implementing proven global innovations that have the potential to significantly improve highway transportation in the U.S. Instead of recreating advances already developed by other countries, the program focuses on acquiring and adopting technologies and best practices already available and used abroad. The GBP Study on Electrically Isolated Tendons (EIT) was conducted to learn how European countries have successfully used EITs in their post-tensioned (PT) bridge structures.

The study included a series of interviews and site visits focused on collecting information relevant to advancing the state of the practice in the United States, particularly with respect to PTI/ASBI M50.3 protection level 3 (PL-3) criteria, and to improving the construction quality, durability, and long-term performance of PT bridge structures, which represent a major component of the U.S. bridge inventory. The primary reason for this study was to investigate how well EIT were serving their international owners and determine unique processes for EIT qualification, installation, and monitoring that should be considered in pursuing domestic implementation. The study team, which comprised representatives from FHWA, State Departments of Transportation, Post-Tensioning Institute (PTI), and American Segmental Bridge Institute (ASBI), determined that the EIT technology successfully provided the following benefits:

- Provides reliable construction quality control on the installation of PT tendons through validation of isolation by means of electrical resistance measurements, to ensure PL3 compliance.
- Provides early warning of PT tendon envelope breaches, before grouting of tendons, which provides the opportunity to repair the breach.
- Provides reliable and easily interpretable PT tendon encapsulation data during the service life of a structure.
- Requires minimal change to the current state-of-the practice PT details and installation processes.

The study was organized around a series of questions regarding the following topics:

- Experience in EIT implementation and planned future improvements.
- Criteria for when EITs are used or not used.
- EIT system approval procedures.
- Approved systems and certification requirements.
- Workforce training.
- EIT construction and installation methods.

- Inspection procedures and reading frequency.
- Tendon voids and damage detection.
- Penalties for not meeting acceptance thresholds.
- Long-term monitoring.
- Costs and benefits of EIT from the owner's perspective.

The study itinerary consisted of one week of site visits and in-person interviews with bridge owners, academics, PT system producers and installers, and technical consultants in the host countries of Italy and Switzerland. These two countries have extensive experience deploying EIT technology and were selected based on the results of a desk review that investigated worldwide examples of EIT design and construction. Participants included:

- International bridge owners:
    - *Rete Ferroviaria Italiana, S.p.A.* (RFI) [Italian Railway Infrastructure Manager].
    - *Italferr, S.p.A.* [Italian State Railways Group Engineering and Design].
    - *Schweizerische Bundesbahnen-Chemins de fer fédéraux suisses-Ferrovie federali svizzere* (*SBB CFF FFS)*[1] [Swiss Federal Railway].
- Universities:
    - *ETH Zurich* [Swiss Federal Institute of Technology in Zurich].
    - *Universita degli Studi di Cagliari* [University of Cagliari].
- PT producers and installers:
    - *Tensacciai S.r.l* [Tensa].
    - *Stahlton AG* [Stahlton].
    - VSL International
- Technical consultants:
    - Ganz Consulting.
    - *Dr. Vollenweider AG.*

Summary of Key Findings

EIT Design

Having evolved from applications in ground anchors for geotechnical stabilization, EIT has been adapted as a method of ensuring construction quality and durability of post-tensioning tendons in transportation structures in rail, transit and highway infrastructure. The EIT system is found to be beneficial in ensuring tendons are protected against corrosion induced by aggressive environmental and chemical exposure, as well as against the influence of stray current. Both Italian and Swiss rail authorities recommend EIT for post-tensioned structures, and in Switzerland, EIT has been required where protection from stray current is a concern.

---

[1] The name and abbreviation *Schweizerische Bundesbahnen-Chemins de fer fédéraux suisses-Ferrovie federali svizzere* (*SBB CFF FFS)* designate the Swiss Federal Railway in three languages (Swiss, French, and Italian); in commercial practice, it is most commonly referred to as simply "SBB".

The development of EIT aligns with the most robust criteria for durability design of PT, Protection Level 3 (PTI/ASBI M50.3), which involves encapsulating tendon designs with corrosion-proof ducts, permanent leak-tight seals at all connections, and adds the ability to monitor or inspect the integrity of the tendon in service. The latter is accomplished by establishing electrical isolation of the internal tendon from all exterior metallic components of a structure, and then being able to monitor to determine if that electrical isolation is breached at any time during the life of the structure.

Critical components of an EIT system are those that make possible the electrical isolation of the PT strand from metallic reinforcement outside the tendon. The basic envelope is formed by non-metallic polymer ducts connected by robust seals at connections and having watertight vent tubes. Anchorages are electrically isolated by use of a non-metallic isolation plate between the anchor head and the bearing plate. A reference connection to the bearing plate extends from the grout cap in an insulated reference wire that runs to a junction box and can be measured with an LCR meter against ground wire connected to the mild reinforcement to verify isolation, or lack thereof.

System Qualification and Approval

In European practice, individual PT suppliers must have their PT systems qualified through a series of tests that verify that anchorage and duct assemblies are air- and water-tight under both positive and negative pressure tests. Other tests evaluate dimensional tolerances, stiffness, external point load resistance, wear and fracture resistance, and bond behavior of the duct components. Robust training is needed for PT installers.

Training and Certification

Producers undergo periodic certification to be authorized to produce PT systems for construction. Some producers have developed rigorous training and personnel certification programs for all aspects of post-tensioning system design, construction and inspection. Such programs include both classroom lecture and hands-on practical training to verify proficiency.

Construction and Quality Control

Both Italy and Switzerland had difficulty properly installing EITs during their early implementations. Coordination among all parties involved in design, fabrication, and inspection, as well as the owners, is important to manage expectations and achieve best results. Experienced practitioners note that precise installation and proper care are needed to successfully install EIT, but that it should not represent extraordinary effort. Rather, it should become part of the routine practice for all PT. A well-encapsulated or isolated tendon is the basis for the EIT concept but does not diminish the need for proper grouting procedures and checks. Implementations of EIT tend to more readily receive the appropriate level of care due to the ability of the technology to verify tendon encapsulation and, therefore, installation quality. However, a number of others tests during the construction process are important to ensure integrity of the system, including checking ducts for local deformation, excessive curvature, blockages, and breaches before pulling strand. A supplemental half-shell added to the exterior of the polymer ducts where it is supported on external reinforcement is effective in preventing local buckling, excessive curvature or abrasion of strand through the duct. Electrical tests can be conducted before and after grouting to screen for breaches.

Post-installation acceptance tests are based on LCR measurements, where acceptable AC resistance criteria are established to guard against stray current, long-term environmental exposure, and fatigue and fretting corrosion. Some percentage (5 to 10 percent) of tendons may not meet established criteria, but experienced practitioners caution against strict punitive enforcement; rather, it is recommended that the information be used to make adjustments to improve details and procedures as the project progresses. Just because electrical isolation is not verified does not mean that corrosion will occur, and resistivity thresholds that have been developed based on expert opinion are not absolute.

Operation and Long-term Monitoring

Full electrical isolation of PT tendons is not necessary to collect meaningful long-term monitoring data. Electrical resistivity has been shown to generally increase over time as the cementitious grout and concrete continue to hydrate. Environment, such as temperature, humidity, and precipitation will affect resistivity readings and should be compensated for when making long-term comparisons.

EIT technology also presents evolving opportunities for supplemental nondestructive evaluation (NDE) methods. A technique to isolate the location of a tendon breach through electromagnetic induction was demonstrated.

Recommendations

From this study, the team developed a series of recommendations to aid in the implementation of EIT in the U.S.:

- Develop design guidance tailored to U.S. practice which familiarizes domestic engineers, fabricators, and contractors with the features and requirements of the technology. This can be accomplished through FHWA, PTI, and ASBI.
- Incorporate EIT into PT specifications, including methods of system qualification and approval. This would involve adapting concepts from *fib* Bulletin 75 into PTI/ASBI M50.3.
- Develop personnel training/certification requirements. This can be accomplished by augmenting PTI PT Installer Training and PT Inspector Training programs.
- Promote guidance on EIT design, installation, and acceptance through a program of education and outreach; professional venues such as FHWA, American Association of State Highway Transportation Officials (AASHTO), PTI, ASBI, and Transportation Research Board (TRB) meetings and conventions can be used as forums to present; trade journals can be used to publish case studies and articles.
- Develop guidance for operation and long-term monitoring that gives direction in LCR instrument selection and use and reflects interpretation in the broad range of climates and conditions across the U.S.

- Conduct additional focused research to address lingering questions or challenges unique to U.S. practice, such as use of epoxy-coated mild reinforcement, the practice of post-grouting inspection of anchorages, influence of environment on acceptance criteria, and long-term creep performance of polymer-composite isolations ring.

Chapter 1 - Introduction

Background

Post-tensioning (PT) is a method of reinforcing concrete that has greatly improved our Nation's bridges with its ability to extend span lengths, reduce concrete cracking, connect prefabricated bridge elements, and accelerate construction. PT uses high-strength steel tendons positioned in ducts or sleeves within a concrete element. Keeping check on tendon condition is vitally important to the load-carrying capacity and durability of PT bridge structures. Currently, the PT state-of-the practice in the U.S. does not provide the ability to remotely monitor in-service tendon condition and relies upon labor-intensive visual inspection.

Experiences with the electrically isolated post-tensioning system with plastic ducts are encouraging in both Italy and Switzerland. Simple and reliable measurements give information on corrosion protection of EIT tendons. EIT provides a simple and straightforward method for long-term monitoring of the encapsulation of structurally important tendons.

State of U.S. Practice

Current U.S. practice for highway bridges is primarily governed by the requirements of American Association of State Highway and Transportation Officials (AASHTO), in collaboration with the Federal Highway Administration (FHWA), whereas current practice for railway and transit structures is governed by American Railway Engineering and Maintenance-of-Way Association (AREMA) in coordination with Federal Railroad Administration (FRA) and Federal Transit Administration (FTA), respectively. The practices specific to post-tensioning of concrete structures are recommended by PTI in conjunction with ASBI. Current PTI guidance provides similar Protection Level schema (PL1 – PL3) as described by *fib* 33. The industry has expressed interest in implementing EIT as a possible option for PL3 design, and FHWA has taken an active role in promoting the technology through a series of pilot construction projects, educational workshops, targeted research efforts, and the advancement of the current global benchmarking program study.

EIT to Enhance Corrosion Durability and Inspectability

This study investigated electrically isolated tendons (EITs), an innovative nondestructive evaluation technology that can greatly improve our current state of the practice. EIT technology offers the ability to validate the integrity of the tendon encapsulation and remotely monitor long-term tendon protection with meaningful and interpretable data. EITs also enable improved long-term performance by providing the highest level of corrosion protection possible with current PT technologies. As such, EITs directly address the most significant needs for PT structures through their ability to improve construction quality, inspectability, and long-term performance.

EIT technology has been used successfully in European countries for over 30 years; however, the U.S. bridge community has just recently started to consider this technology for their PT structures.

As part of its efforts to promote this technology, FHWA's Office of Bridges and Structures is conducting demonstration/showcase projects and developing specification language for the EIT technology. Due to limited U.S. expertise or experience with EITs, these efforts are mostly "learn as you go." This study was undertaken to provide much needed information at a critical time in FHWA's implementation of EITs. Understanding effective practices and lessons learned from the long-term use of EIT technology by European countries will allow FHWA and its partners to more effectively promote this technology in the U.S.

Several States have expressed interest in implementing EIT, and demonstration projects are thus far underway in Pennsylvania (PA) and Texas. FHWA hosted a workshop in fall 2018 in Lehigh, PA to highlight the features and experiences of the first demonstration project.

Study Objectives

This study sought to learn how other countries have successfully used EITs as a nondestructive evaluation technology to ensure durability of PT bridge structures. The goal was to understand effective practices and lessons learned and then bring this information to U.S. bridge owners so that they can advance the state of the practice and improve the monitoring, construction quality, durability, and long-term performance of PT bridge structures, which represent a major component of the U.S. bridge inventory.

Amplifying Questions

The U.S. study team was interested in obtaining information on topics as they relate to the use of EITs in highway and transportation structures. Appendix B provides the list of Amplifying Questions, as conveyed to the European hosts, which guided the inquiries. Topics of interest are amplified herein and cover several broad categories, including:

- EIT Design.
- System Qualification and Approval.
- Training and Certification.
- Construction and Quality Control.
- Operation and Long-term Monitoring.

Host Countries

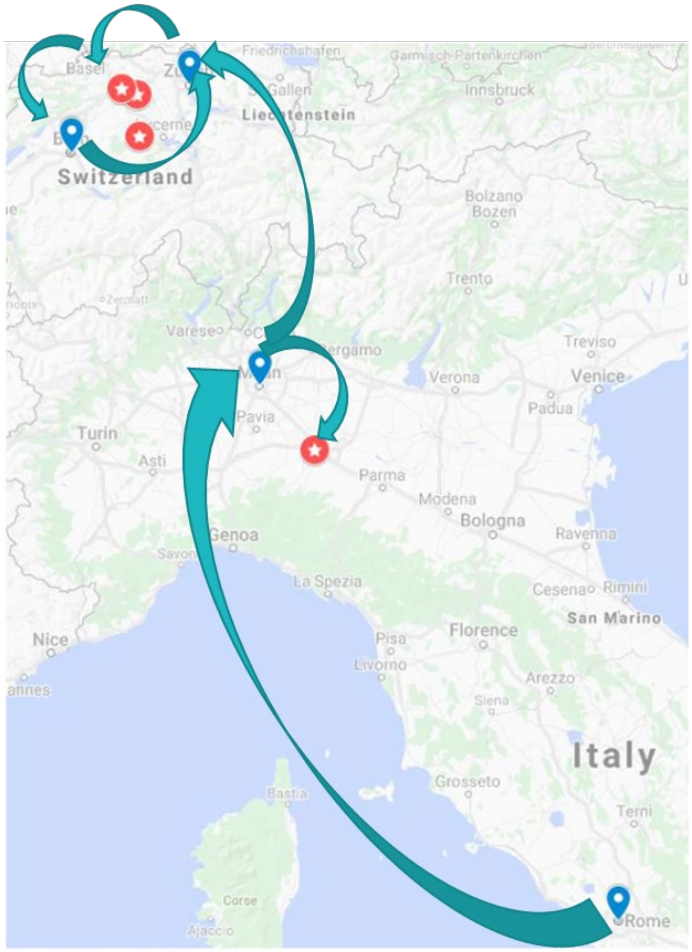
Based on findings of a desk study that identified entities with experience deploying EIT technology, the U.S. study team traveled to Italy and Switzerland to meet with representatives from national transportation agencies. These representatives included bridge owners, designers, and operators, as well as with system fabricators, researchers, and expert consultants. Appendix C presents a summary of personnel with whom the study team met, with a listing of biographies for key individuals.

Study Itinerary

Meetings were held in Italy (Rome and Milan) and Switzerland (Zurich and Bern) during the week of May 20-24, 2019. In addition to the meetings, the U.S. study team conducted technical site visits to gain first-hand observations of EIT systems while under construction or in service. Additional review was made of electrically isolated ground anchorage systems used for slope stability applications, which was the predecessor to EIT technology for bridge applications. Table 1 summarizes activities during the GBP tour and Figure 1 provides a map of the tour route.

Table 1. Electrically Isolated Tendons Global Benchmarking Program itinerary.

Day (Date)	Location	Activity
Monday (May 20)	Rome, IT	Meet Italian Railways and Italferr (Designer/Owner/Operator)
Tuesday (May 21)	Milan, IT	Site visit - Piacenza Viaduct (in-service) Meet Tensa (Producer/Installer)
Wednesday (May 22)	Zurich, CH	Workshop at ETH Zurich (Researchers/Owners/Producers)
Thursday (May 23)	Hirschthal, CH	Site Visit - Mittelmuhen Bridge (in-service)
	Wolhusen, CH	Site Visit - Wolhusen Bridge (under construction)
	Olten, CH	Site Visit - Ground Anchor Wall near Olten Rail Station (in-service)
Friday (May 24)	Bern, CH	Meet VSL and Stahlton (Producers/Installers)



Blue – Meetings or Lodging
Red – Site Visits

Source: FHWA.

Figure 1. Map. Overview of EIT GBP travel itinerary.

Team Members

This study was undertaken by the FHWA, an agency of the United States Department of Transportation (USDOT). It was conducted under the FHWA's Global Benchmarking Program, which serves as a tool for accessing, evaluating, and implementing proven foreign innovations that can help improve highway transportation in the U.S. The study team, for whom short biographies are presented in Appendix A, included the following members:

- **Mr. Reggie Holt**—Team Lead, Senior Bridge Engineer, FHWA Office of Bridges and Structures.
- **Dr. Zachary Haber**—Research Structural Engineer, FHWA Office of Infrastructure Research and Development.
- **Mr. Graham Bettis**—Bridge Division Director, Texas Department of Transportation.
- **Mr. Kevin Western**—State Bridge Engineer, Minnesota Department of Transportation.

- **Mr. Gregg Freeby**—Executive Director, American Segmental Bridge Institute (ASBI).
- **Mr. Miroslav Vejvoda**—Managing Director, Post-Tensioning Institute (PTI).
- **Dr. Michael Brown**—Consultant, Sr. Supervising Engineer, WSP USA, report facilitator.

Chapter 2 - Findings on Electrically Isolated Tendons

References and Standards

Switzerland

Swiss authorities, for both roadways and rail, have issued collective guidance for PT applications in a publication under the *Bundesamt für Strassen (ASTRA)* [also known as Federal Roads Office (FEDRO)] in ASTRA 12 0010 (2007). Swiss railway and tramway systems that employ DC power systems are now required to comply with PL3 design to prevent stray current-induced damage.

European Standards Organizations

The evolution of corrosion-resistant post-tensioning design is reflected by the progressive advances reflected in pertinent reports published by the *féderation internationale du béton* (*fib)* [the International Federation for Structural Concrete], including:

- *fib 7,* "Corrugated plastic ducts for internal bonded post-tensioning" in January 2000. — Introduces appropriate sheathings for monostrands, types and applications of smooth plastic tubes, types and applications of corrugated plastic tubes, including material properties and specifications for primarily HDPE and PP ducts. The report also introduces the concepts of component and assembled system approval testing for aspects of flexibility, load resistance, wear bond, leak tightness, and electrical resistance (superseded by *fib* 75).

- *fib* 20, "Grouting of tendons in prestressed concrete" in July 2002. — Discusses the types, sizes and configuration of ducts, connectors and couplers, as well as inlets, outlets and vents, and proper methods for their protection, installation, and testing. Grout materials and performance are reviewed and regimes of tests for suitability and acceptance are prescribed. The details of grout production and injection are summarized, including equipment, batching, mixing and grouting operations, and methods to ensure complete filling of tendons. Finally, the document details qualifications and training requirements for grouting personnel.

- *fib* 33, "Durability of post-tensioning tendons" in December 2005. — Introduces design concepts to ensure durability of PT tendons and introduces a progressive system of design to address degrees of environmental exposure and inherent system protection offered by the structural components. It discusses requirements for PT materials and construction. The document also introduces strategies for maintenance, assessment and rehabilitation of PT systems during their service life.

- *fib* 75, “Polymer-duct systems for internal bonded post-tensioning” in December 2014. — Intended to update and replace *fib* 7, this report provides more detailed consideration of the steps in design, fabrication and construction of PT systems, building upon the concepts of *fib* 33. It provides updates to the materials, components, and system approval requirements for PT systems.

Several standard specifications and technical assessment programs were developed to guide design and acceptance of post-tensioning systems, such as European Technical Approval Guidelines ETAG 013 (2002).

EIT Design

Discussions with European hosts revealed a significant history leading to the evolution of electrically isolated tendons for post-tensioning. Post-tensioned structures have been built for more than half a century, and most of such structures have proved durable. However, there have been notable exceptions, some of which have resulted in severe corrosion, and in the case of the Ynys-y-Gwas Bridge in the United Kingdom, collapse occurred without warning. These events highlighted the shortcoming that grouted post-tensioned tendons are inherently difficult to inspect, wherein the condition of the most important structural element (the tendon) cannot be observed, and no effective nondestructive methods have previously existed to detect damage. This led to efforts to improve the design, the construction, and the quality control of post-tensioned elements.

Evolution of Electrically Isolated Tendons

The evolution of EIT began with ground anchors and then was adapted to bridge structures, primarily in Switzerland, and then in other parts of Europe.

Ground Anchors

In Switzerland, grouted rock anchors were first implemented in 1951 and adaptation to ground anchors occurred in 1962. Through the 1960s, the design of ground anchors evolved from a) full-length solid grouted tendons to b) the incorporation of “free” lengths inside polymer ducts with soft protective filler, and then c) grouted monostrands in smooth pipe extending up from the strands grouted in corrugated PE pipe at the base of the tendon. Collapse of the Dietfurt Bridge, a “prestressed-ribbon type bridge,” in 1981 and other stories of ruptured tendons (see Figure 2) led to a partial moratorium on such anchors (Ryser, 2019).

Source: M. Ryser.

Figure 2. Photo. Examples of early ground anchorage tendon failures prior to development of EIT technology.

In 1985, authorities were concerned with the phenomenon of stray-current corrosion related to a large retaining wall adjacent to the Stadelhofen Railway Station (designed by Santiago Calatrava) in Zurich. Engineers had to determine how to ensure the integrity of 940 ground anchors against the potential for corrosion caused by stray current from the 500 VDC tramway. The solution was to establish electrical isolation of the anchors from the ground using a system that incorporated polyethylene pipe with leak-tight couplings and end cap. The integrity of the isolation could be checked after grouting and load-testing of the anchors by measuring electrical resistance against the criterion of R > 0.1 MΩ.

Source: M. Ryser.

Figure 3. Photo. Encapsulated anchorages in retaining wall adjacent to Stadelhofen Railway Station, Zurich.

Development of the electrical isolation concept continued; in 1992, the first completely electrically isolated anchors were installed in the north portal of the Seelisburg Tunnel. The design featured an isolation plate between the anchor plate and anchor head, and leak-tight trumpet connections. The complete electrical isolation allows for a periodical check of the integrity of the corrosion-protection barrier (polyethylene pipe) during the working life of the anchors. Code provisions and technical assessment documents have continued to mature; electrical isolation of permanent prestressed ground anchor tendons is now standard practice for public works and most major private works in Switzerland.

Source: M. Ryser.

Figure 4. Photo. Electrically isolated anchors in stabilized rock cuts at the Seelisburg Tunnel.

One fundamental distinction is that ground anchorage EIT measurements are conducted in DC with high voltage because of the resistivity of soil. The criterion does not consider the length of the tendon. As will be discussed, this differs from PT application in bridges.

Rail and Highway Bridges

Because DC tramway and railway structures may subject PT systems to stray currents that can result in corrosion, and because heavy railway loads, on the order of 20-22 tons per axle, induce significant fatigue, the designs of PT systems for rail bridges have evolved. In the 1990s, use of plastic ducts became prevalent, as it was found that plastic ducts had benefits in mitigating both of these phenomena.

Olten Ground Anchor Wall

As a modern example of an electrically isolated ground anchorage, the team reviewed a rock and soil retaining wall, located in the town of Olten, Switzerland, which lies along a cut for a roadway adjacent to the Olten railyard and station (Figure 5).

Source: WSP/FHWA.

Figure 5. Photo. Overview of in-service ground anchor wall containing EIT ground anchors in Olten, Switzerland.

The anchorages are regularly monitored to ensure encapsulation is retained. The details of the anchorage configuration and EIT monitoring equipment and procedures were demonstrated to the study team (Figure 6).

Source: WSP/FHWA.

Figure 6. Photo. Overview of ground anchor wall (left) and close-up view of ground anchorage with end cap removed and lead wire clipped to a strand for electrical resistance measurement (right).

Note the lead wire clipped to the end of a strand for electrical measurement. Ground anchors for this wall were of more than one generation. Figure 7 shows a junction box associated with the most recent generation of anchors, with the plugs for force measurement and electrical resistance measurement on selected anchors. The use of a junction box with permanently installed leads precludes the need to remove the end cap and expose the tendons for inspection.

Source: WSP/FHWA.

Figure 7. Photo. In-service measurement of anchor force by electrical load cells. The leads for the electrical resistance measurements on selected anchors are connected to the same junction box (blue plug sockets).

Protection Levels

In the mid- to late-1990s, European industry recognized the need for targeted design based on exposure (risk) and importance (consequence) of a structure. The *fib* Bulletin 33 (2005) introduced protection levels, indicating that the type of tendon should be defined at the design stage of a structure to provide necessary assurance of corrosion durability. The effort was to address the issues of exposure from the environment, resulting in:

- Uniform, pitting, or stress-corrosion cracking.
- Potential for hydrogen embrittlement.
- Stray currents (especially from DC railways).
- Fretting fatigue.

It is recognized that high-strength steel wire while the most cost-effective material for post-tensioning, may be prone to corrosion if not properly protected, and the implications for prestressed concrete are more severe than for normal reinforced concrete. Emphasis has been conventionally placed on ensuring robust protection for the tendons through a combination of concrete cover, ducts, and cement grout (for bonded tendons).

The recommendation was to institute a principle of multi-layer protection to ensure durability. Tendon categories were defined according to Protection Levels (PL) (as excerpted from *fib* 33):

- PL-1: A duct with a filling material providing durable corrosion protection.
- PL-2: PL1 plus an envelope, enclosing the tensile element bundle over its full length, and providing a permanent leak tight barrier.
- PL-3: PL2 plus integrity of tendon or encapsulation to be monitorable or inspectable at any time.

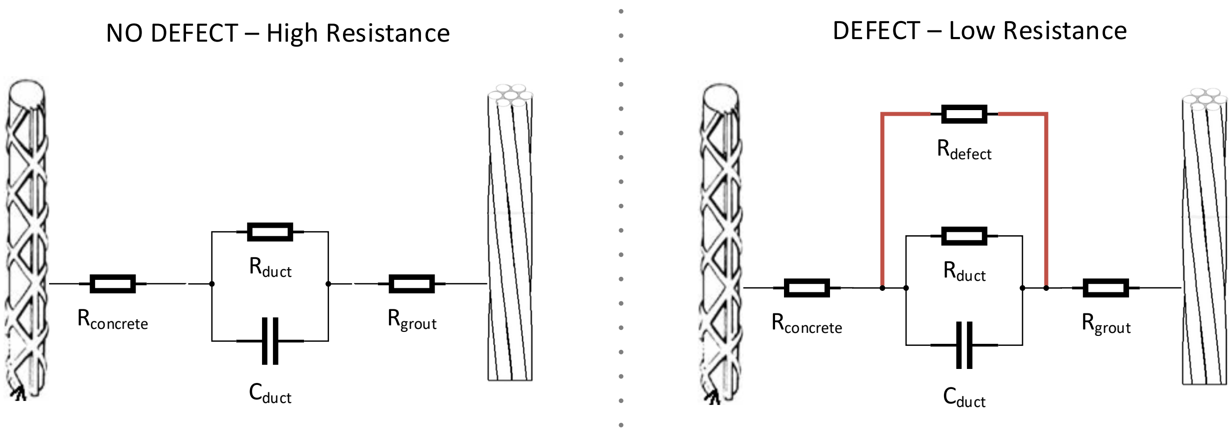
The protection scheme is conceptualized as one where increasing rigor is required as the aggressiveness of the environment increases (low to high) and the number of structural protection layers inherent to the general structural design decline (more to less). Aggressivity of the environment considers modes of carbonation, seawater, non-seawater chloride, immersion or splash zones, freezing and thawing, and chemical attack. Protection layers consider concrete cover, waterproofing, drainage, expansion, construction and segment joints, tendon configuration and layout, cracking, and access for inspection and maintenance.

PL1 encourages provision of a strong and durable, sufficiently leak-tight duct filled with chemically stable grout that is not deleteriously reactive such that there are no voids in the duct. PL2 adds the provision of full encapsulation of the entire tendon assembly, impermeable to both water and vapor, with a chemically and dimensionally stable envelope. PL3 provides an additional requirement that the integrity of the envelope can be checked at any time with a repeatable means of measurement. EIT is explicitly cited as an example of PL3.

EIT Concept

As noted, the intent of EIT systems is to comply with PL3 requirements of a fully encapsulated, electrically isolated, and monitorable system to ensure protection of the post-tensioning tendon. In practice, the polymer duct and anchorage assembly isolate the tendon and grout inside the duct from electrolytic contact with the concrete and reinforcement outside the duct. A polymer duct without defects may be characterized by geometry [length (L), diameter (d), and wall thickness (t)] and material properties [specific resistance (ρ), and dielectric constant (ε)].

In an EIT tendon, the resistive component of impedance, $Z_R = R$, represents the combined electrical resistances of the concrete, the duct and grout that lies between the conventional reinforcement and the post-tensioning strand. The resistances of the duct itself and a defect in the duct act in parallel; the occurrence of a defect would have a very low resistance that would dominate and be directly reflected in the impedance measurement (Figure 8).



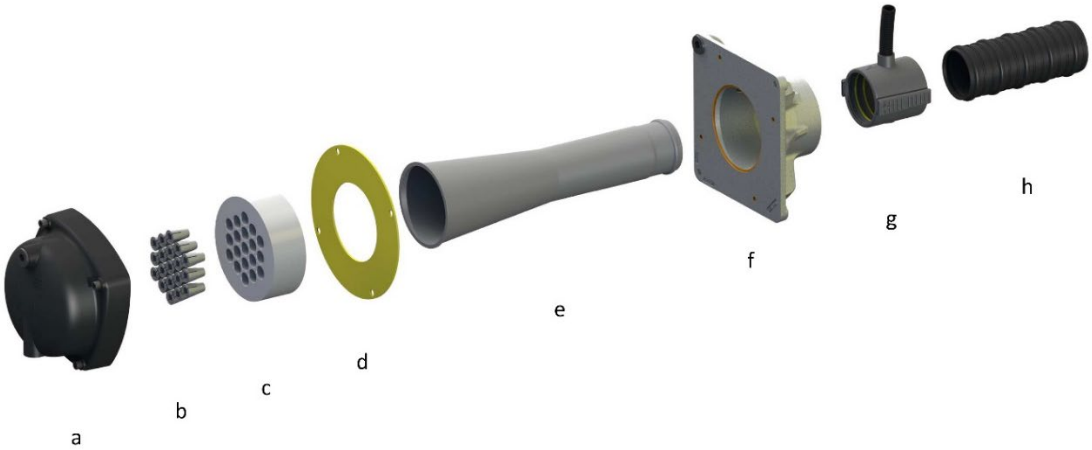
Source: WSP/FHWA.

Figure 8. Diagram. Schematic equivalent circuit of cumulative resistance and capacitance of concrete, duct, and grout between mild reinforcement and post-tensioned strand (left) and influence of a duct defect (right).

Capacitance is a less-important factor but is proportional to tendon length and dielectric property of the duct and is influenced by the proportion of inner to outer radii of the duct. The total impedance is a function of frequency of the alternating current applied. Another parameter of interest is the Loss Factor, D, which is a unitless ratio of the real and imaginary components of the impedance and is influenced by resistance, capacitance and the frequency of the alternating current applied. Loss Factor is completely independent of tendon length but sensitive to number of defects in the duct, and therefore a potentially useful measure. More detailed information about the AC impedance parameters for EIT can be found in the companion FHWA report on Monitorable Post-Tensioned Tendons (FHWA, 2020a).

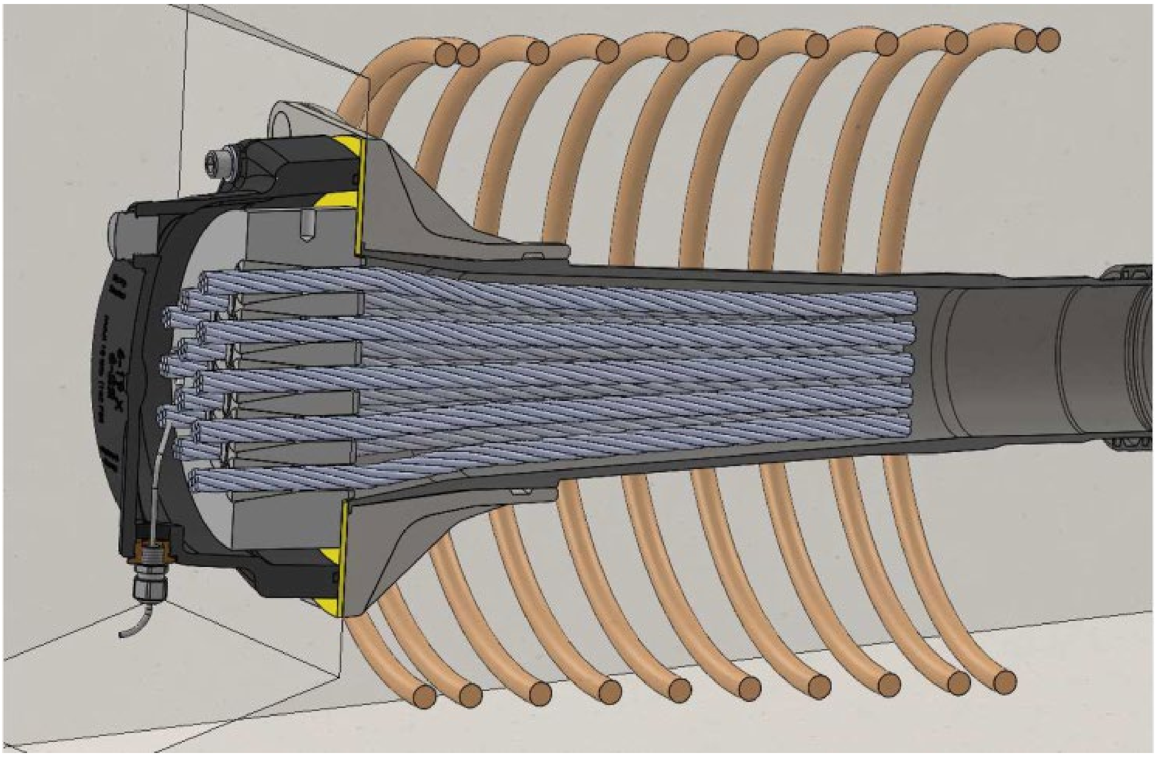
EIT Components

Components of a modern electrically isolated tendon anchorage assembly are illustrated in Figure 9. Features of electrically isolated tendons that have evolved for bridge structures include the use of thick corrugated plastic ducts, plastic couplers and plastic trumpet, which provide a tight envelope that prohibits intrusion of water and chloride (ion transfer) and prevents metal-to-metal contact between the strands and mild reinforcement or supports outside the tendon. Similarly, isolated anchorages provide the dual function of excluding stray currents from reaching the steel strands and preventing electrolytic contact between the tendon grout and the concrete at the anchorage. As with conventional post-tensioning, stress is still transferred from the individual post-tensioned strands via wedges in an anchor head that in turn presses against a bearing plate embedded in the surrounding concrete. Electrical isolation of the anchor-bearing plate from the anchor head is achieved by a special electrically non-conductive isolation plate that supports the high compression forces. The configuration of an assembled anchorage with strands is illustrated in Figure 10.



Source: VSL.

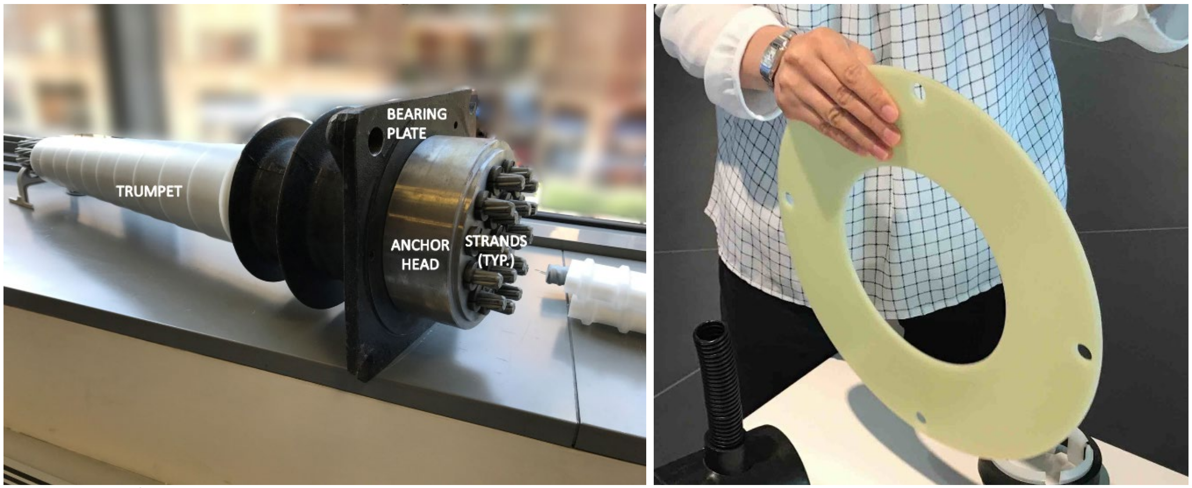
Figure 9. Diagram. Exploded perspective view of electrically isolated tendon anchorage assembly; components include: a) protection cap, b) wedges, c) anchor head, d) isolation plate, e) trumpet, f) bearing plate, g) coupler with grout connection, and h) polymer duct.



Source: VSL.

Figure 10. Diagram. Cutaway view of electrically isolated tendon anchorage assembly showing tendon encapsulation and surrounding spiral reinforcement.

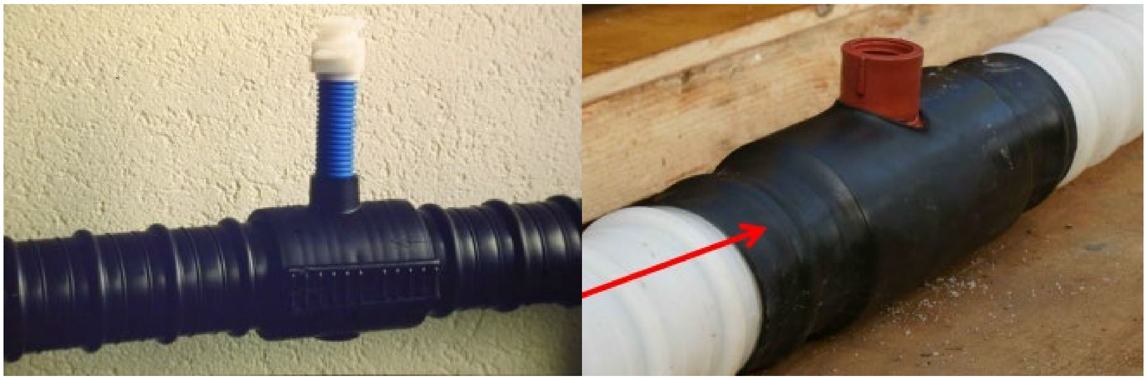
Many of the structural components of an EIT anchorage assembly resemble those used in conventional post-tensioning, with the critical component for electrical isolation being the non-conductive isolation plate (Figure 11).



Source: WSP/FHWA.

Figure 11. Photo. Conventional anchorage assembly (left) and EIT isolation plate (right).

It is also critically important that water-tightness and electrical isolation be maintained at couplers, grout vents, and trumpet connections. The duct connections are sealed with a combination of shrink wraps and polymer sealants. Grout and vent tubes must be incorporated into the design and sealed to prevent contact of grout in the ducts and vents with the external concrete (Figure 12).



Source: VSL and Stahlton.

Figure 12. Photo. Duct couplers with grout connectors provide watertight seal and maintain electrical isolation while allowing proper grout placement and venting.

According to Europe's experience, proper implementation of EIT systems requires a team effort. A successful project requires good tendon profile layout by designer with regard to minimum tangent distance, minimum radius of curvature, and similar detailing. Early experiences with plastic ducts and EIT also revealed issues with wear, wherein plastic ducts supported on steel bars and abrasion from pulling of strand could easily create a breach or short circuit when the support bar indents into the duct. The industry developed an external clip-on (half-shell) support interface to provide greater plastic thickness and resistance to localized bending or buckling of the duct between cable and support to mitigate this effect, and greater constraints were placed on routing and allowable bend radii in ducts as they run between supports and through mats of reinforcement (Figure 15). In addition, wire ties are not allowed to be used to tie EIT duct; plastic zip-ties are commonly used.

Source: SBB and Stahlton.

Figure 13. Photo. Abrasion of inside surface and potential breach of plastic ducts from pulling of strands around tight bends or local protrusions (left and center, courtesy of SBB) and protective half-shells at duct support points (right, Stahlton).

The prevention of metallic short-circuits between strands and mild reinforcement or ionic bridges between concrete and grout permits the measurement of impedance (resistance and capacitance) between the internal tendon steel and external reinforcement, thereby indicating the effectiveness of the duct and anchorage enclosure in isolating the strands and grout. This is achieved by establishing an independent electrical connection to the anchor head, with an insulated electrical lead that penetrates the protective cap and extends from the anchorage head to a junction box conveniently located for security and easy access. Another wire is connected to the mild steel reinforcement outside the tendon and runs to the junction box for monitoring purposes. The impedance between the leads at the junction box are measured with a hand-held LCR meter (Figure 14).

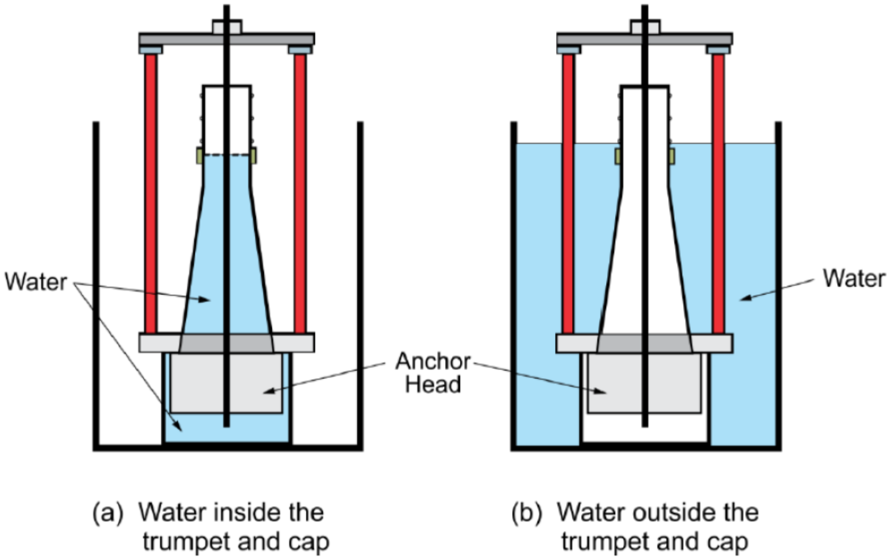
Source: Stahlton.

Figure 14. Photo. Wire conductors lead from mild reinforcement (top left) and strand anchor head (bottom left) to junction box where an LCR meter can be used to measure impedance (right).

System Qualification and Approval

Current European practice for PT incorporates a rigorous set of pre-qualification tests that must be completed for a post-tensioning tendon system to be accepted for production, especially in PL2 or PL3 designs. In accordance with *fib* 75 (2014), these involve a series of individual materials tests, followed by qualification of components that check aspects of dimensional tolerance, stiffness, or flexibility, longitudinal and lateral load resistance, wear resistance, fracture resistance (optional), bond behavior, and water-tightness. The final stage involves qualification tests for the assembled system, including:

- Water-tightness of the anchorage-duct assembly under both positive and negative air pressure for 30 minutes each (Figure 15).
- Air-tightness of the full-scale duct system assembly.
- EIT performance of the duct only and the duct with connector (with/without vent).
- EIT performance of the anchorage-duct assembly for a test period of 28 days.



Source: WSP/FHWA.

Figure 15. Diagram. Leak tests of PL2 or PL3 anchorage assembly under a) positive pressure and b) negative pressure.

A European Technical Assessment (ETA or "approval") is a documented assessment of the performance of a construction product, in relation to its essential characteristics. Development of assessment guidelines for construction products such as PT systems (including EIT) is managed at the European level through the European Organization for Technical Assessment (EOTA), which specifies methods and criteria in European Assessment Documents (EADs). Prior to July 2013, such documents were known as European Technical Approval Guidelines (ETA Guidelines or ETAGs). Both EADs and ETAGs establish how Approval Bodies should evaluate the specific characteristics and requirements of a construction product or a family of construction products. The current governing guideline is EAD16 (2016), the Guideline for the European Technical Assessment on PT systems, which refers to *fib* 75 (2014) for EIT systems assessment and superseded ETAG 013 (2002). EADs or ETAGs are enforced via national approval bodies in each country, each known as a Technical Assessment Body (TAB). One or more TABs are identified for each European country on the EOTA website. As an example, in Switzerland, qualification tests for PT systems are reviewed by an Expert Group for Post-Tensioning Systems (EGS) - registered through the site of the Swiss Society of Engineers and Architects.

Training and Certification

Careful execution and training of workmen is necessary for proper installation of EIT systems, because there is a learning curve. Comprehensive training and certification for all levels (designers, contractors, PT system installers, grout installers, inspectors) is necessary to ensure a successful outcome.

Producer Certification

Annual certification of PT and grout producers and installers is required to perform grouting in Switzerland and other European jurisdictions. PT system producers are required to complete a number of periodic certifications and audits (one to two per year) by an authorized third party, compliance with which takes a typical producer about two weeks per year (D. Meyer, personal communication). The number of problems with projects was reported to have declined greatly since implementation.

Personnel Certification

One post-tensioning system manufacturer reports that they have developed standardized in-house practices that are defined in a field manual. Personnel responsible for design, installation, grouting, and inspection of PT systems are required to attend one of two internal post-tensioning Academies, a rigorous training program with up to three levels of proficiency in a range of technical topic areas targeted at functional roles ranging from foremen/supervisors to project manager/site manager.

The program includes provision and review of pertinent reference documents, including the field manual, product catalogues, and companion lecture materials. Classroom-style presentations provided by experienced lecturers are augmented by hands-on exercises under guidance and supervision of experienced site people, where students try their skills in a realistic environment and then analyze the results of their efforts to determine successes and failures and how to adjust. Installation, stressing and grouting of a 0.6-inch strand diameter, 19-strand, profiled external tendon for the post-tensioning of a 30m- or 40m-long mock-up beam in concrete, which is reusable, is a key practical module to vocationally teach correct practices and management to the site workforce. The day after the grouting is the ultimate moment of truth, when the students open up the tendon's duct at critical sections to verify effectiveness of their grouting work. Successful completion of the program is validated through 40 percent written exams and 60 percent practical evaluations to support an internal certification process. To site assemble PT tendons to high quality requires not only a trained and certified project manager and supervisors but, as importantly, a trained and certified workforce. It is the responsibility of the trained and certified person in charge of a PT project to train and certify the project's work force on site through on-the-job training and to ensure that site work is only carried out by suitably trained and certified workers. In practice, there is also a follow-on quality assurance of the implementation of correct practices through independent site audits.

Having a rigorous product assessment and approval program combined with standardized producer and installer certifications is reported to have resulted in a significant decrease in poorly performing installations.

Construction and Quality Control

Quality control (design stage, handling, execution, workmanship, instruction) is crucial for success. There have been problems where designers/owners do not recognize the challenges and requirements change during the course of the project. It is important to assemble the various parties (drilling company in the case of ground anchors, PT system supplier, concrete contractor) to coordinate with the designer and owner prior to and during construction. It is important to define expectations at the beginning of a contract based on the level of risk. Pilot or demonstration mock-ups may be good practice but do not necessarily represent in-place field conditions.

EIT by itself is not sufficient to ensure good performance. EIT allows project personnel to verify the integrity of a tendon's encapsulation. To protect a tendon from corrosion, it is additionally necessary to have the strands within the leak tight encapsulation fully embedded in stable grout. The quality of grouting materials and operations is therefore as important as the encapsulation. To this end, Europeans have adopted the use of clear end caps in some cases to ensure the anchorage is completely grouted while avoiding the need to remove the grout caps during post-grouting inspection. In European practice, vacuum-assisted grouting is strongly promoted to prevent the occurrence of voids.

During construction of EIT PT tendons, tests are conducted at different stages to provide stepwise checks on the integrity of the system. These involve tests prior to concrete placement, prior to grouting and after grouting.

Pre-Strand Installation Testing

Before pulling strands through ducts placed in the structure, there are a few tests that may be useful. To check the duct for kinks or wall deformations, a cable-drawn plunger (or “pig”) of proper size may be drawn through the duct to detect obstructions (Figure 16). To screen for tears or incomplete seals in the duct and connections, a test may be performed by pumping the “fog” formed by dry ice (CO_2) through the duct and observing the length of duct where the fog may be escaping (Figure 17). It will be easier to seal or repair these locations without tendons installed. When installing tendon ducts and performing such checks, note that duct support spacings for European practice (10-12 times the duct diameter) differ from U.S. requirements (2 ft.), and may need to be considered.

Source: VSL.

Figure 16. Photo. Plunger test to detect duct kinks, deformations, or obstructions.

Source: VSL.

Figure 17. Photo. Dry ice (CO_2) fog test to detect leaks in duct.

Pre-Concrete Placement Testing

In Europe, it is common to place the strands in the PT duct prior to placement of concrete for short-span structures. The purpose of conducting EIT tests prior to concrete placement is to ensure that no direct electrical contact between the strand and external reinforcement may occur as a result of the placement of the reinforcement and post-tension duct assembly. The test is conducted after the EIT tendon has been placed and all reinforcement is in place, ready to receive concrete. A negative result of the test would be indicated by extremely low resistance, indicating that a short circuit has occurred. The occurrence of direct contact between strand and bar or duct supports may most likely indicate that either a duct connection has failed or that abrasion of the duct during the pulling of the strand has caused wear through the wall thickness of the duct, permitting direct electrical contact of the metallic elements. Testing at this stage permits the cause of the short circuit to be addressed in advance of concrete placement, which is far simpler than after the fact.

Pre-Grout Testing

After concrete has been placed, the strands are tensioned, and ducts are ready to be grouted, another EIT check is warranted to ensure that the duct has not been breached (e.g., due to pressure of the plastic concrete causing failure or penetration at couplings or vents or damage by vibratory probes used for concrete consolidation), and that application of prestress has not further abraded the duct or otherwise caused electrolytic contact with the external concrete, reinforcement, or supports. Once again, measurement of relatively low resistivity may suggest a breach, and if necessary, the affected tendon can be investigated to address the issue prior to placement of the grout.

Post-Grout Testing

Testing of EIT tendons after grouting represents the goal acceptance measurement for the system, wherein integrity of the fully constructed tendon enclosure can be confirmed. Measurements are made of both the capacitance and the resistance of each tendon; however, resistance is considered to be more sensitive and forms the basis for standard acceptance criteria. Capacitance is dependent upon the length (L), diameter (d), and material (ε) of the duct. Resistance is influenced by the quality of the concrete and the grout, though the expectedly much higher resistance induced by the nonconductive duct is of primary interest to ensure the physical barrier is continuous. Electrical resistance measurement on each tendon is very effective as a quality control measure for installation.

Tendon Probing (Post-Grouting Inspection)

While it is common practice in the U.S. to probe the duct behind the anchorage with a borescope to check for grout voids, this is not a routine practice in Europe. Hence, production EIT anchorage assemblies do not currently include inspection ports in their design. A significant concern is breaching the isolation trumpet and establishing unintended electrolytic contact that violates the isolation. FHWA is sponsoring research to evaluate potential solutions. The modification of current designs to accommodate an inspection port was discussed with fabricators but will require further coordination if the technology is to be adopted in the U.S. and the practice of post-grouting inspection is to be retained, which is likely. The use of vacuum-assisted grouting, which ensures complete filling of the anchorages with grout, could eliminate the need for post-grouting visual inspection of the anchorage with a borescope. Another interesting option is the use of special sensors installed between the anchor block and bearing plate, as available through one manufacturer, which can be used to verify complete filling and passivation by electric potential measurement.

Wolhusen Bridge

As an example of a bridge under construction containing EIT, the team visited a replacement railway bridge under construction near the downtown of Wolhusen, Switzerland. The bridge comprises a single-span post-tensioned concrete through-girder (or "U-shaped") superstructure being constructed directly adjacent to an in-service multiple arch concrete structure it is intended to replace (Figure 18). Once bridge superstructure fabrication is complete, the existing bridge will be closed and demolished, the new substructure finalized, and the new superstructure will be slid into place. An adjacent span over a city road had been replaced more than 10 years prior.

Source: WSP/FHWA

Figure 18. Photo. New post-tensioned concrete superstructure being formed adjacent to an in-service rail service rail bridge.

The study team observed the duct and anchorage assemblies and discussed installation, grouting, and inspection procedures with the project personnel and fabricator. At the time of the visit, the contractor had completed formwork for the superstructure, placed and tied all of the reinforcing steel (Figure 19), assembled the post-tensioning ducts and anchorages, and pre-placed the tendons in the ducts (Figure 20) in preparation for concrete placement, scheduled for the following day.

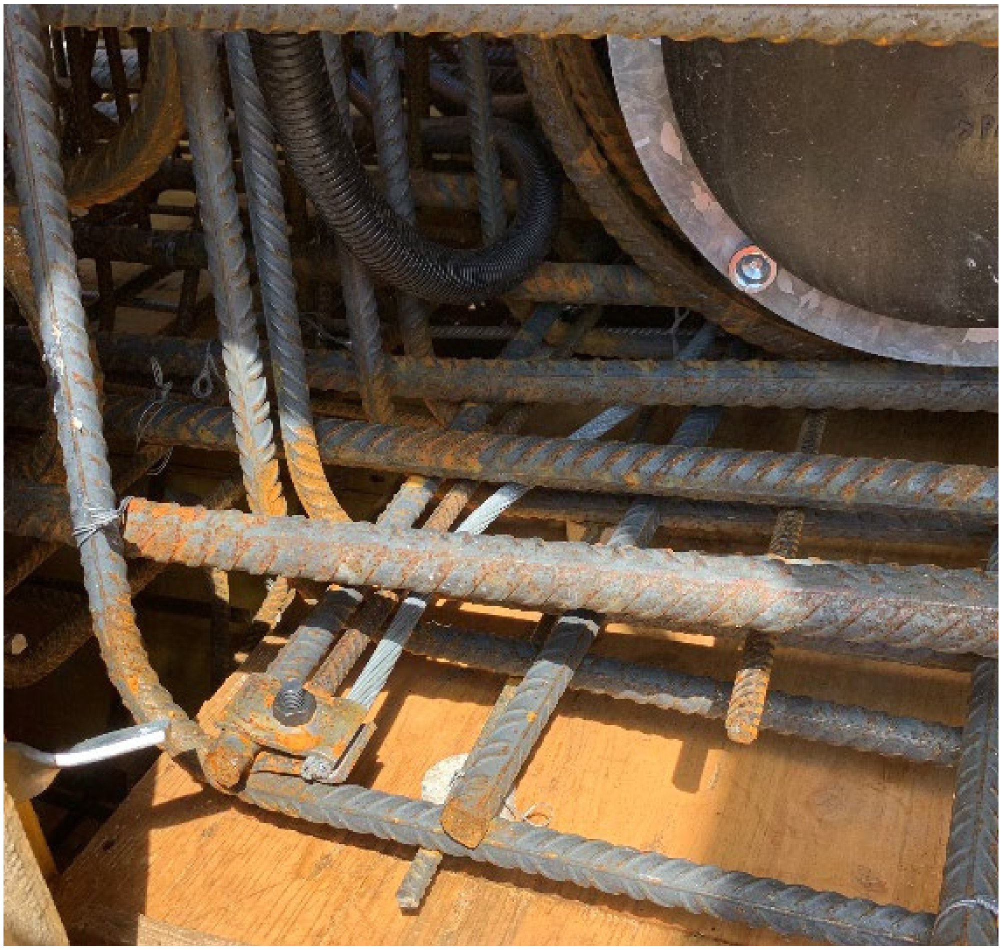
Source: WSP/FHWA.

Figure 19. Photo. Formed through-through-girder with reinforcement and PT ducts in place, awaiting place, awaiting concrete.

Source: WSP/FHWA.

Figure 20. Photo. Post-tension assembly awaiting concrete; dead end (left) and live end (right).

Note the port for grouting (12 o'clock position) and conduit for EIT sensor cabling (11 o'clock position) extending from the perimeter of the anchorage cap at the dead end. Exposed strand ends already in place were encapsulated with conduit and protective tape to prevent moisture and concrete intrusion into the duct during construction. To address concerns for stray current corrosion of the mild reinforcing, grounding wires were attached to the reinforcing cage as shown in Figure 21.



Source: WSP/FHWA.

Figure 21. Photo. Grounding wire attached to steel reinforcement cage.

Mittelmuhen Bridge

For an example of a completed bridge, the team visited the Mittelmuhen Bridge, a 23-m single-span, through-girder ("U"-shaped) post-tensioned concrete rail bridge that carries the *Wynental- und Suhrentalbahn* (Wyna Valley and Suhre Valley Railway; WSB), a privately owned narrow gauge railway, through Muhen, Switzerland (Figure 22).

Source: WSP/FHWA.

Figure 22. Photo. View of the Mittelmuhen Bridge as the Wynental- und Suhrentalbahn train passes.

The team was given a short field presentation about the design, construction, and monitoring history of the bridge (Figure 23).

Source: WSP/FHWA.

Figure 23. Photo. Field presentation of design and construction of EIT in the Mittelmuhen Bridge.

The fabricator noted that their practice is to ship pre-assembled, ungrouted strand and anchorage assemblies for tendon lengths that are not prohibitively long, to reduce the likelihood of quality control problems on site. Note the use of polymer trumpets and ducts with shrink wrap to ensure electrical isolation and physical seal against moisture (Figure 24, right).

Source: Stahlton.

Figure 24. Photo. Construction of the Mittelmuhen Bridge showing end of span with EIT wires extending from anchorage caps (left) and PT anchorage assemblies prior to concrete placement (right).

Acceptance

Construction acceptance criteria, based on resistivity readings of the EIT system, are prescribed according to the Swiss Guideline (ASTRA 2007):

- To protect from stray currents, full electrical isolation requirement for length-normalized resistance is $R_l \geq 250$ to 125 kΩ-m (acceptance value is dependent on duct diameter). Note that stray current is the primary reason that Swiss Authorities made use of EIT mandatory on DC railways and tramways.
- For long-term monitoring, criteria for length-normalized resistance is $R_l \geq 50$ kΩ-m. EIT can be used to monitor the degree of isolation (corrosion protection) of the tendons and detect ingress of water (and chlorides).
- To avoid fatigue and fretting corrosion, suggested criteria for resistance is $R \geq 20\ \Omega$. This is to ensure that the plastic ducts are effective in preventing direct contact between high-strength steel and the normal reinforcement (no short circuit).

Piacenza Viaduct

Italy's experience with EIT was in construction of the Piacenza Viaduct, a 5.1-km long rail structure that lies along the high-speed rail segment from Milan to Bologne, which mixes passenger rail traffic (traveling up to 300 km/hr) and freight rail traffic (traveling up to 180 km/hr). Frecciarossa, Trenitalia's premiere high-speed rail service, runs along this corridor. The viaduct, shown in Figure 25, is comprised primarily of a series of (150) 33.1-m-long simply-supported, post-tensioned concrete boxes, each weighing approximately 9,750 kN (219 kips).

Source: WSP/FHWA.

Figure 25. Photo. Piacenza viaduct viewed near its southern terminus as a Frecciarossa high-speed train passes.

Source: WSP/FHWA.

Figure 26. Photo. View of interior left cell, facing north, of 3-web box segment.

The concrete cross-section comprises a 2-cell, 3-web trapezoidal box containing (15) 19-strand tendons in 100mm ducts distributed among the webs and (9) 12-strand tendons in 76 mm duct in the bottom flange. The structure represented Italian Railway's first effort to incorporate electrically isolated tendon design of PT in accordance with provisions developed by féderation internationale du béton [the International Federation for Structural Concrete] (*fib*) in *fib* 7 (2000) and *fib* 33 (2005) standards. Figure 26 depicts the interior of a typical cell, and Figure 27 shows inspection of a web-mounted junction box where electrical leads to the reinforcement and isolated strands can be used to measure impedance. The support bearing in Figure 28 features a prethreaded hole in the sole plate designed for connection of an electrical ground lead.

Source: WSP/FHWA.

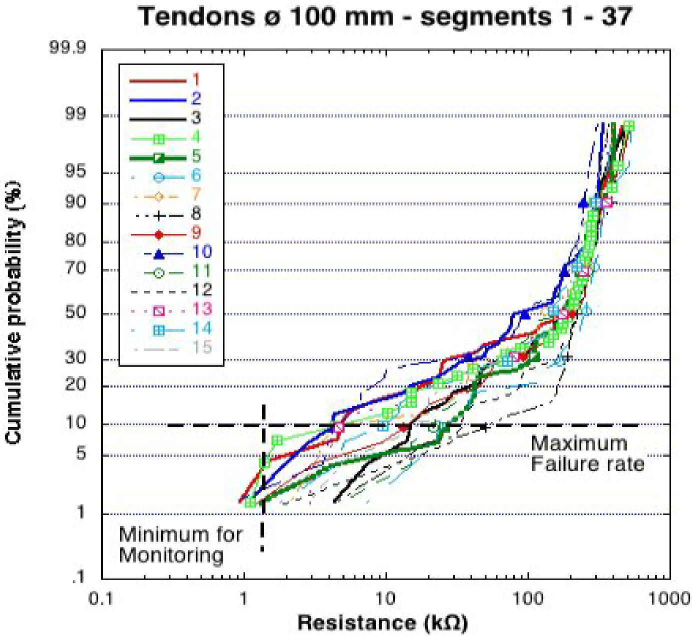
Figure 27. Photo. Engineers inspecting an EIT junction box; inset is close-up of the junction box.

Source: WSP/FHWA.

Figure 28. Photo. View of bridge bearing – note the pre-drilled hole in sole plate to connect EIT ground.

Experience in Europe has shown that it can be challenging but not impractical to put EIT technology into practice under construction site conditions. As the testing method is very rigorous, normally a quota of 5 to 10 percent of tendons not obtaining the required electrical resistance are accepted. It was recommended by several of the experts that acceptance criteria be observed carefully to guard against potential problems with the construction, but that they not be enforced so strictly as to penalize the contractor unnecessarily. There are instances where readings may not meet criteria but may still indicate adequate protection for the intended purpose. It is also expected that not all tendons may meet the criteria, and an acceptable percentage of non-compliant readings should be determined based on acceptable risk. Elsener noted in a cumulative probability plot of resistance (log-scale) that the distribution showed a bi-linear trend (Figure 29), with 95 percent of tendons meeting criterion (along the upper line) and approaching the theoretical value of resistivity for the system as designed. About 2 percent (along the lower line) were reported to have indicated a short circuit.

Resistivity thresholds are not absolute, but based upon expert opinion. It was noted that the acceptance criteria were developed specifically within the central European region, and it may be important when developing guidance for North American application to consider climate as an influence on the chosen criteria. A (too) low value of electrical resistance does not indicate a corrosion process, but only damage of the corrosion protection barrier (ducts) of the PT system. The inner corrosion protection barriers may still be intact (e.g., grout) and the tendons still can be monitored over time (except short circuits).



Source: B. Elsener.

Figure 29. Chart. Distribution of EIT acceptance test results for 100-mm diameter tendons at Piacenza viaduct.

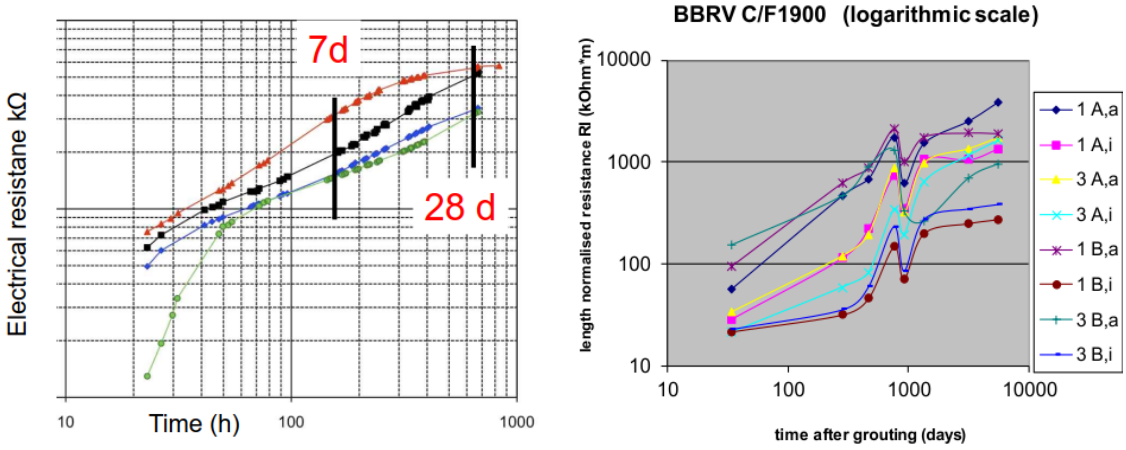
Operation and Long-Term Monitoring

Periodic Testing and Detecting Loss of Isolation

EIT systems can be periodically tested in service to assess whether the tendon remains electrically isolated, as indicated by resistance and capacitance from LCR measurements. A sharp change may indicate the system has been breached in some way that may permit exposure of the encapsulated tendons to moisture and aggressive elements from the environment, or perhaps stray electrical current, if applicable.

It is important to note that EIT resistivity measurements are sensitive to extremes in both temperature and moisture. Care should be taken to record ambient or structure temperatures at the time readings are taken. With proper monitoring of temperature along with the resistivity, a correlation can be made over time to correct for temperature. Effort should be made to avoid taking measurements immediately following precipitation events that may skew the readings.

Long-term monitoring by Prof. Elsener and by others has shown that the common trend in resistivity readings, when plotted on a log scale, will exhibit an approximately linear increase. Elsener suggested a formula to compensate for time of measurement versus 28 days as $R_{28d} = R_t\sqrt{\frac{28}{t}}$, which was adopted into the Swiss guidelines (ASTRA 2007). This is illustrated in Figure 30 wherein long-term laboratory studies (courtesy of B. Elsener) show near-linear behavior after the first few days, and in field measurements on an in-service bridge (courtesy of K. Lupold). An overall linear trend can be seen, though periodic peaks and valleys may be observed, which may be partially attributable to variations in temperature at time of measurement. This is consistent with the establishment of proper isolation from the tendon envelope and continued hydration and maturity of both the concrete outside the duct and the grout inside the duct. If the duct were to be breached by moisture, a precipitous drop in resistivity should be observed, indicating the need for further investigation. Indeed, one case study was discussed wherein the structure was not vented and accumulated moisture caused the resistivity to decrease.

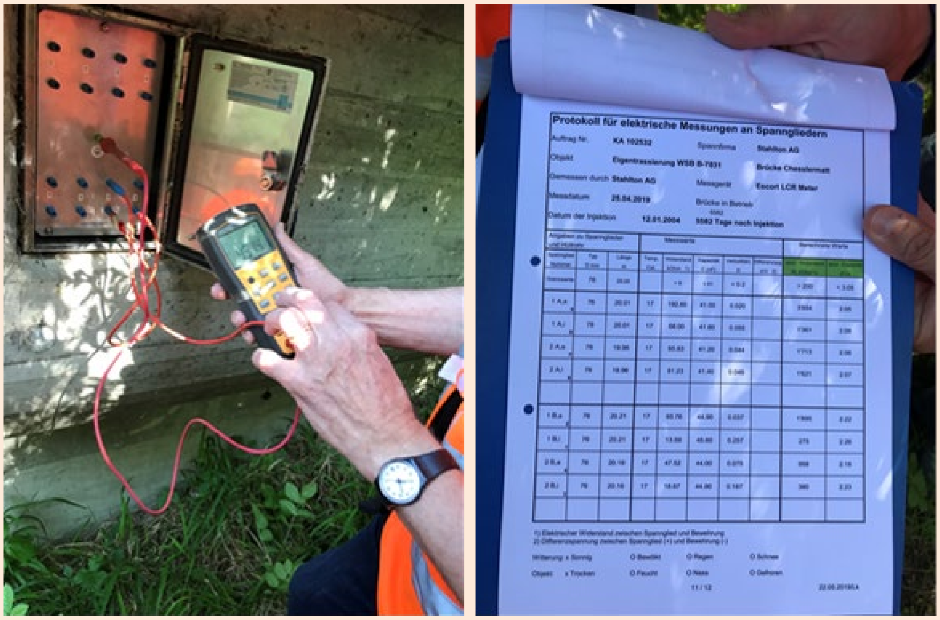


Source: Left, B. Elsener; right, K. Lupold.

Figure 30. Charts. Trends of EIT resistance versus time from laboratory and field.

Mittelmuhen Bridge

As an example of long-term testing of EIT systems in service, a demonstration was made at the Mittelmuhen Bridge in Switzerland that was previously introduced. The bridge was constructed in 2003 with 12 PT tendons using EIT technology and has been periodically monitored through its lifespan. Details of the bridge and PT anchorage configuration were discussed (Figure 24, left), including the location and routing of EIT cabling to a junction box that is located in an accessible yet secure location on the bridge. The team then proceeded under the bridge to the north abutment, where the EIT junction box was located. The measurement was demonstrated, and values compared to previous readings (Figure 31).



Source: WSP/FHWA.

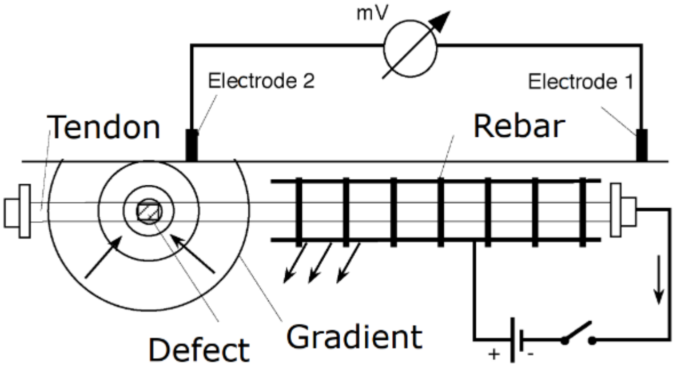
Figure 31. Photo. EIT in-service measurement using LCR meter (left) and data sheet (right).

The site demonstration at the Mittelmuhen Bridge showed that periodic measurement of EIT performance can be made in a short and simple test using a hand-held LCR meter and test leads (Figure 31). With proper configuration of conductors at both ends of each tendon, it is also possible to test tendons in parallel as a check on continuity of the conductors.

Locating System Breaches

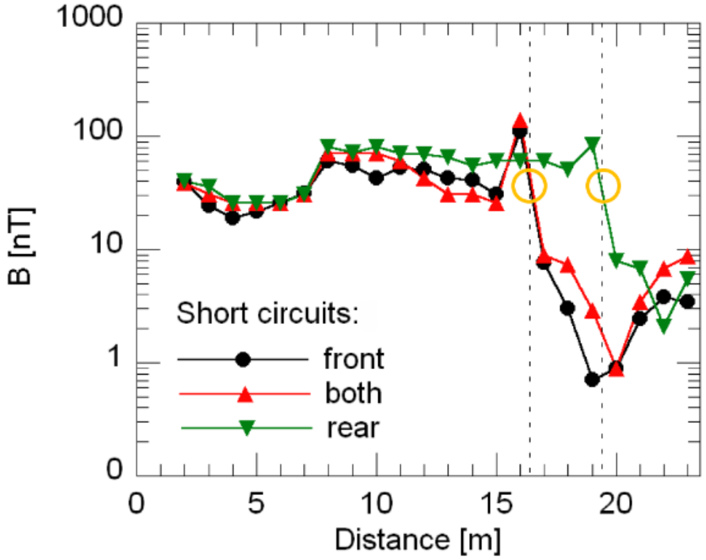
During a workshop at ETH Zurich, a demonstration was made of a system for detecting the location of breaches in an EIT duct. The method is predicated upon the tendons being close enough to an accessible concrete surface to permit the detection of an electromagnetic field around the tendon. To make best use of the method, it is highly recommended that independent electrically conductive leads be extended from each end of the tendon. The method works on the principal that when a breach in a tendon occurs, there will be a short-circuit path, such that when an alternating current is induced it can be detected with an external sensor (by inductance), and beyond where the breach is encountered the field will no longer be present (Figure 32). With independent leads at each end, breaches can be detected at a distance from either end, such that the location of a single breach may be confirmed from both sides or the presence of an additional breach may be found from the other direction by observing reduction in the magnetic flux density, *B*, expressed in a unit of magnetic induction termed the tesla (T) (Figure 33). Theoretically, the method is not able to detect breaches beyond the first occurrence from a lead point.

With EIT, a cost-effective early warning system for post-tensioned tendon condition is available. For the monitoring of tendons during the working life, electrical resistance measurements are useful to validate electrical isolation, but should be used in combination with visual inspections, force and deformation measurements, or other means to ensure structural integrity. Electrical resistance measurement is sensitive to weather conditions (not reliable under rainy conditions and may be erratic under temperature extremes) and correct electrical grounding. In appropriate circumstances, it is possible to exploit EIT systems to locate breaches or defects along the length of a tendon that indicates low resistivity.



Source: U. Angst.

Figure 32. Diagram. Locating defects in the duct by means of an electro-magnetic field.



Source: Swiss Society for Corrosion Protection (SGK)

Figure 33. Chart. Localizing breaches or short-circuits by means of electro-magnetic field.

Source: Swiss Society for Corrosion Protection (SGK)

Figure 34. Photo. On-site detection of EIT breach on a post-tensioned structure.

Chapter 3 – Recommendations and Implementation

The primary reason for this study was to investigate how well electrically isolated tendons (EIT) were serving their international owners and determine unique processes for EIT qualification, installation, and monitoring that should be considered in pursuing domestic implementation. The study team determined that the EIT technology successfully provided the following benefits:

- Provides reliable construction quality control on the installation of PT tendons through validation of isolation by means of electrical resistance measurements, to ensure PL3 compliance.
- Provides early warning of PT tendon envelope breaches, before grouting of tendons, which provides the opportunity to repair the breach.
- Provides reliable and easily interpretable PT tendon encapsulation data during the service life of a structure.
- Requires minimal change to the current state-of-practice PT details and installation processes.

Experiences with the electrically isolated post-tensioning system with plastic ducts are encouraging both in Italy and in Switzerland. Simple and reliable measurements give information on corrosion protection of EIT tendons. EIT provides a simple and straight-forward method for long-term monitoring of the encapsulation of structurally important tendons.

Recommendations

Based on the findings of the EIT Global Benchmarking effort, a series of recommendations has been developed to promote adoption of EIT in the U.S. with regard to design, system qualification and approval, training, construction and quality control, as well as long-term monitoring. Further, a set of research recommendations has been identified to fill information gaps.

Develop Design Guidance Tailored to U.S. Practice

The EIT GBP team recommends that tailored guidance be provided to introduce U.S. practitioners to EIT concepts and provide guidance on how the technology can be employed in U.S. highway bridges.

- The Federal Highway Administration has developed a state-of-the-art report on Monitorable Post-Tensioned Tendons (FHWA, 2020a). The report discusses the technology of electrically isolated tendons (EIT) as a concept to protect and monitor tendons against corrosion attack from the outside of the tendon through full encapsulation of the tendon in a plastic duct, shielding the tendon from chlorides, oxygen, and moisture. The complete electrical isolation of the tendon from the reinforcing steel permits monitoring of the tendon over time and reduces the risk of stray current—induced corrosion. The report reviews existing literature and guidelines concerning EIT, and describes the principles of the EIT technology, the required components, performance testing, and monitoring procedures in order to provide a basis for potential implementation of the technology in the U.S.

- This FHWA report on Electrically Isolated Tendon technology, summarizing the findings of the Global Benchmarking Program effort, is also meant to convey the highlights of the technology and lessons learned by European practitioners in its implementation. This report will be accompanied by associated presentations, which will be addressed to U.S. bridge owners and designers through conferences and webinars.

Incorporating EIT into PT Specifications, including Methods of System Qualification and Approval

The EIT GBP team recommends that standard specifications be developed through PTI and ASBI for selection, use and approval of EIT technology in PT bridges in the U.S.

- As a benefit of the current EIT GBP effort, work is already underway toward development of EIT system qualification testing to be implemented in U.S. practice. The Post-Tensioning Institute (PTI)/American Segmental Bridge Institute (ASBI) joint committee M50 is working to develop and adopt acceptance standards for EIT systems. The guidance, once developed, will be folded into the industry standard guide specification PTI/ASBI M50 Acceptance Standards for Post-tensioning Systems. The specifications will likely reference International Federation for Structural Concrete (fib) Bulletin 75 for proof-test requirements for EIT tendon assemblies and will adopt a tiered approach for acceptance criteria, similar to those used in Swiss practice (ASTRA 12 0010).

Develop Personnel Training/Certification Requirements

The EIT GBP team recommends that training programs be developed or tailored to cover both the installation and the inspection of EIT PT systems, and that appropriate certifications be developed to indicate mastery of such training.

- A significant step to implementing EIT in the U.S. will be development and provision of PT Installer Training for the U.S. workforce. PTI intends to work with U.S. industry partners to augment existing Level 1 & 2 Multistrand & Grouted PT Specialist training with EIT installation skills. (https://www.post-tensioning.org/certification/fieldpersonnelcertification/personnelcertificationoverview.aspx)

- In addition, with respect to PT Inspector Training, current training programs will be augmented with EIT components to convey appropriate methods for testing and acceptance. Current practice for PT Inspector Training involves a written examination. It is envisioned that vocational training may permit practical/hands-on development and evaluation of an inspector's skills with the technology.

Promote Guidance on EIT Design, Installation, and Acceptance

The EIT GBP team recommends that a program of Education and Outreach be undertaken to broaden awareness of EIT as a suitable technology for PTI/ASBI M50 specified Protection Level 3 (PL3) design and construction to support adoption of guidance and specifications outlined above.

- FHWA will support and promote delivery of presentations about EIT in PT bridges at national conferences, including PTI and ASBI conventions, AASHTO Committee on Bridges and Structures, select committees at the Transportation Research Board Annual Meeting, and other suitable venues.

- FHWA and its State and industry partners will provide workshops at EIT demonstration projects in the U.S. Technical and promotional articles of the pilot projects and demonstrations will be disseminated through industry journals. (e.g., Aspire – http://www.aspiremagazinebyengineers.com/publication/?i=609800&p=38&pp=1&view=issueViewer)

Develop Guidance for Operation and Long-Term Monitoring

The EIT GBP team recommends that guidance be developed for owners in the monitoring of EIT systems in service, including methods and timing of monitoring, expected behavior over time, what constitutes acceptable or abnormal readings, and what to do if unusual results are obtained.

- Guidance should be developed for design of monitoring system, including junction box configuration and access, LCR meter selection and use. It may be possible to promote or adapt guidance already under development, such as a Special Provision developed by TxDOT for its EIT pilot project. Some guidance has been developed on LCR meter selection (https://ascelibrary.org/doi/10.1061/%28ASCE%29BE.1943-5592.0001551) that can be consulted.

Research

The EIT GBP committee recommends that research be performed to accommodate conditions unique to U.S. construction and inspection practices and fill gaps in information not addressed elsewhere. The following are some examples.

- Challenges exist in use of EIT systems in structural components with epoxy-coated reinforcing, since the epoxy coating will create an impedance barrier that theoretically inhibits the measurement of the tendon enclosure. Problems with epoxy-coated reinforcement as a reference (lack of electrical continuity) can be overcome by placing a metallic conductor (wire) parallel to the duct. FHWA initiated research into acceptance thresholds that might be associated with epoxy-coated reinforcement but shifted to develop guidance on surrogate reference electrodes embedded with EIT PT tendons, to remove influence of the coated reinforcement from measurements. This information is available through an FHWA Tech Brief (FHWA, 2020b).

- In European practice, it is not common as in the U.S. to probe the anchorage to verify after grouting. Thus, research will need to determine the best configuration of EIT anchorage systems that will allow for post-grouting inspection. Alternative approaches that may be further investigated include:
    - Requiring mandatory vacuum-assisted grouting in combination with density measurement of grout at outlet port prior to closing; or
    - Suitability of embedded sensors that can indicate the presence of quality grout installation without physical probing. Such a system has been developed and successfully used on projects in Europe and the Far East by a major PT manufacturer.
- The U.S. represents a very broad geography with widely varying climates, whereas experience with EIT in central Europe has been confined to a relatively uniform set of environmental conditions. The development of EIT resistance thresholds with methods to normalize for varying ambient temperatures and climates is needed. Researchers should gather and analyze data to determine trends related to climate as well as changes in the system responses over time as grout continues to hydrate and lose moisture or take in moisture. FHWA - TFHRC plans to explore influences of moisture, temperature and age on a specimen from the acceptance thresholds research task.
- Based on discussions with European manufacturers of EIT systems, it seems that creep behavior of the fiber-reinforced polymer isolation ring has not been fully established. Their current practice is to accept based on a visual inspection after loading to 400 minimum MPa. Research should be conducted to establish creep test and performance criteria for the EIT isolation ring to prevent long-term deformation under load from compromising the EIT system integrity.

References

ASTRA 12 0010, “Measures to Ensure Durability of Post-Tensioning Tendons in Structures,” Guideline 12 0010, v.2.00, Departements für Umwelt, Verkehr, Energie und Kommunikation (UVEK), Bundesamt für Strassen (Federal Department for Environment, Traffic, Energy and Communication, Federal Roads Authority ASTRA), 2007.

EAD 160004-00-0301 "European Assessment Document for Post-Tensioning Kits for Prestressing of Structures", European Organization for Technical Assessment (EOTA), Brussels, 2016.

Elsener, B. 2005. “Long-Term Monitoring of Electrically Isolated Post-Tensioning Tendons.” Structural Concrete 6 (3): 101 –106. https://doi.org/10.1680/stco.2005.6.3.101.

ETAG 013,” Guideline for European technical approval of post-tensioning kits for prestressing of structures,” European Organization for Technical Approvals (EOTA), Brussels, 2002.

FHWA, “Monitorable Post-Tensioned Tendons,” FHWA-HIF-19-094, Federal Highway Administration, U.S. Department of Transportation, Washington, DC, 2020a.

FHWA, “Tech Brief: Development of Reference Criteria for Electrically Isolated Post-Tensioning Tendons in U.S. Bridge Applications,” FHWA-HIF-20-042, Federal Highway Administration, U.S. Department of Transportation, Washington, DC, 2020b.

fib 7, “Corrugated plastic ducts for internal bonded post-tensioning,” Bulletin No. 7, Task Group 9.6 *Plastic Ducts* of *fib* Commission 9 *Reinforcing and Prestressing Materials and Systems*, Fédération Internationale du Béton (International Federation for Structural Concrete), January 2000.

fib 20, “Grouting of tendons in prestressed concrete,” Bulletin No. 20, Task Group 9.8 *Grouting* of *fib* Commission 9 *Reinforcing and Prestressing Materials and Systems*, Fédération Internationale du Béton (International Federation for Structural Concrete), July 2002.

fib 33, “Durability of post-tensioning tendons,” Bulletin No. 33, Working Party 5.4.2 *Durability specifics for prestressed concrete structures*, Fédération Internationale du Béton (International Federation for Structural Concrete), December 2005.

fib 75, “Polymer-duct systems for internal bonded post-tensioning,” Bulletin No. 75, Task Group 9.16 *Plastic ducts* of *fib* Commission 9 *Reinforcing and Prestressing Materials and Systems*, Fédération Internationale du Béton (International Federation for Structural Concrete), December 2014.

PTI/ASBI M50.3-19, “Guide Specification for Grouted Post-Tensioning,” The Post-Tensioning Institute (PTI) Bonded Tendon Committee M-50 and American Segmental Bridge Institute (ASBI) joint task group, 2012.

PTI/ASBI M55.1-19, “Specification for Grouting of Post-Tensioned Structures,” The Post-Tensioning Institute (PTI) Bonded Tendon Committee M-55 and American Segmental Bridge Institute (ASBI) joint task group, 2012.

Ryser, M., “Ground anchors: the origin of EIT in Switzerland,” presentation, FHWA EIT GBP workshop, ETH-Zurich, May 22, 2019.

APPENDICES

Appendix A - Study Team Members

Reggie Holt, PE (Study Team Lead)
Structural Engineer, Federal Highway Administration
Reggie Holt is the concrete bridge specialist in the Federal Highway Administration's (FHWA) Office of Bridges and Structures in Washington, D.C. He is responsible for national policy and guidance on bridge design and analysis. Mr. Holt's interests include analysis, design and construction of concrete bridges, bridge/infrastructure security, and application of methods of probability and statistics to structural engineering. He is a registered professional engineer, a member of the American Association of Highway and Transportation Officials (AASHTO) T-10 Committee on Concrete Design, and a professional member of the American Segmental Bridge Institute, the PTI Post-tensioned Bridge Committee, the PTI Grouting Committee, the PTI Cable Stay Bridge Committee, and the PTI/ASBI Grouted Post-tensioning Committee. In addition, Mr. Holt has participated on multiple National Cooperative Highway Research Program (NCHRP) technical review panels.

Zachary D. Haber, PhD
Research Structural Engineer, Federal Highway Administration

Zach Haber is a research structural engineer on FHWA's Bridge Engineering Research Team at the Turner-Fairbank Highway Research Center (TFHRC) in McLean, Virginia. Dr. Haber's research areas include prefabricated bridge systems and applications of innovative materials in bridge engineering. He provides technical assistance and outreach to bridge owners, designers, and consultants interested in developing or deploying innovative bridge engineering solutions. Dr. Haber also supports the Bridge Engineering Research Group's involvement in high-profile FHWA initiatives such as *Every Day Counts* (EDC). In late 2018, Dr. Haber began leading a new research thrust area at TFHRC entitled *Innovative Methods in Bridge Preservation*. This research effort aims to identify, develop, and characterize innovative solutions to preserve and extend the service life of existing highway bridges. He is involved with numerous American Concrete Institute technical committees, serves as a reviewer for multiple peer-reviewed engineering journals, and serves as an adjunct professor at George Mason University in Fairfax, Virginia.

Graham Bettis, PE
Bridge Division Director, Texas Department of Transportation

Graham Bettis is the State Bridge Engineer at the Texas Department of Transportation and is responsible for the oversight of Bridge Project Development, Design, and Field Operations throughout the State. He has 20 years of experience in structural and transportation engineering, primarily focused on bridge preservation, forensics, and emergency response. He is a member of the AASHTO T-9 Committee on Bridge Preservation and is heavily involved in several national initiatives focused on bridge evaluation and preservation. Mr. Bettis also has extensive experience providing construction engineering services, including numerous post-tensioned elements. Prior to joining the Texas Department of Transportation in 2006, Mr. Bettis worked for seven years in consultant structural design and forensics for vertical construction.

Kevin Western, PE
State Bridge Engineer, Minnesota Department of Transportation

Kevin Western in the State Bridge Engineer for Minnesota Department of Transportation (MnDOT). During his 32 years with MnDOT, Mr. Western worked in the areas of bridge design, standards, and construction. He also served as the State Bridge Design Engineer and Design Manager for the St. Croix River Crossing project (MnDOT's first Extrados bridge) and was the Deputy Project Manager for Design on the 35W Bridge Replacement Project. Mr. Western serves as vice-chair of AASTHO's Bridge T-13 Culvert Committee and is Chair of the T-10 Concrete Committee.

Miroslav F. Vejvoda, MBA, PE
Managing Director, Engineering & Professional Development,
Post-Tensioning Institute (PTI)

Miroslav Vejvoda is the Managing Director of Engineering & Professional Development at the Post-Tensioning Institute (PTI). He is responsible for PTI's technical publications development and certification and educational programs. Mr. Vejvoda's experience working as a Specialty Contractor, Design Consultant, and Technical Director of PTI, have involved him in all aspects of engineering including design, construction, inspection and testing, including development of numerous national technical publications and specifications relating to post-tensioned concrete construction. He earned a BS in civil/structural engineering in 1980 in Bern, Switzerland and an MBA in 1997 in Sheffield UK. He is a registered PE in several States, Fellow of ACI and ASCE, and a member of several ACI committees.

Gregg Freeby, PE
Executive Director, American Segmental Bridge Institute (ASBI)

Gregg Freeby is the Executive Director of the American Segmental Bridge Institute (ASBI). In this role, Mr. Freeby oversees day-to-day operations for the institute as well support for the various ASBI committees. ASBI has nearly 80 member organizations and hosts an annual convention that draws on average over 350 professionals from across the country including international attendees. Mr. Freeby has over 30 years of bridge engineering experience having spent the past seven years as the State Bridge Engineer at the Texas Department of Transportation (TxDOT). While at TxDOT, Gregg was involved with the design and construction of several segmental and post-tensioned bridges.

Michael C. Brown, PhD, PE
Senior Supervising Engineer, U.S. Bridge Asset Management Lead, WSP USA, Inc.

In his role as U.S. Bridge Asset Management Leader with WSP, Dr. Brown conducts condition evaluation of bridges and transportation structures with broad knowledge of materials, testing and NDE techniques, preventive maintenance, repair and rehabilitation strategies, structural load testing and in-situ monitoring. Dr. Brown was previously the Associate Director of Research at the Virginia Department of Transportation (VDOT), where he managed and conducted research on corrosion performance, innovative design, preservation, rehabilitation and management of highway bridges and pavements. He is a Registered Professional Engineer in Virginia and has served on professional committees, including: ACI 90 Technical Activities Committee, 222 Corrosion of Metals in Concrete, ACI-SEI 343 Concrete Bridge Design (chair), and 345 Concrete Bridge Construction and Preservation (former chair); FHWA Bridge Preservation Expert Task Group; TRB AHD30 Structures Maintenance (former chair), AHD37 Bridge Preservation, and AHD45 Corrosion; as well as several NCHRP panels.

Appendix B - Amplifying Questions

Specific Areas of Interest

Rather than specific questions, the Study Team developed a desired list of topics for discussion. The following topic areas summarize the information that the U.S. study team expressed interest in exploring. Participants were not expected to provide written responses on the topics. Rather, these were provided to make participants aware of the topics, issues, and areas that the team wished to discuss during meetings and site visits.

Electrically Isolated Post-Tensioning Tendon Technology Implementation and Improvements:

- European EIT implementation
- Recent or planned improvements to EIT technology
    - Research, trials, or demonstrations
- Prevalence of EITs systems. When are EITs used and/or not used?
- Background on development of acceptance thresholds
    - Number of tests performed to establish thresholds
    - Rationale for establishing 28-day acceptance readings; were other time-frames considered?
    - Status on research and development of Capacitance and Loss Factor D acceptance thresholds

EIT System Approval:

- System approval process
    - System qualification requirements
    - Re-certification requirements

EIT Construction/Installation:

- Procurement Issues
    - Costs
        - Cost of the EIT vs. traditional systems? For a recent demonstration project in Houston, the cost for installing two EITs ranged from $2,000 per location to $50,000 per location. The successful contract bid $32,000 per location. Was magnitude and variability a product of being a new technology for the contractors or are the EIT systems really that expensive?
    - Availability
    - Concerns with proprietary products
- Lessons learned from both experienced and inexperienced installers

    - Modifications to address issues
- Installer training / certification
- Measures for failed EIT readings
    - Percentage allowed
    - Ramifications (e.g., reduced payment)
    - Owners expectations

EIT Long-Term Monitoring:

- Percentage of EITs used for long-term monitoring
- Inspection procedures and frequency
- Long-term performance experiences (success identifying issues)
- Junction Box details
- Integration into structural health monitoring systems
- Contractual issues between owner and contractor
- Testing (acceptance, inspection, long-term monitoring)
- Have European practitioners observed different levels of corrosion in EIT vs. traditional tendons (cementitious grout, flexible filler) that are side by side or in similar environments? Since the EITs are supposed to not only allow for long-term monitoring, but also help in preventing corrosion from occurring, have European practitioners seen that to be the case.
- What NDE methods do Europeans utilize to detect corrosion in traditional (non-EIT) grouted tendons?
- Prefabricated elements with ground contact (substructure elements); Have they had implementation of vertical or underground elements?
- Is there any sort of fatigue concern related to the EIT details/elements?

Appendix C - European Participants

The following individuals participated in meetings and/or site visits during the GBP tour.

Name	Title	Affiliation
Franco Iacobini	Technical Director – Infrastructure Standards	RFI
Marco Tisalvi	Bridges and Structures Manager (retired)	RFI
Andrea Vecchi	Bridges and Structures Manager	RFI
Luigi Evangelista	Area Manager	Italferr S.p.A.
Fabio Coppini	Structural & Geotechnical Sr. Engineer	Italferr S.p.A.
Bernhard Elsener	Professor	University of Cagliari/ETH Zurich
Tommaso Ciccone	Technical Director	Tensa
Riccardo Pontiggia	Business Development Director	Tensa
Eric Palos	Business Development Manager	Tensa
Jean-Jacques Reber	Senior Structural Engineer	SBB
Matthias Ryser	Consultant	Dr. Vollenweider AG
Ueli Angst	Professor	ETH-Zurich
Nicolas Ruffray	PhD Candidate	ETH-Zurich
Hans-Rudolf Ganz	Principal	Ganz Consulting
Dominik Meyer	Product Manager	Stahlton AG
Karl Lupold	(retired)	Stahlton AG
Adrian Gnägi	Director, PT Systems	VSL International
Max Meyer	Group Technical Officer	VSL International
Karsten Bohn		VSL International
Yuan Wu		VSL International
Benjamin Schneuwly		VSL International
Phillip Egger	R&D Engineer	VSL International

Meeting Hosts

Italian Railways and Italferr

Rete Ferroviaria Italiana (RFI S.p.A.) [Italian Railway Infrastructure Manager] and *Italferr* S.p.A. (The engineering company of Italian State Railways Group "*Ferrovie dello Stato Italiane*") together represent the infrastructure arm of *Ferrovie dello Stato Italiane* [Italian State Railways]. Whereas RFI is directly responsible for daily maintenance, safety, investments and upgrades of Italy's high speed and conventional railway infrastructure, Italferr is an engineering company offering worldwide global solutions for infrastructure projects that has built up a 30-year long experience at the forefront of cutting-edge Italian engineering, in Italy and internationally, with large-scale infrastructure projects.

RFI manages approximately 17,000 km of railway lines and about 18,500 structures with spans greater than 3m (1,612 viaducts, 7,984 bridges and 8,844 underpasses) totaling 570 km in length. There are also 1,671 tunnels totaling over 1,592 km in length.

Tensa

Tensacciai S.r.l. [Tensa] is a company based in Milan, IT that designs and produces stay cables, post-tensioning systems, anti-seismic devices, structural bearings and expansion joints. Their post-tensioning systems include EIT anchorages for ground-anchors and concrete structures.

ETH Zurich

ETH Zurich [Swiss Federal Institute of Technology in Zurich] is a university, focusing on science, technology, engineering and mathematics, located in the city of Zurich, Switzerland. Hosts at ETH-Zurich assembled a cadre of owners, researchers, producers and consultants with PT expertise to discuss the development and current practice of EIT technology.

VSL and Stahlton

VSL International and Stahlton AG are both companies that specialize in cable-stay and post-tensioning systems, headquartered in Bern and Hinwill, Switzerland, respectively.

Select Biographies of European Hosts

Franco Iacobini, Eng.
Infrastructures Standard Department – Technical Direction of RFI, S.p.A.

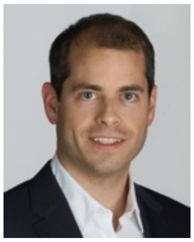
Franco Iacobini graduated with honors in Mechanical Engineering. After an experience in the Technical Department of the Financial Ministry, in 1993 continued his career in the Italian Railways Company as an inspector with competencies in Engineering & Constructions. Until 2003 he has worked for the Bridge Department, where he applied his expertise in bridge structures (especially steel), aerodynamics, and cross-wind effects.
From 2003 to 2016, he has been Civil and Geotechnical works Department Responsible. From 2016 to 2018, he has been Tunnels Responsible. Since 2016 he is Infrastructures Standard Responsible. He strengthened his experience thanks to the role assumed in National and International commissions which encompass: Responsible for Brownfield Projects in RFI Investments Direction (from 2007 to 2009); Member of the Commission for Technical Verification (CVT), set up by RFI, on civil works of the HS/HC line Roma-Napoli, Torino-Novara, Milano-Bologna, Bologna-Firenze and Novara-Milano (2005-2009); member of the Panel of Structural Experts (PoSE) within the UIC Rail System Forum, Track & Structures Sector (until 2014); Member of the Commission, set up by the Infrastructure & Transport Ministry, for the regulation of subservices interfering with railway infrastructure and the monitoring of technical regulations for constructions.

Luigi Evangelista, Eng.
Centre and South Italy Area Manager at Italferr, S.p.A.

Luigi Evangelista is very experienced in structural design and construction of rail infrastructure, with more than 25 years' experience on rail and road infrastructure design and construction, especially in bridges, buildings, stations, and tunnels. He has experience in structural design and construction of steel and reinforced and prestressed concrete bridges and structures, especially in seismic areas. Luigi has led several infrastructure designs at different levels (feasibility study, preliminary design, final design, and detailed design) for both conventional and high-speed/high-capacity railways all over Italy. Since 2003, he has performed designs, checks, and technical coordination of structural designs of railway infrastructure in foreign countries (Syria, Algeria, Venezuela, and Saudi Arabia). Before his current role as Area Manager, Luigi was Head of the Construction Department and Technical Director from Jan. 2015 to Apr. 2016, head of the "Infrastructural Engineering Department" from Dec. 2006 to Dec. 2014, and Head of the "Structural and Geotechnical Departments" from Jun. 2001 to Nov. 2006. He has played an important role in design and construction of the Italian High-Speed Railway Project. Luigi took part (in 1997, 2005, and 2009) in developing the new Italian code for design of railway bridges. In the same field, he was the Italian member of the international Committee E.R.R.I. (European Railway Research Institute) D216, which worked to update the U.I.C. leaflet for fatigue in reinforced concrete railway bridges. Since January 2011, he has been involved, as Italian member, on the "European Committée for Standardizations CEN TC 250." Luigi has been a speaker in the national and international congresses; author of several articles and publications since 1990; and has taught in the Master on Railway Engineering Infrastructure at University of Rome "La Sapienza" for Civil Engineering from 2008 to 2019.

Tommaso Ciccone, Eng.
TENSA (Tensacciai, S.r.l.)

As technical director of the company specializing in supply and installation of post-tensioning systems, stay cables, ground anchors, bearings, joints, and anti-seismic devices, Tommaso Ciccone has 18 years of experience in this field. He is a member of PTI/ASBI M 50 multistrand tendon committee, DC 45 Cable stayed bridge committee, CRT 70 PT system qualification testing and certification committee. He holds membership or officer positions in other organizations including fib commission C5, Group 5.5 – Cable supported structures, and Chairman of Task Group 5.3 – Manual for prestressing materials and systems. His educational background includes a degree in Civil Engineering, Structures from Politecnico of Milan and Executive Master of Business Administration from MIP Business School of Milan.



Ueli M. Angst, Prof. Dr.
ETH Zurich

Ueli Angst is a civil engineer by training who specialized in durability and corrosion of reinforced concrete and other infrastructures. He has a professorship at ETH Zurich. His research interests include inspection of structures (such as with drones and robots), sensors and monitoring, nondestructive testing, corrosion mechanisms, and corrosion mitigation strategies. Ueli's research group uses experimental and computational methods covering materials science, electrochemistry, porous media and reactive mass transport, and civil engineering. Ueli is a member of RILEM (the *international union of laboratories and experts in construction materials, systems and structures*) and ACI (American Concrete Institute). He chairs RILEM technical committee 262-SCI "characteristics of the steel/concrete interface and their effect on initiation of chloride-induced reinforcement corrosion" and is the president of the Swiss Society for Corrosion Protection (SGK).

Dominik Meyer, Dr.
Stahlton AG

Dominik Meyer is a civil engineer who specialized in materials science and post-tensioning (geotechnical). During his PhD he was working on concrete technology and fracture mechanics of lightweight concrete and fiber-reinforced concretes. In his role as product manager at Stahlton AG he is responsible for all geotechnical products including commercial and technical aspects. Beside this he is responsible for all general technical issues including assessments, innovation, and development. As actual president and representative of the Suisse Organization of Posttensioning Companies (VSV, ASEP) he is a member of the SIA 262 technical committee post tensioning as well as board member of fib Switzerland.

Hans Rudolf Ganz, Dr.
Ganz Consulting

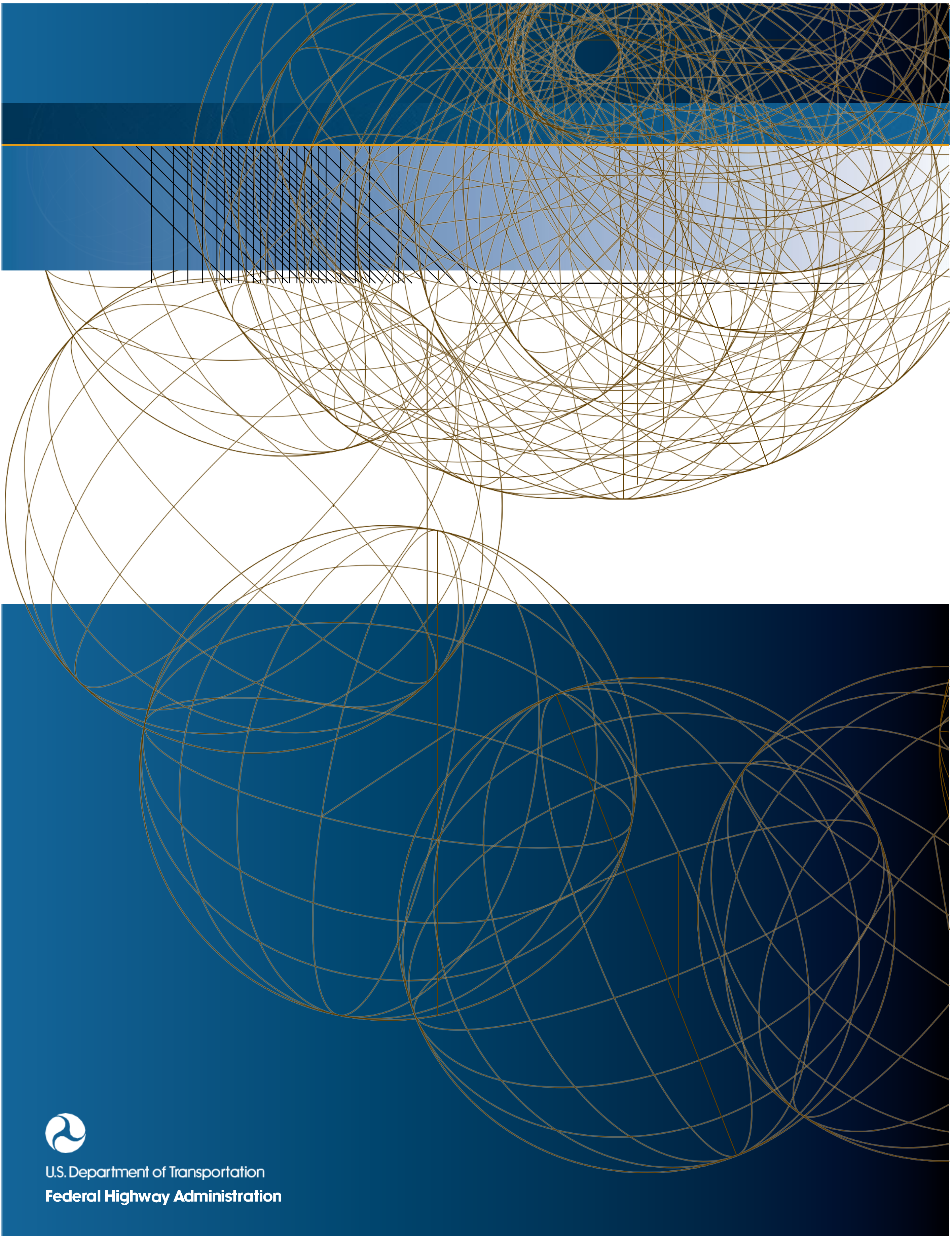
Hans Rudolf Ganz is a civil engineer who specialized in prestressed structures and prestressing technology, which is also the main activity of his consulting firm, formed in 2011. Previously, he has been employed by a specialist contractor with core activity in prestressing technology. After working in the design office, he has become technical director of the company and has held this position for more than 20 years. He has been chairman of the fib Commission on reinforcing and prestressing materials and systems for 10 years and served as president of fib in 2007-2008. Currently, he chairs the SIA committee for structural standards. In addition, he chairs the committee for concrete Eurocode, CEN/TC 250/SC 2. He has been a member of the working group which has drafted European standards for grouting.

Max Meyer, Dr. sc. h.c. ETH
VSL International

Max Meyer has been working in the Far East for more than 30 years. He was until 2015 responsible for VSL's Technical Centre in Singapore, a VSL internal engineering office with more than 50 staff. This Centre supports VSL companies technically through alternative designs, construction engineering and the design and detailing of specialist erection equipment during tender and execution stage of prestressed and stay suspended structures on projects all over the world. Since 2013 he has been VSL International's Group Technical Officer. In this position he is overall responsible for the Group's technical activities and the development of VSL's proprietary construction systems (Post Tensioning and Stay Technology, etc.). He has a master's degree in civil engineering from ETH-Zurich, was awarded an honorary doctorate from the same university in 2016, is a registered PE in Singapore, and is active in several professional committees (IABSE WG6 about Bridge Deck Erection Equipment, CEN/TC250/SC3/WG11-EN1993-1-11-Tension Components, fib TG5.5-acceptance of cable stays systems using prestressing steel).

Adrian Gnägi
VSL International

Adrian Gnägi has been working since 1990 for VSL. In the first years with VSL he was working as a development engineer for the VSL group. On some international sites he gathered practical experience with PT and stay systems. Since more than 25 years he is now responsible for PT systems of the VSL group. In this position, he is looking after the developments and approvals of the PT systems and is giving support to the VSL identities. He earned a BS in mechanical engineering in 1989 in Bern, Switzerland. He is active in several professional committee working groups (fib C5 TG 5.6 PT in low temperature storage tanks, fib C5 TG 5.4 for ground anchors, WG for the fib bulletin 75 for polymeric ducts). He is active in several professional committee working groups (fib C5 TG 5.6 PT in low temperature storage tanks, fib C5 TG 5.4 for ground anchors, WG for the fib bulletin 75 for polymeric ducts).



U.S. Department of Transportation

Federal Highway Administration