Post-Tensioning Technology Exchange

Outcomes Report

May 2023

RPT NO FHWA-PL-23-009

U.S. Department of Transportation
Federal Highway Administration

FOREWORD

The FHWA Offices of Bridges & Structures and Research & Development leveraged the services of other offices within FHWA (Office of International Programs and the Office of Innovation Management, Education, and Partnership) to collaborate with international bridge owners and experts on advancements in post-tensioning (PT). These collaborations have resulted in the identification of several technologies that will advance the state-of-practice in the United States in PT durability, monitorability, and construction quality.

Bridges all over the globe are facing similar issues. Even though practices may differ in various countries, they all have similar goals when addressing these issues. Exchanges with bridge experts and owners from other nations have revealed similar efforts from multiple countries to address pressing issues with PT bridges.

Through international exchanges, FHWA has identified four common goals that are globally shared: (1) Advance Infrastructure Intelligence, (2) Improve Infrastructure Resilience, (3) Improve Infrastructure Service Life and (4) Develop a Well-trained Workforce. This exchange highlighted eight PT advancements that will improve PT tendon resilience, intelligence, and corrosion resistance. It concluded with a round-table discussion from bridge owners across the globe. The United States, France, Belgium, Germany, Switzerland, and Italy were represented in this bridge owner group.

This PT Technology Exchange was the result of a collaboration between FHWA and the American Segmental Bridge Institute (ASBI) and multiple sponsorships from ASBI members.

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. They are included for informational purposes only and are not intended to reflect a preference, approval, or endorsement of any one product or entity.

Non-Binding Contents

The contents of this document do not have the force and effect of law and are not meant to bind the public in any way. This document is intended only to provide information to the public regarding existing requirements under the law or agency policies. However, compliance with applicable statutes or regulations cited in this document is required.

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-23-009	**2. Government Accession No.**	**3. Recipient’s Catalog No.**

4. Title and Subtitle Post-Tensioning (PT) Technology Exchange: Outcomes Report	**5. Report Date** February 2023
	6. Performing Organization Code:
7. Author(s) Lautzenhiser, Casey; Holt, Reggie	**8. Performing Organization Report No.**
9. Performing Organization Name and Address FHWA Office of Infrastructure 1200 New Jersey Avenue SE Washington, D.C. 20590 U.S. Department of Transportation, John A. Volpe National Transportation Systems Center 55 Broadway Cambridge, MA 02142	**10. Work Unit No.**
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address FHWA Office of International Programs 1200 New Jersey Avenue SE Washington, D.C. 20590	**13. Type of Report and Period**
	14. Sponsoring Agency Code FHWA-OIP
15. Supplementary Notes Cover image: FHWA	

16. Abstract

On Thursday November 3, 2022, 58 attendees representing post-tensioning bridge constructors, inspectors, subject matter experts and bridge owners gathered at the Hyatt Regency Conference Space in Austin, Texas to discuss the progress and current state of post-tensioning (PT) technology and associated materials. This report presents the outcomes of the workshop as a contribution to the ongoing effort to improve this technology and advise on its use in future bridge designs.

The purpose of this report is to summarize the information presented by experts in the field of PT technology in order to improve the process and quality of PT implementation in future construction and designs. Future readers may use this report both as an informative guide when implementing PT technology and to improve the service-life of current designs. Finally, the technologies discussed in this this report will serve to guide structural health and monitoring as well as non-destructive testing to advance the overall PT state of practice.

17. Key Words Post-tensioning, bridges, 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)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		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

Table of Contents

List of Abbreviations

Abbreviation	**Term**
AASHTO	American Association of Transportation Officials
ACI	American Concrete Institute
ASBI	American Segmental Bridge Institute
BOTDR	Brillouin Optical Time-Domain Reflectometry
CF	Consequence Factor
DI	Damage Index
DIC	Digital Image Correlation
EIT	Electrically Isolated Tendon
FEDRO	Swiss Federal Roads Office
FHWA	Federal Highway Administration
FIB	International Federation for Structural Concrete
FDOT	Florida Department of Transportation
GBP	Global Benchmarking Program
IABSE	International Association for Bridge and Structural Engineering
Italferr	Italian State Railways Group Engineering Firm
NCHRP	National Cooperative Highway Research Program
NDT	Nondestructive Testing
NDE	Nondestructive Examination
OF	Occurrence Factor
PC	Prestressed Concrete
PCI	Precast/Prestressed Concrete Institute
PE	Polyethylene
POF	Probability of Failure
PT	Post-Tensioning
PTI	Post-Tensioning Institute
PIARC	World Road Association
RAP	Risk Assessment Panel
RBI	Risk Based Inspection
SBB	Swiss Federal Railways
SPW	Service Public Wallonie
UF	University of Florida
VAG	Vacuum Assisted Grouting
VCsensor	Void/Corrosion Sensor

Table of Figures

Introduction

On Thursday November 3, 2022, 58 attendees representing post-tensioning bridge constructors, inspectors, subject matter experts and bridge owners gathered at the Hyatt Regency Conference Space in Austin, Texas to discuss the progress and current state of post-tensioning (PT) technology and associated materials. This report presents the outcomes of the workshop as a contribution to the ongoing effort to improve this technology and advise on its use in future bridge designs.

This exchange was the result of a collaboration between FHWA and the American Segmental Bridge Institute (ASBI). Many thanks to all participants for bringing energy and enthusiasm to the day, as well as to all ASBI member sponsors, without whom this event would not have been possible.

The purpose of this report is to summarize the information presented by experts in the field of PT technology in order to improve the process and quality of PT implementation in future construction and designs. Future readers may use this report both as an informative guide when implementing PT technology and to improve the service-life of current designs. Finally, the technologies discussed in this this report will serve to guide structural health and monitoring as well as non-destructive testing to advance the overall PT state of practice.

The 58 attendees represented 33 organizations across 7 countries and 3 continents. Many of the attendees are experts in their fields and have extensive knowledge in the areas of bridge design, inspection, management, and research, as well as in PT materials and installation. The conference attendees are members of many committees and professional organizations, including American Association of Transportation Officials (AASHTO), American Segmental Bridge Institute (ASBI), Post-tensioning Institute (PTI), Precast/Prestressed Concrete Institute (PCI), National Cooperative Highway Research Program (NCHRP), American Concrete Institute (ACI), World Road Association (PIARC), International Federation for Structural Concrete (fib) and several others. The attendees also represented 10 technical/industry executives, 31 technical committee chairs/conveners, 58 technical committee members, and multiple technical journal editors.

Background and Overview of Current State of the Practice

The state of practice for PT bridge design, construction and management across the globe is similar with subtle variabilities in their practices. The primary objective of this PT technology exchange was to examine these variabilities by assessing emerging technologies and practices that are not widely used and that demonstrate promise in advancing the state-of-practice.

One such promising technology is the electrically isolated tendon (EIT). The Federal Highway Administration (FHWA) identified this technology as one that could advance the ability to assess corrosion protection of the PT tendon pre-stressing steel. This technology is widely used in Europe yet is just beginning to be implemented in the United States. To learn more about the experience of

European countries with EIT, FHWA conducted a study through its Global Benchmarking Program (GBP), which 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. The study, which included multiple face-to-face meetings and field visits, found that both Italy and Switzerland use EITs to provide a high level of corrosion protection as well as provide the ability to monitor PT tendon condition throughout a structure's intended service life.[1]. During this study, additional technologies were discovered that enhance PT durability. Two of these technologies, void/corrosion sensor and vacuum assisted grouting, were presented at this exchange along with other promising PT technologies.

Bridges all over the globe are facing similar issues. Even though practices may differ in various countries, they all have similar goals when addressing these issues. Exchanges with bridge experts and owners from other nations have revealed similar efforts from multiple countries to address pressing issues with PT bridges. FHWA has identified four common goals that are globally shared: (1) Advance Infrastructure Intelligence, (2) Improve Infrastructure Resilience, (3) Improve Infrastructure Service Life and (4) Develop a Well-trained Workforce. This exchange highlighted eight notable and deployable PT advancements that will improve PT tendon resilience, intelligence, and corrosion resistance. The following practices and technologies that advance the state of practice for these common goals were presented at this exchange:

- For the goal of advancing infrastructure intelligence, three notable advancements from the United States, Switzerland, and Japan that were presented included the use of intelligence to assess PT tendon encapsulation, corrosion state and stress conditions.
- For the goal of improving infrastructure resilience, three notable advancements from the United States, France, Japan, and Germany that were presented included technologies that provide tendon replaceability.
- For the goal of improving infrastructure service life, two notable advancements from the United States and Italy that were presented included design and construction methods that improve PT tendon durability.

Key information and findings from this exchange were synthesized into this outcomes report. This report provides useful information to countries for consideration when developing their roadmaps to improve the state of practice for PT bridge design, construction, and management.

---

[1] Electrically Isolated Tendons in European Transportation Structures: https://international.fhwa.dot.gov/pubs/pl20013/fhwa_pl20013.pdf

Figure 1: Exchange Presenters and Panel Members (listed left to right – Tommaso Ciccone, Clay Naito, Jim Nelson, Jon Cornelius, Luigi Evangelista, Franco Iacobini, Reggie Holt, Will Potter, Adrien Houel, Adrian Gnagi, Pierre Giles, Glenn Washer, Gero Marzahn, Kevin Western, Walter Waldis, Gregg Freeby; missing from photo Christian Glaser). (Source: FHWA)

Event Agenda

The event was divided into segments according to the impact of the relevant technologies: 1. Improve Infrastructure Intelligence, 2. Improve Infrastructure Resilience, 3. Improve Infrastructure Service Life. The event culminated with a round table discussion with domestic (US) and international bridge owners.

Time	Session
8:00 – 8:30 AM	Welcome and Introduction • Welcome | Gregg Freeby (ASBI) • Self-Introduction | All • Meeting Agenda Review | Reggie Holt (FHWA)

Time	Session
8:30 – 10:00 AM	Improve Infrastructure Intelligence • Detailing PT Bridges to Accommodate NDE | Dr. Clay Naito (Lehigh University) • Void / Corrosion Sensor| Adrian Gnagi, (VSL International) • PT Strand with Fiber Optic Technology| Dr. Chris Williams (Purdue University)
10:00 – 10:30 AM	Break
10:30 AM – 12:00 PM	Improve Infrastructure Resilience • FDOT Implementation of Flexible Fillers | Will Potter (FDOT) • External PT with Epoxy Coated Strand| Jon Cornelius (Sumiden – Wire) • European External Unbonded PT Tendon Practices | Dr. Christian Glaser (DSI International)
12:00 – 1:00 PM	Lunch
1:00 – 2:15 PM	Improve Infrastructure Service Life • Risk Assessment of PT Tendons |Dr. Glenn Washer (University of Missouri) • Vacuum Assisted Grouting | Tommaso Ciccone (TENSA) & Luigi Evangelista (Italferr)
2:15 – 2:45 PM	Break
So	Owner Round Table: Q&A with US and International Owners | Gregg Freeby Moderator • State DOT Invitees o Kevin Western – Minnesota Department of Transportation o Will Potter – Florida Department of Transportation o James Nelson – Iowa Department of Transportation • International Owner Invitees o Walter Waldis – Swiss Federal Roads o Luigi Evangelista – Italian State Railway – Italferr o Franco Iacobini – Italian Railway – RFI o Pierre Giles – SPW Belgium Mobility and Infrastructure o Adrien Houel – French Ministry of Transportation o Prof. Dr.-Ing Gero Marzahn – German Ministry of Transport
4:15 – 4:30 PM	Exchange Close-out • Next Steps | Reggie Holt Moderator

Presentations

The following sections summarize the presentations on PT design, implementation, and testing that were provided by leading experts from around the world.

Improve Infrastructure Resilience

Detailing PT Bridges to Accommodate NDE | Dr. Clay Naito (Lehigh University)

Dr. Naito provided a description of the problem to be addressed: failure of pretensioned adjacent box beam bridges caused by strand corrosion. To investigate, Dr. Naito's team needed to create an accurate map of the beam damage, called the Damage Index (DI), which is determined at 1645 locations and has 5 stages of severity. They then used this DI to assess the accuracy of a variety of nondestructive testing (NDT) methods and found that these NDT methods were mostly lacking, apart from Magnetic Flux Leakage and Remnant Magnetism, which were determined to be semi-effective.

Dr. Naito's team worked to develop a method for inspecting the PT system both during and after construction. During construction, they checked for obstructions on the pretensioned beams and performed quality control on the grout. For the grout, they first built a mock-up of a single PT Strand to ensure flow and proper placement of the grout at scale (Fig. 2). Within the construction process, they checked the pressure of the duct prior to grouting, locking off grout ports and pressurizing to 20 psi for 1 minute, checking for pressure loss. Post grouting, they checked for soft grout at the ports and high points.

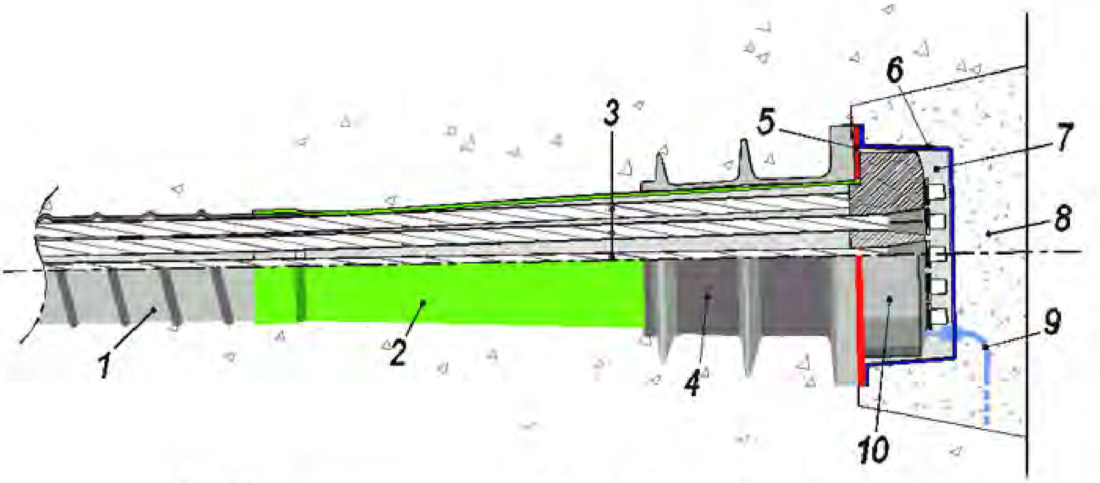
To enable inspection of the PT strands during service, Dr. Naito posited several possibilities, including the incorporation of inspection vaults within the bridge abutments, using laced tendons on larger bridge spans, incorporation of half-cell probes, and the use of EIT. Dr. Naito's team incorporated EIT into their designs and outlined the advantage of this technology and specifics of its use throughout the remainder of the presentation.

The EIT technology relies on the electrical isolation of the tendon ensuring that an electrical connection is not formed, thus removing a vital corrosion-causing component of the electrical half-cell. As the concrete hydrates, resistance of the tendon will continue to increase over time. Measurement of the resistance of tendons is provided by an LCR meter, where abrupt changes in resistance indicate a breach and the possibility of corrosion. Dr. Naito detailed a very careful system for electrical isolation of the tendon that includes the duct, plastic trumpet, wedges to block the strands, a cast iron bearing plate, a mechanically resistant isolation plate, plastic grouting caps, fully grounded resistant isolation plate, non-shrinkage reinforced concrete, an electrical terminal, and the anchor head (**Figure 3**).

The LCR monitor used was an 880 B&K and measurements were taken at 0.6 volts with a frequency of 1kHz and with the LCR meter set to parallel. The measurements were taken at the following times: 1) after tensioning and prior to grout, 2) after grouting, 3) 28 days after grouting, and 4) at long term intervals. Images of the components fabricated prior to construction and the general outline of the measurement system are provided in **Figure 4** and **Figure 5**.

For future construction, Dr. Naito noted that the contractor needs to allow for adequate closure pour openings to facilitate PT duct coupling, and that PT duct half-shells should not increase the duct out-to-out dimension. Additionally, detailing issues need to be resolved such as duct shields, web widths, and splicing. Finally, Dr. Naito acknowledged the need to further develop the EIT capacitance and loss factor criteria.

Figure 2: A mock-up built at the construction site of a single PT strand. (Source Dr. Clay Naito)



1. duct
2. plastic trumpet
3. wedges that block the strands
4. cast iron bearing plate
5. mechanically resistant isolation plate
6. plastic grouting caps
7. fully grouted resistant insulation plate
8. non-shrinkage reinforced concrete
9. electrical terminal
10. anchor head

Figure 3: Various components of the electrically isolated tendon. (Used with permission from the International Federation for Structural Concrete – fib)

Figure 4: The various ducts and ports necessary for the implementation of the electrically isolated tendons. (Source: Dr. Clay Naito)

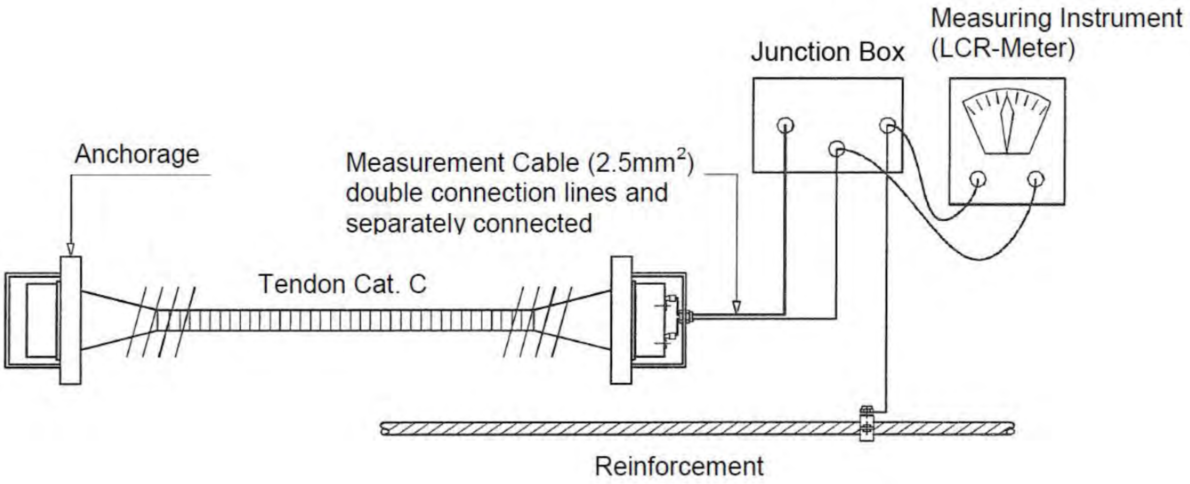


Figure 5: The general layout of the measurement system in relation to the EIT. (Source: ASTRA/SBB AG)

Void/Corrosion Sensor | Adrian Gnagi (VSL International)

Adrian Gnagi began by introducing the Void/Corrosion Sensor (VCsensor) – a cylindrical unit consisting of a center electrode and a ring electrode offset at a distance by an insulator, allowing for the measurement of potential between the two electrodes (**Figure 6**). Gnagi stated that by installing these VCsensors at selected locations along the tendon, they can be used to check for voids in the grouting and identify whether strands become passivated, as well as if the tendons are subjected to corrosion throughout the lifetime of the bridge.

The installation of the VCsensors allows for flexibility in location along tendons, and at each location two VCsensors are placed in-line (without the need to splice the duct), above and below the tendon, with the top sensor being the critical measurement point and the bottom sensor being the reference (**Figure 7**, **Figure 8**, **Figure 9**). Importantly, the sensors will not work if in direct contact with the strand. To define the effectiveness of the grouting operation or passivation on the tendons, directly after the grouting operation the user applies a current density and measures the potential between the center and ring electrodes until the grout hardens. Early sensor readings could allow for grout re-injection if voids are identified. Using the same steel grade for the center electrode and the PT strand is important because it serves as way to check for corrosion. In this case, both the potential and current flow between the electrodes is measured, with sudden significant variation in potential or current flow indicating corrosion on the strand.

These sensors have been tested both in published research and in the field. At the Exe Viaduct in the United Kingdom, 24 sensors were installed and allowed the contractor to forego a grout mockup due to the sensors enabling verification of the effectiveness of the grouting operation. The sensors have also been applied in the Cross Bay Link in Hong Kong where 2500 sensors have been installed at anchorages, and along the SH 146 in Houston where they are applied post-construction behind the anchor heads, avoiding the need for drilling into the anchorage, and can be removed to allow for visual inspection of the grout.

Currently, Gnagi's team is researching smaller diameter sensors and is continuing to update the measurement equipment and software.

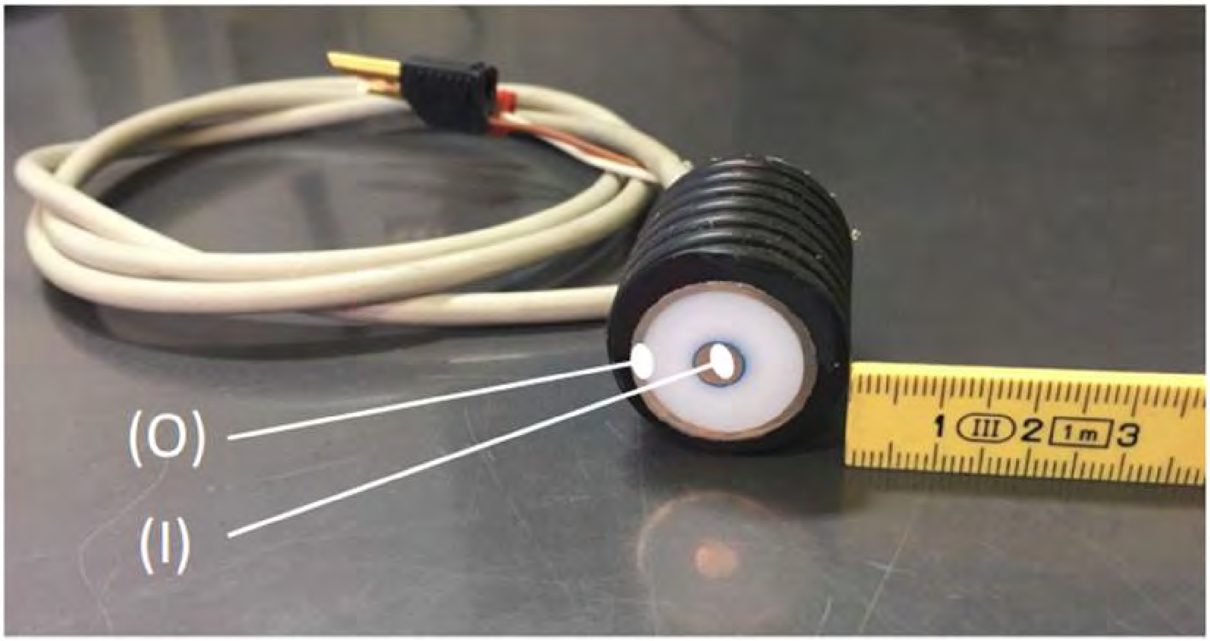


Figure 6: The VCsensor with the ring electrode (O) and center electrode (I) separated by the white insulator. (Source: VSL International)

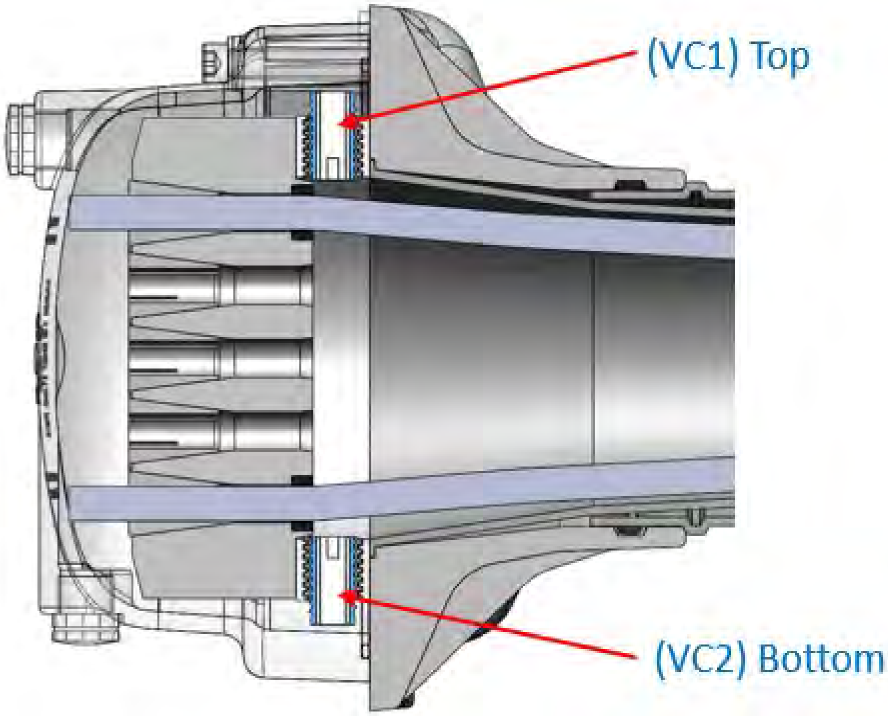


Figure 7: VCsensor implementation at the anchor of a tendon. (Source: VSL International)

Figure 8: Schematic of the VCsensor placement along the duct of a tendon. (Source: VSL International)

Figure 9: Field implementation of the VCsensors. (Source: VSL International)

PT Strand with Fiber Optic Technology | Dr. Chris Williams (Purdue University)

The primary goal of Dr. Williams' team is to use optical fibers to capture strain data along in-situ PT strands. This objective is accomplished by using a prestressing strand with two optical fiber cables embedded within the epoxy coating (**Figure 10**). The fibers extend along the full length of the strand. The optical fiber cables are extracted from the ends of each strand and are then fusion-spliced to optical fiber extension cables. The optical fiber sensor-embedded strand is available with two different surface finishes: grit-impregnated for bonded applications and smooth for unbonded applications.

The optical fiber extension cables are connected to a Brillouin Optical Time-Domain Reflectometry (BOTDR) module that is used to measure the strain within the fiber. The acquisition time for collecting strain data along the fibers connected to a single channel on the module can be several minutes and is dependent on the details of the prestressing system (e.g., total length) and settings within the BOTDR module. For this analysis, a pulsed light wave travels along the length of the fiber. For any section under tension, a shift in the frequency of the backscattered light indicates a change in strain within the fiber when temperature is constant. Dr. Williams provides illustrations of test setups that have been used during the ongoing experimental program, as shown in **Figure 11**. The 12-m long pigtail cables are used to avoid interference caused by unwanted reflection at the connectors. By connecting the optical fibers in series, the user can reduce overall measurement time (**Figure 11B**). The technology being used for the research provides a minimum spatial step for the measurements of 8 cm, meaning that strain measurement data points can be collected at a spacing of 8 cm.

To help validate the system, the research team conducted tensile testing on the optical fiber sensor-embedded PT strands and correlated the elastic modulus obtained through digital image correlation (DIC) data and the load data output from the universal testing machine with the value provided by the BOTDR analysis (**Figure *12***). Within the linear range, this testing resulted in a correction factor of approximately 0.95 that can be used to correlate the strain indicated by the BOTDR module and the longitudinal strain along the length of the strand (**Figure 13**). Week-long testing was also conducted for these optical fiber sensor-embedded PT strands, with these results also indicating a sufficient level of accuracy for the BOTDR data. Future consideration includes structural tests on girder specimens in the laboratory, developing analytical models for further assessment of the optical fiber strain data, and providing recommendations for its implementation in the field.

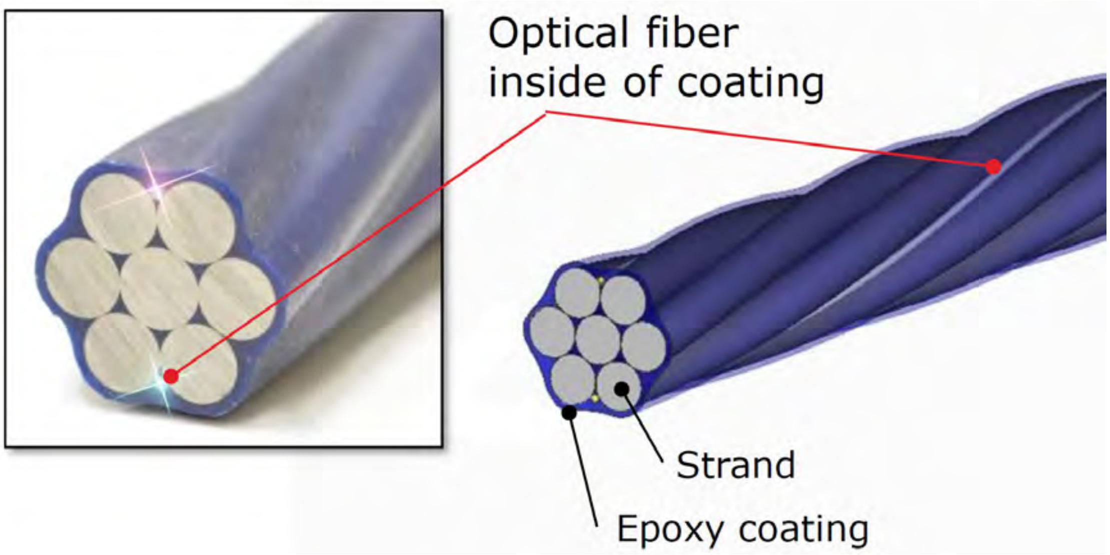


Figure 10: Locations of optical fiber cables embedded within the epoxy coating of the PT strands. (Source: Sumiden Wire Products)

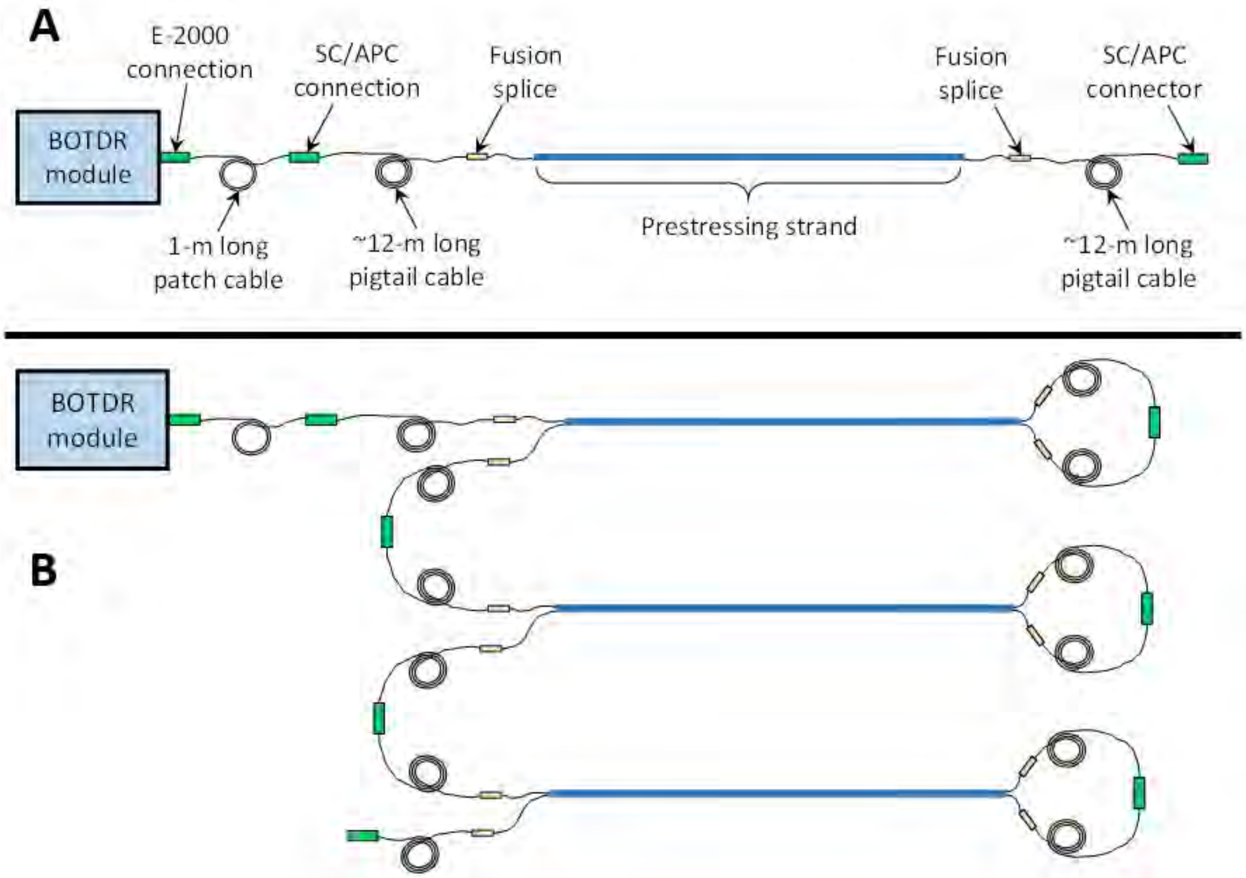


Figure 11: (A) Arrangement of the BOTDR module and all components of the optical fiber strain measurement system; (B) Example of the system connected in series. (Source: Purdue University)

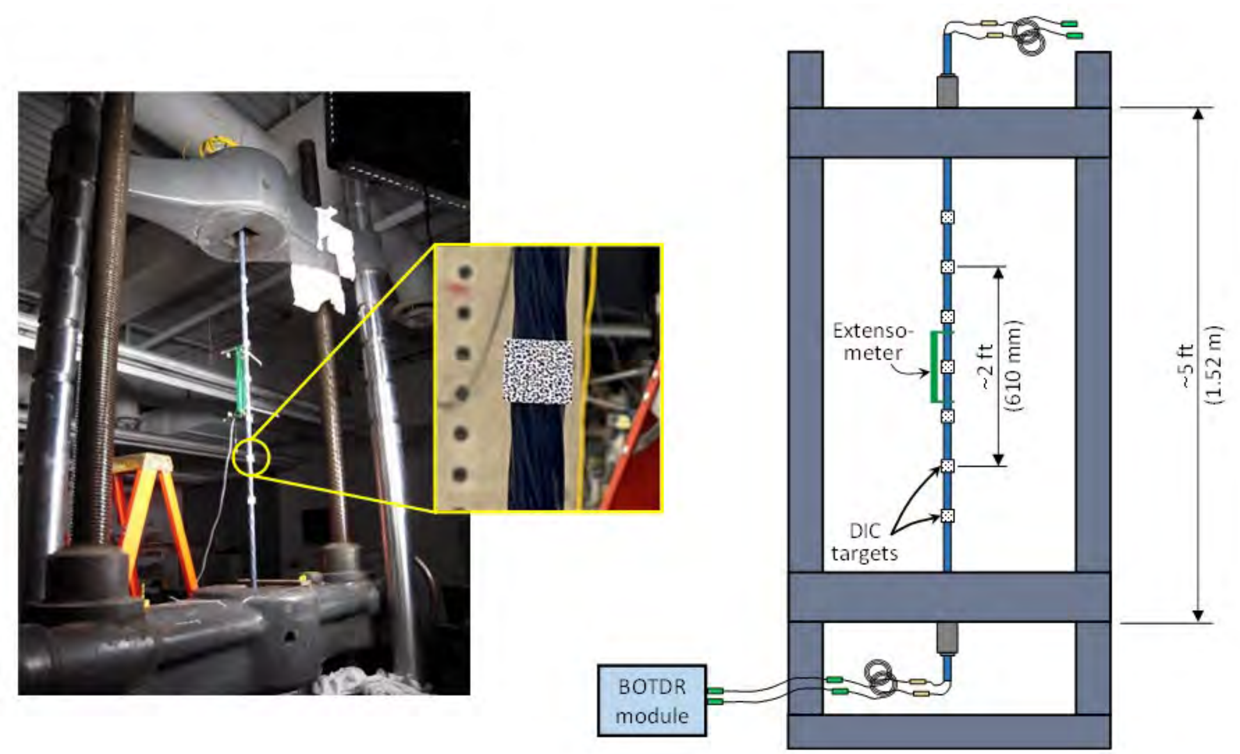


Figure 12: Test setup for tensile tests performed on the optical fiber sensor-embedded PT strand. (Source: Purdue University)

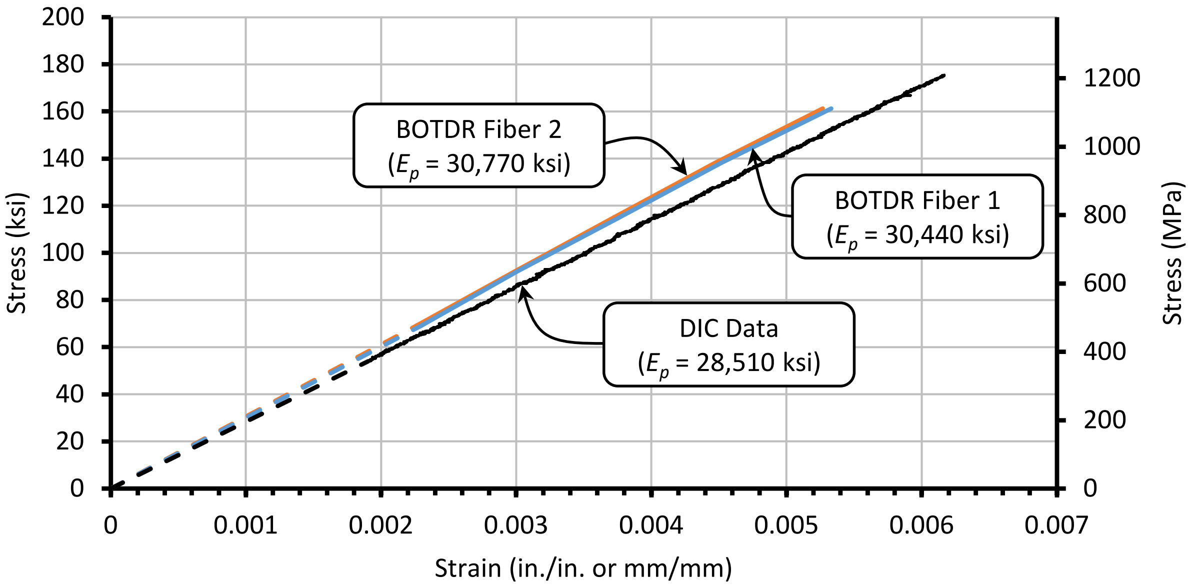


Figure 13: Tensile test results showing the difference between BOTDR and DIC results. (Source: Purdue University)

Improve Infrastructure Resilience

FDOT Implementation of Flexible Fillers | Will Potter (FDOT)

In an effort to mitigate the possibility of tendon corrosion, the Florida Department of Transportation (FDOT) explored multiple technologies, such as traditional grout, wax, and grease, before deciding on flexible wax-filled tendons. Initial research included a scan tour to France to observe the injection of the wax filler in PT strands used on a segmental bridge under construction. During the scan tour, FDOT obtained information about material properties, specifications, performance, cost, and construction challenges. In April of 2014, FDOT went on to implement the use of wax filling in lieu of grout filling in PT construction projects.

FDOT and the University of Florida (UF) developed an injection mock-up, which included a 200’ total profile, with two “external” sections of 70’, and a single “internal” section of 60’ (**Figure 14**). This mockup had light tension on the tendon within the duct, and wax was injected into the duct at a rate of 40’-70’/min. This system requires that heat-shrink wrap not be used at external duct connections due to softening of the material, and metal vents and outlets must replace all plastic components. The injection utilizes a vacuum-assisted process that requires the ability to achieve a 90% vacuum within the tendon, to ensure a quality sealed system (see **Figure 15** and **Figure 16** for additional flexible filler details).

FDOT enacted policy changes including a structures manual, construction specifications, material specifications including filler materials and PT components, and standard plans including tendon profiles, PT anchorage protection, and PT anchorage and filling details. An important detail for the filler requirements is that grout filler may still be used on segmental box girders in top slab transverse tendons and top slab cantilever longitudinal tendons, as well as slab type structures where tendons are draped 2’-0” or less. Straight strand or parallel wire tendons, other than continuity tendons in U-beams and girders, may be either bonded or unbonded. In addition, bar tendons that are predominately vertical or horizontal may be either bonded or unbonded. FDOT requires all other tendons to use flexible filler, and the contractor is required to perform a tendon mock-up before construction (**Figure 17**).

FDOT continues to develop the technology, including developing equations to modify the current AASHTO approximate method to incorporate increased stress in unbonded tendons, an updated resistance factor, and minimum bonded reinforcement provisions to prevent rupture of the bonded strand. Further, FDOT limits the duct diameter to a web width ratio of 0.4 and reduces the allowable principal tension in the web due to shear concerns.

Contractors have been learning to make minor adjustments to allow venting after the initial vacuum-assist, how to deal with both clogs and leak points, how to mitigate moisture in the ducts, and how to deal with the lead times on the wax material. Continued enhancements include minimizing human and environmental factors, extending the time between tendon install and injection, updating PT components, re-writing the PT specifications, ensuring a dry tendon prior to injection, and exploring alternate flexible materials.

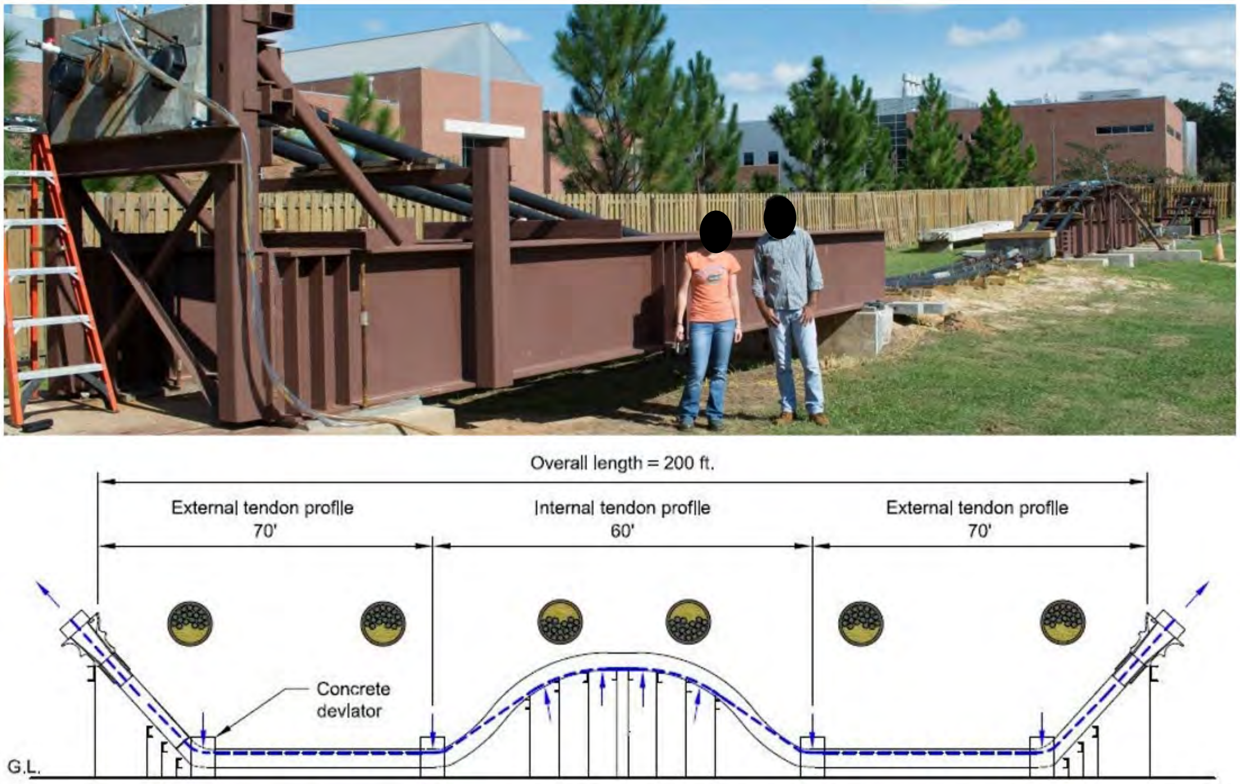


Figure 14: 200’ profile injection mock-up for testing of wax-filled tendons along with the outline of the design in the lower portion of the image. (Source: FDOT)

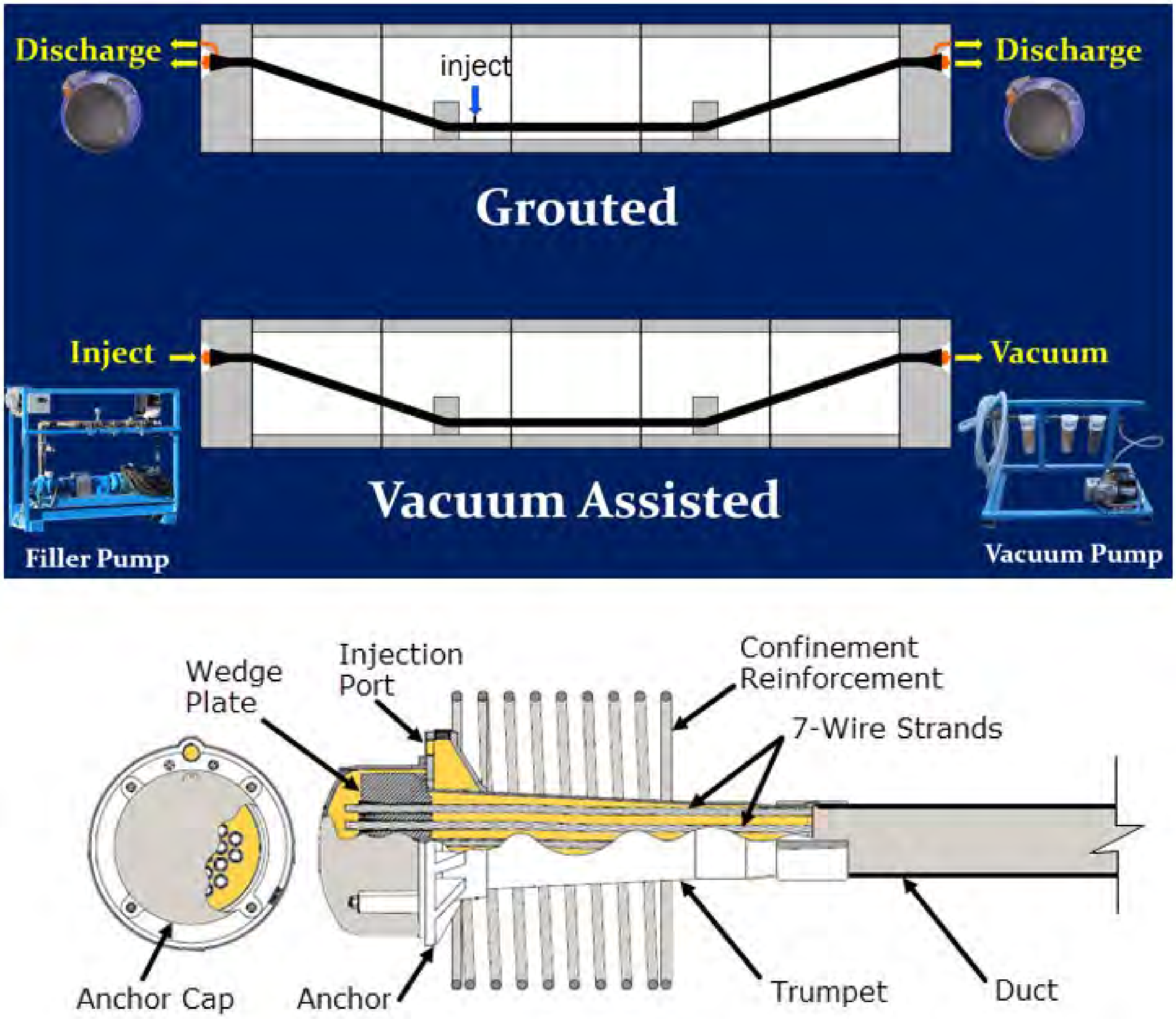


Figure 15: The design of the vacuum-assisted, flexible filler tendon in comparison to the original grouted tendon, with additional details of the anchor in the lower image. (Source: FDOT)

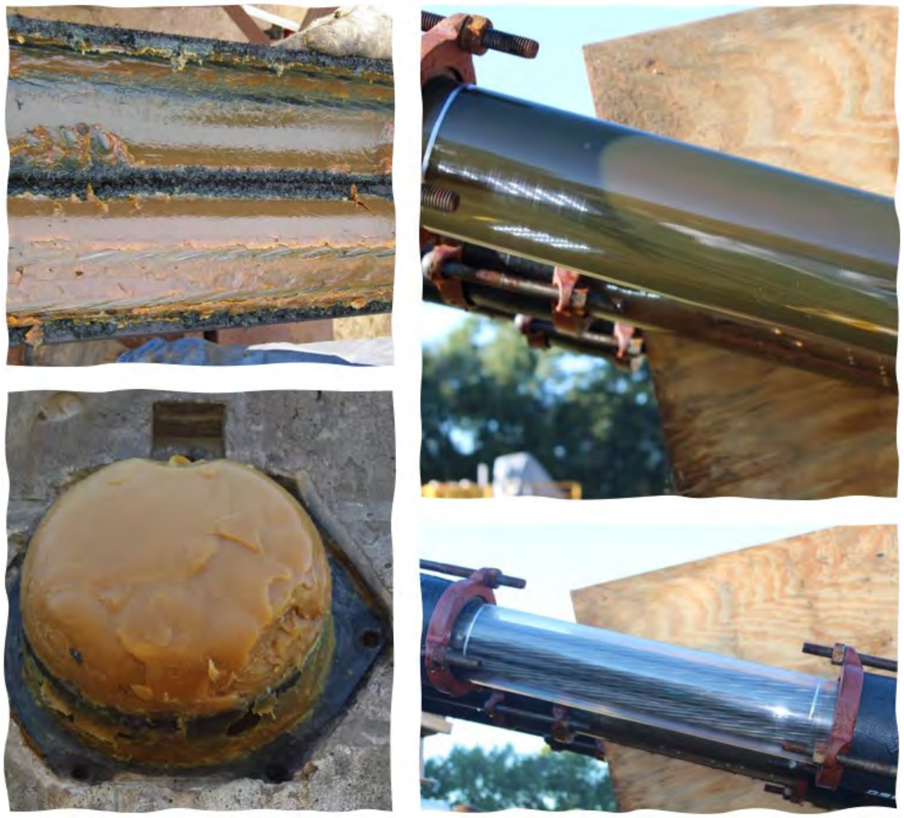


Figure 16: Images of the wax-filled tendons, including clear housing, cross-section, and an anchor point. (Source: FDOT)

Figure 17: Pre-construction tendon mock-up (Source: FDOT)

External PT with Epoxy Coated Strand| Jon Cornelius (Sumiden – Wire)

Jon Cornelius began his presentation by detailing epoxy-coated PC strands, dating the invention back to 1981. The modern version has each individual wire coated with epoxy, and all internal voids are also completely epoxy-filled. Cornelius cited the following standards for the epoxy-coated strands: ASTM A882/A882M (USA), ISO 14655 1999-12-15 (international), and JSCE-E 141-2010 (Japan). The current iteration of this technology passes 3,000-hour salt fog testing and has been tested up to 7,200 hours without any corrosion to the strands.

The epoxy coating is capable of elongating greater than 50%. Elongation performance is also confirmed by bending around a mandrel with a 32x strand diameter and tensile testing without any cracking or loss of adhesion. Epoxy-coated strands have also demonstrated excellent long-term ductility by passing the mandrel and tensile tests with no cracking or debonding even after more than 10 years of coiled storage. Salt fog testing for 3,000 hours showed no loss of tensile strength, no corrosion on the wires (except on intentionally exposed wire surfaces), and no corrosion migration or loss of adhesion even at a location with an exposed steel wire surface. Additionally, tensile fatigue performance demonstrates the epoxy-coated strand fatigue property is much better than bare strand due to the epoxy coating restricting individual wire movements. See **Figure 18** for a table detailing the various epoxy-coating types used in both the US and Japan.

Where possible, Japanese construction projects prefer external PT tendons over internal PT tendons due to the ease of inspection and maintenance. For these external PT tendons, epoxy-coated strands are used without ducts and grout to further simplify inspection and maintenance, reduce installation time, and maximize the replaceability of the strands. The first application using ductless, non-grouted external epoxy-coated PT strands was constructed in Japan in 1994, and this project continues to show no corrosion on the strands after more than 28 years. For Japanese construction projects, the epoxy-coated strand is shipped and handled using large wooden spools, a reel-less configuration, or on steel drums with separated pre-cut strand lengths (**Figure 19**). For these projects, the strands are pulled rather than pushed through the structure (**Figure 20**). The installed strands are then inspected using a portable holiday spark detector to confirm the full epoxy coating has remained intact throughout the installation process, and repairs are made using a touch-up two-part epoxy resin if an exposure is found. Japan has experienced a 47% reduction in tendon installation time and an 8% reduction in Japanese labor construction costs when using ductless, non-grouted epoxy-coated strand external tendons.

Cornelius provided several examples of construction projects throughout Asia, Spain, and the United States. No corrosion issues have occurred in any of these epoxy-coated strand projects.

Type		Main Application
Standard (US, Japan)	No grit	• External tendon • Stay cable
	With grit	• Internal tendon • Pre-tensioning • Ground anchor
Muli-layer (Japan)	PE sheathing	• External tendon • Stay cable
	PE + wax coated	• Stay cable

Figure 18: Illustration. This table details the various epoxy-coating types and applications for each, used in both the US and Japan. (Source: Sumiden Wire Products)

Figure 19: Illustration. Reel-less strands and Steel drums for transportation of the epoxy coated strands. (Source: Sumiden Wire Products)

Figure 20: Epoxy-coated strand being unwound and pulled through the ducts during construction. (Source: Sumiden Wire Products)

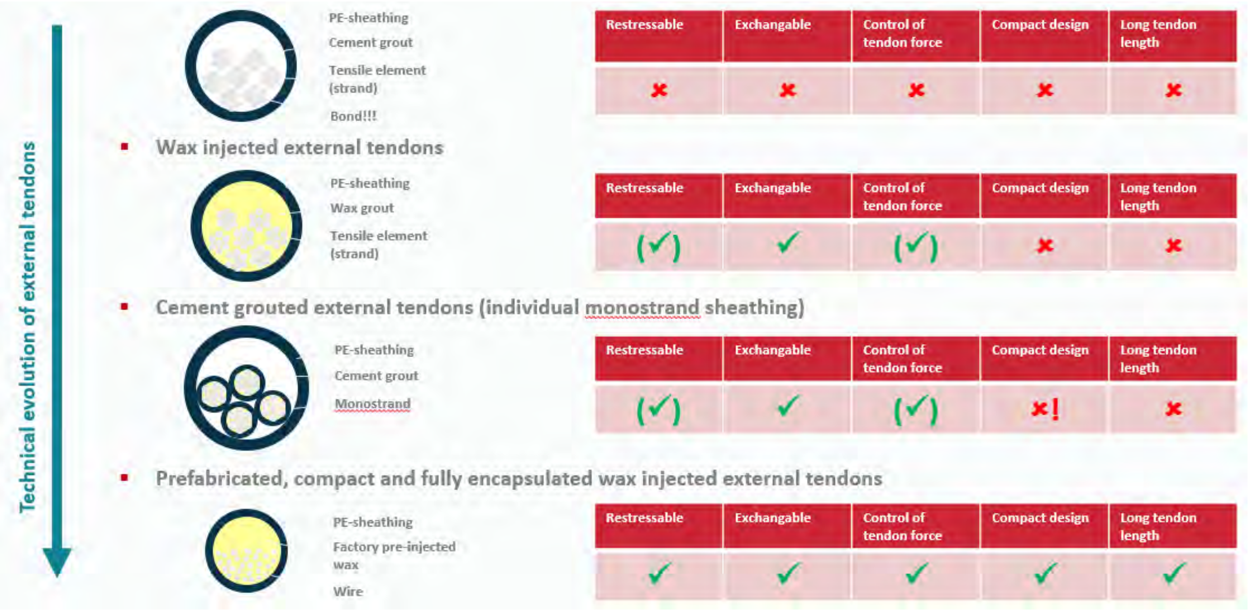
European External Unbonded PT Tendon Practices | Dr. Christian Glaeser (DYWIDAG)

Dr. Glaeser began with a general overview of the PT concepts and external tendon types with various corrosion protection methods. He also provided an evolution of external tendon systems and filling types with variable pros and cons (**Figure 21**). First generation (grouted) external tendons have been experiencing issues, including cracked PE ducts, grout voids, and tendon corrosion. When corrosion leads to failure in one tensile element, the tensile load is then transferred via bond to the remaining tensile elements, increasing risk of tendon failure. To mitigate the possibility of corrosion, countries have adopted varying policies, like prohibiting cement grout (France 2001, Florida 2016) or adopting epoxy coated strands (Japan). European policies have been revised to require replaceability for external tendons, with several countries requiring the ability to adjust tension of the tendons post-construction.

Dr. Glaeser then laid out the various types of external tendons that use flexible fillers and have various levels of prefabrication. Tendons assembled on-site are the most flexible and frequently used. They can use standardized and lighter equipment, the components are delivered separately to the construction site; but they have major drawbacks of being on the critical path of the bridge construction. In addition, corrosion protection is applied on site which can lead to unreliable performance and weather dependencies. Partial or semi-prefabricated tendons have a corrosion protection of the free length applied under constant conditions, adaptable tendon lengths, and final assembly and connection is to the anchorages on site. Their major drawbacks are that prefabricated corrosion protection is limited to the free length and coiling and transportation limit the size and length of the tendons. For fully prefabricated tendons, the tendon along with anchorages are prefabricated and connected with a PE duct. Fully prefabricated tendons have the most reliable corrosion protection which is applied under factory conditions, and they are shipped to the site prior to installation. Their major drawback is that length adjustability on site is limited so exact tendon length must be determined prior to fabrication.

For prefabricated tendons manufactured using specified diameter wires with high-grade steel, with wire anchors held by cold formed button heads, they have low relaxation, high resistance to fatigue, and are tested specifically for application in bridges and wind towers (**Figure 22**). These anchorages are built from variable wire amounts, have no tendon length limit, have flexible application of pre-stressing load due to threaded anchor, are re-stressable, and have a thick robust PE duct for external mechanical protection (**Figure 23**). The tendons are transported on steel transport drums for bridges or are reelless for application in wind towers. They are installed using pneumatic uncoiling devices. During installation within bridge girders, the winch may either be positioned inside or outside the girder and the tendons require only small access windows. At the deviation points, rotatable deviator half shelves are positioned within pipes embedded in the concrete to consider the actual geometry of the structure and avoid any kinks (**Figure 24**).

According to Dr. Glaeser, Germany has found the combination of internal bonded and external bonded PT to be the most economical solution. Using this method, primary post-tensioning is provided by internal bonded tendons, and secondary post-tensioning is provided by external unbonded tendons within the box girder.



Technical evolution of external tendons

PE-sheathing
Cement grout
Tensile element (strand)
Bond!!!

Restressable	Exchangable	Control of tendon force	Compact design	Long tendon length
✗	✗	✗	✗	✗

- Wax injected external tendons

PE-sheathing
Wax grout
Tensile element (strand)

Restressable	Exchangable	Control of tendon force	Compact design	Long tendon length
(✓)	✓	(✓)	✗	✗

- Cement grouted external tendons (individual monostrand sheathing)

PE-sheathing
Cement grout
Monostrand

Restressable	Exchangable	Control of tendon force	Compact design	Long tendon length
(✓)	✓	(✓)	✗!	✗

- Prefabricated, compact and fully encapsulated wax injected external tendons

PE-sheathing
Factory pre-injected wax
Wire

Restressable	Exchangable	Control of tendon force	Compact design	Long tendon length
✓	✓	✓	✓	✓

Figure 21: This table details the various external tendon and filling types along with the potential advantages and drawbacks of each (Source: DYWIDAG)

Figure 22: An example of a prefabricated tendon (Source: DYWIDAG)

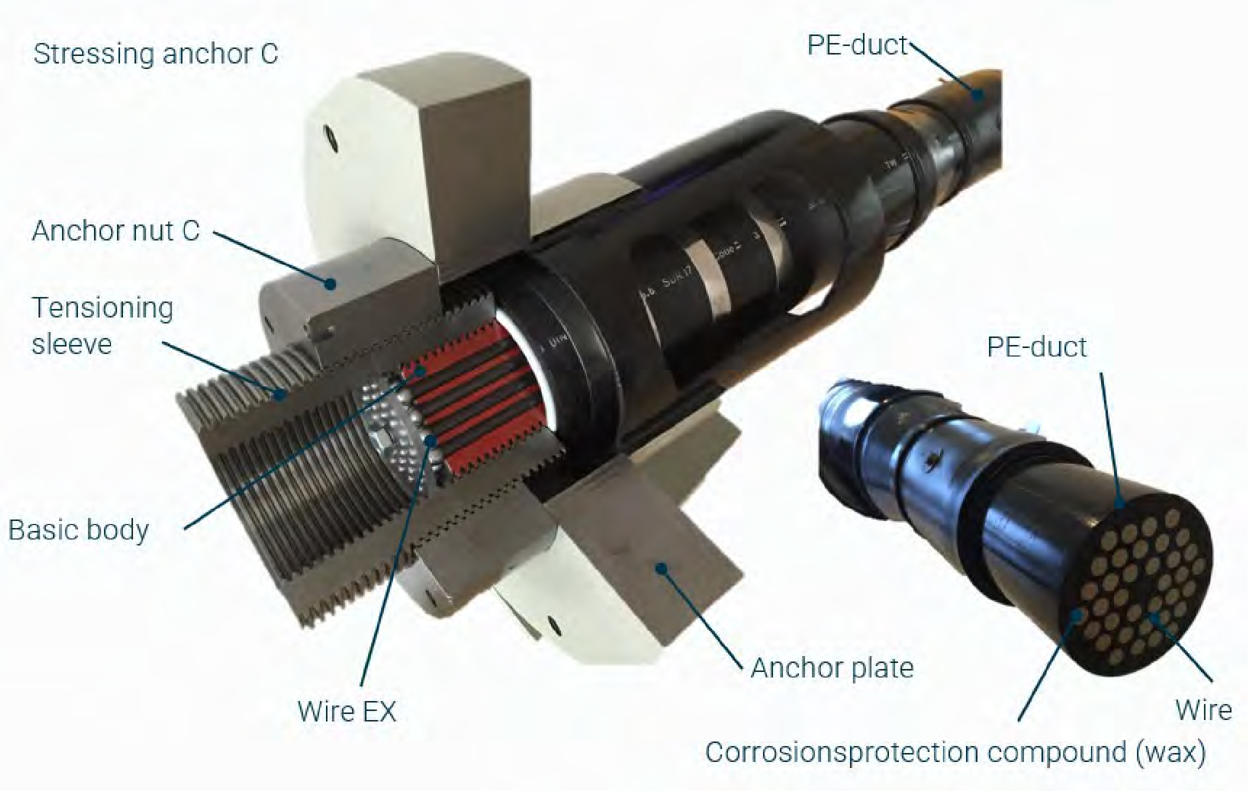


Figure 23: An image of the anchorage system used for fully prefabricated tendons. (Source: DYWIDAG)

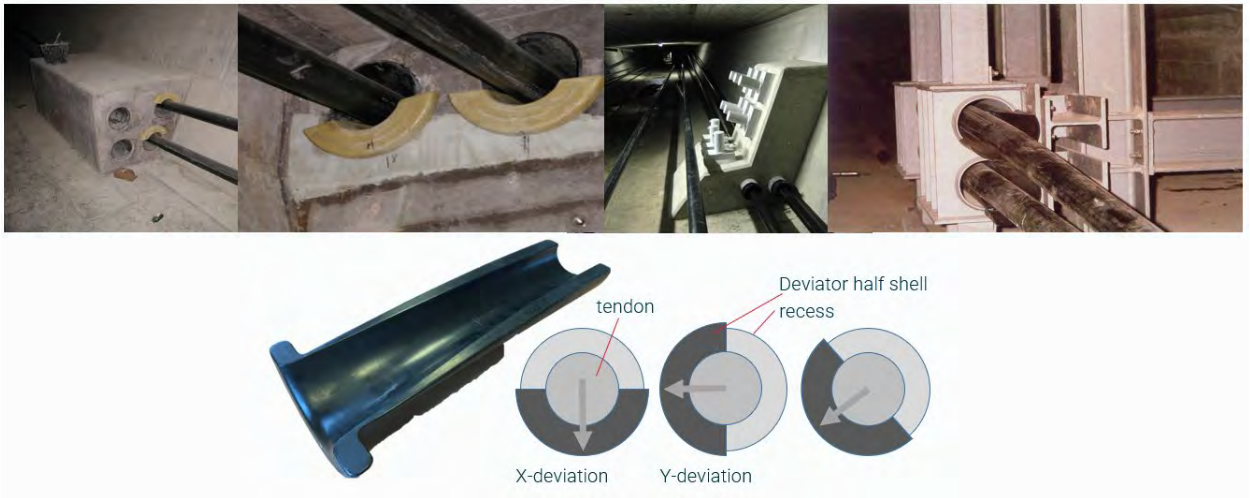


Figure 24: This image shows the usage of deviator shelves implemented within the bridge girders. (Source: DYWIDAG)

Improve Infrastructure Service Life

Risk Assessment of PT Tendons | Dr. Glenn Washer (University of Missouri)

Dr. Washer aims to apply the risk-based decision-making process to the goal of improving the durability of PT bridges. According to Dr. Washer, to evaluate risk on any project, engineers must answer three fundamental questions as part of the Risk-Based Inspection (RBI) process: 1) What can go wrong? 2) What are the chances of the event happening across X timeframe? 3) What are the consequences? Formulaically, this is $R = POF * C$, where R is the risk, POF is the probability of failure, and C is the consequence of the failure. Probability of failure may be defined in terms of likelihood, frequency, or occurrence (i.e., how likely is a certain event to occur). To determine the probability of failure, engineers use failure testing, deterioration models, expert knowledge, or point estimates. Consequences are typically described in terms of either 1) economic impacts, 2) environmental impacts, or 3) safety impacts, and these evaluations may rely on expert judgement. Risk may be visually represented using either a risk scale (1-100, with higher values indicating higher risk) or a risk matrix (**Figure 25**). For the risk scale, the risk factor can be expressed by the following: $Risk\ Factor = OF * CF * 100$, where OF (Occurrence Factor) is a measure of the likelihood of the event, and CF (Consequence Factor) is a measure of consequence.

Applying the process to the risk assessment of PT tendons, the strategy was to use the processes developed for the National Cooperative Highway Research Program (NCHRP) Report 782.[2]. This process requires first forming a risk assessment panel (RAP) of experts in the subject of the risk analysis. Relevant attributes and risk criteria are developed from an expert elicitation of the RAP. The process was applied to PT tendons for the purpose of providing guidance on risk reduction and mitigation strategies for bridge designers. Based on input provided by the RAP assembled for the project, Dr. Washer developed a risk model where 19 attributes were ranked and scored to provide an estimate of the likelihood of corrosion damage, and three attributes were ranked and scored to estimate the consequence of corrosion damage (**Figure 26** & **Figure 27**).

To calculate the likelihood of an event, individual attribute scores are summed to provide the relative estimate of the likelihood of corrosion damage: $OF = \frac{\sum S_i}{\sum S_0}$, where S_i is the score recorded for each attribute and S_0 is the maximum score for each attribute. The same process was used to provide a relative estimate of the consequence: $CF = \frac{\sum C_i}{\sum C_0}$, where C_i is the score recorded for each attribute and C_0 is the maximum score for each attribute. The scoring for this system is shown in the flow chart in **Figure 28**.

Dr. Washer goes on to describe the process for developing a sensitivity study to assess the scoring process. The results of this study were used to set risk thresholds with three different levels of consequence: low, moderate, and high. Using these processes, appropriate risk reduction and mitigation procedures may then be developed by bridge designers.

---

[2] https://www.trb.org/Publications/Blurbs/171448.aspx

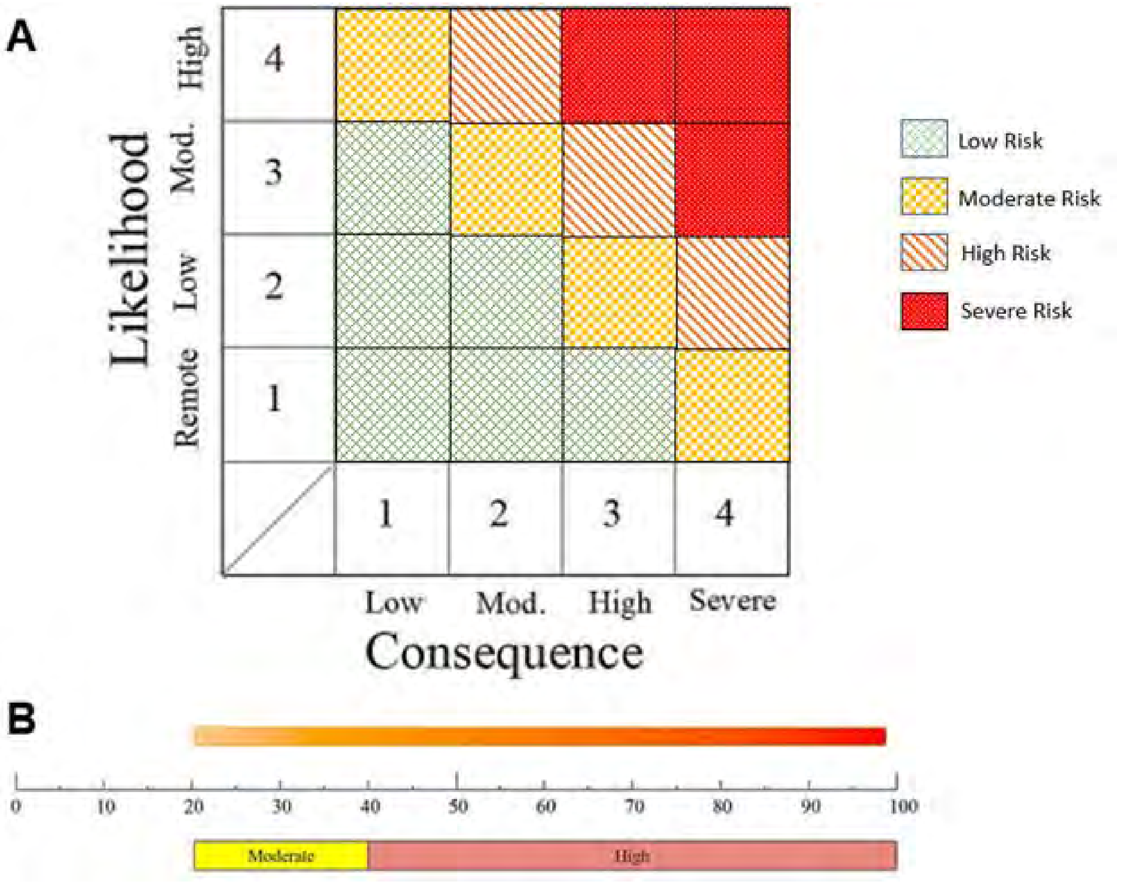


Figure 25: (A) shows an example of a risk matrix and (B) shows an example of a risk scale (Source: FHWA)

Attribute	No.	Attributes	Rank
PT Tendon and Profile	A1	Tendon Length	High
	A2	Tendon Vertical Profile	Very High
	A3	Tendon Curvature	High
	A4	Profile Conflict Avoidance	Moderate
PT Tendon Joint and Closure	A5	Cold Joints, Precast Segments	High
	A6	Cold Joint, Cast-in-Place (CIP) Segments	Moderate
	A7	Closure Pours	High
PT System Materials and Components	A8	Anchorage Protection, Interior	Moderate
	A9	Anchorage Protection, Exposed	High
	A10	Venting Protection	High
	A11	Grout Material Performance	High
	A12	Materials Specification	Moderate

	A13	Venting	High
	A14	Use of Diabolos	High
PT Installation Quality	A15	Construction Quality	High
	A16	Quality Assurance	Moderate
	A17	Grouting Procedures	High
Environmental	A18	Macro Environment	Very High
	A19	Micro or Local Environment	High

Figure 26: An outline of all attributes included in the risk assessment split into respective categories. (Source: FHWA)

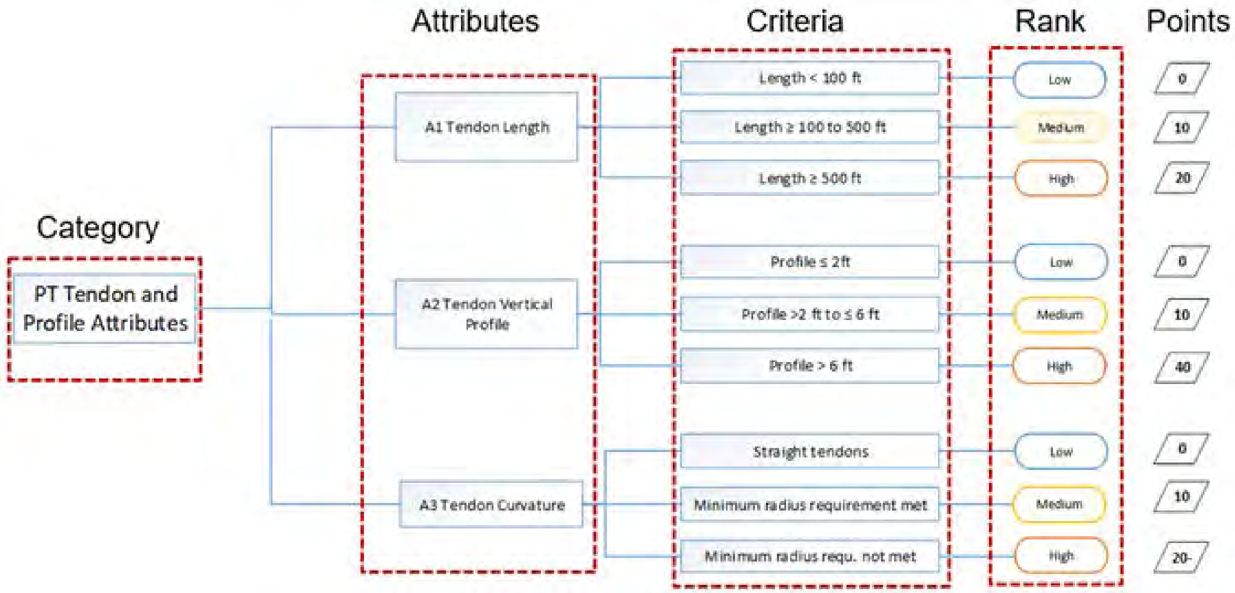


Figure 27: The flow chart for the risk assessment including the overall category, individual attributes, the specific risk criteria, a given risk rank, and the possible risk points for each. (Source: FHWA)

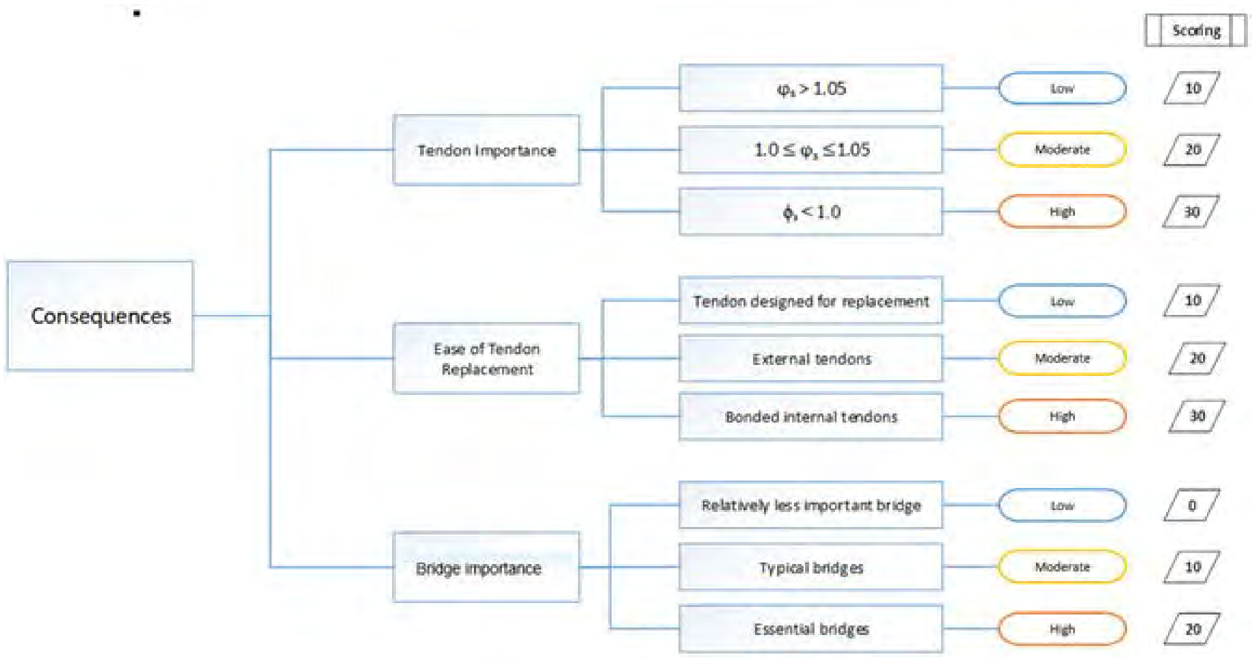


Figure 28: An example of a final scored flow chart for the risk assessment. (Source: FHWA)

Vacuum Assisted Grouting | Tommaso Ciccone (TENSA) & Luigi Evangelista (Italferr)

The team provided an overview of Vacuum Assisted Grouting (VAG), including key features, advantages, and disadvantages of the technology, and their experiences incorporating this technology in construction projects. The presentation began with an overview of the standards that detail VAG, including FIB20 — *Grouting of Post-Tensioning Tendons* (2002),[3] FIB33 — *Durability of Post-Tensioning Tendons* (2005), FWHA — *Post-Tensioning Tendon Installation and Grouting Manual* (2013),[4] and FDOT — *Standard Specifications for Road and Bridge Construction*.[5] According to current Italian standards (RFI Civil Works Design Handbook),[6] for pre-stressed structures, if post-tensioning systems with bars or strands are to be incorporated into the structure, the VAG process must be used. Further, VAG is required for all post-tensioning tendons in Italian rail bridges.

The VAG process provides control over the air void content of the grout filler but requires special equipment for the implementation (**Figure 29**). The process is accomplished through the following steps: 1) by extracting any air present inside the ducts and verifying that the ducts are air-tight, 2) by allowing measurement of the injected filler volume, and 3) by avoiding the scenario where air bubbles are entrapped into the filler when flow rate is higher than pump rate (**Figure 30**). The optimal application type for VAG is within horizontal tendons and continuity tendons (tendons having peaks and troughs throughout the profile). The VAG process is rendered nearly useless, and may even be detrimental, to the cases of vertical tendons or single slope tendons (tendons with a slope of at least 10-

---

[3] https://www.fib-international.org/publications/fib-bulletins/grouting-of-tendons-in-prestressed-concrete-118-detail.html
[4] https://www.fib-international.org/publications/fib-bulletins/durability-of-post-tensioning-tendons-detail.html
[5] https://www.fdot.gov/programmanagement/specs.shtm
[6] http://www.staticaesismica.it/normative/istruzioni_ferroviarie/OM2298_1997.pdf

15 degrees).

Vacuum Assisted Grouting can provide superior durability for the PT systems, but the process must be carefully implemented. The following are three fundamental requirements for this process: 1) the post-tensioning system must be air-tight, 2) the process requires the use of a dedicated set of equipment, and 3) there must be a detailed method and trained operators for the equipment. The presenters provided a brief overview of this VAG process shown in **Figure 30** and **Figure 31**.

Figure 29: Image of the equipment used for the VAG process. (Source: FIB Bulletin 33 – Fig. 2.22)

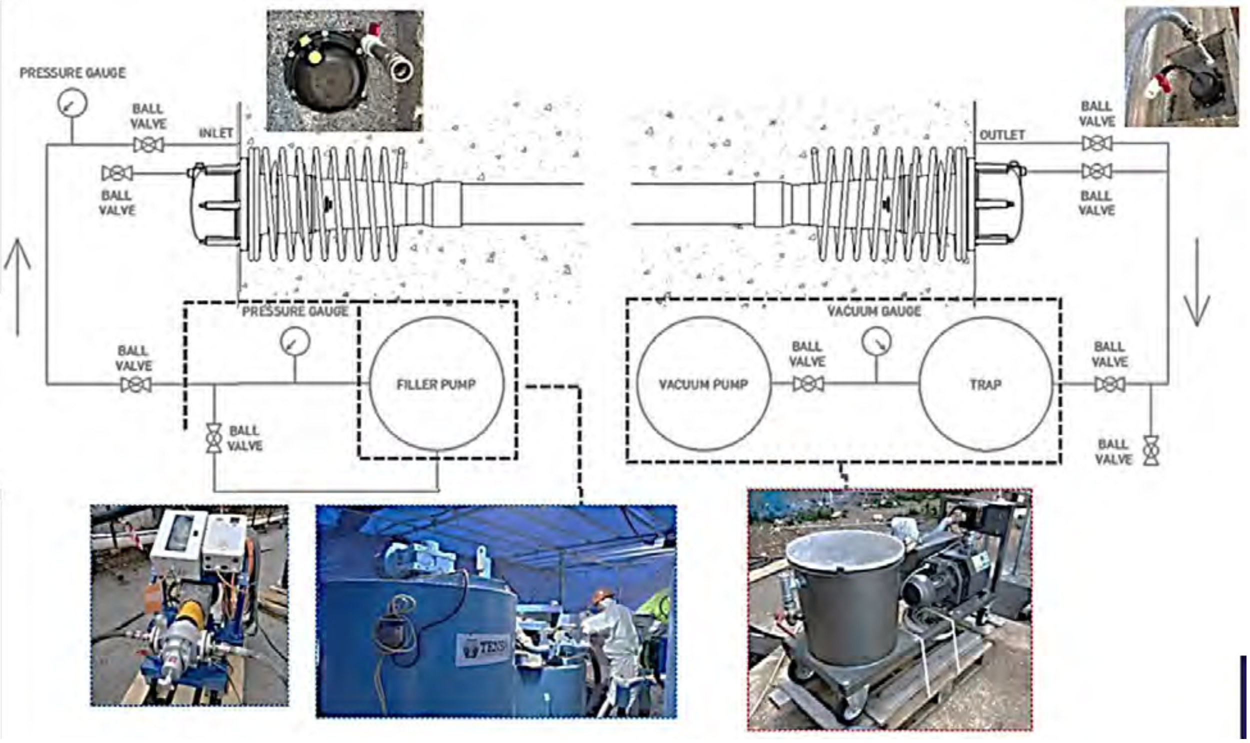


Figure 30: An overview of the VAG process and important components. (Source Ciccone and Evangelista)

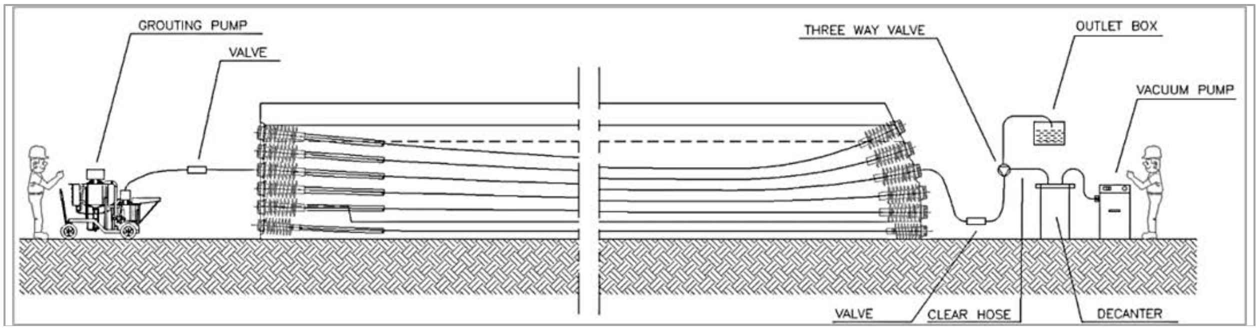


Figure 31: The general layout of all components during implementation of the VAG process. (Source Ciccone and Evangelista)

Summary of Owner Roundtable Findings

The event culminated with a roundtable discussion with domestic (US) and international (Germany, Italy, Switzerland, Belgium, and French) bridge owners. Invited bridge owners included:

- State DOT Invitees:
    - James Nelson - Iowa Department of Transportation
    - Kevin Western – Minnesota Department of Transportation
    - Will Potter – Florida Department of Transportation

- International Owner Invitees:
    - Walter Waldis - Swiss Federal Roads Office
    - Luigi Evangelista – Italferr - Italian State Railway
    - Franco Iacobini – RFI - Italian State Railway
    - Pierre Giles – SPW Belgium Mobility and Infrastructure
    - Adrien Houel – French Ministry of Transportation
    - Prof. Dr. Gero Marzahn – German Ministry of Digital and Transport

Roundtable Introduction

The roundtable discussions revealed that both the US and European agencies place a tremendous value on their program's user safety, durability, and serviceability. The agencies placed a major emphasis on ensuring that there is no service interruption due to bridge performance issues with a growing reliance on the use of innovative processes and technologies to evaluate their structures.

The roundtable discussion identified many practices and technologies related to developing a well-trained workforce, advancing infrastructure intelligence, and improving infrastructure service life and resilience. The items that generated the most discussion and provide the most promise are discussed in this section. The order in which they are presented does not reflect the priority of the finding.

Improve PT Bridge Design Processes

For improvements in the design process, both Germany and FDOT identified the need to advance the design practices for bridges with combined bonded and unbonded PT technologies. Germany uses the technique of the combined internal bonded PT with external unbonded strands and is investigating the use of internal unbonded PT for future implementation. These internal unbonded tendons will be fully assembled or prefabricated in a controlled manufactured environment.

FDOT uses minimum bonded PT to protect against strand rupture. Additionally, the possibility of future additional PT strands should be considered in designs. For example, Germany requires designs to allow for two future PT tendons to increase bending and shear capacity (draped tendons). Designs may also allow for the possibility of tightening PT strands post-construction to increase the capacity. There should be a systematic approach to the design for additional future capacity. Additionally, there needs to be design provisions for PT replacement, such as the stay replacement designs in cable stay bridges. External PT bridges have a unique advantage in this area. The topics specific to future, replaceable, and adjustable post-tensioning are discussed in the sections below.

Future and Adjustable Post-tensioning to Provide Structural Resilience

Most agencies require designs to include the ability to add future post-tensioning during the bridge's service life. This practice is used to address unexpected loss of prestress force and meet unexpected future structural demand. A few agencies provide additional future capacity by requiring their post-tensioning tendons to have adjustable prestress force. All the agencies agreed on the importance to have the ability to increase structural capacity either through adjusting or adding prestress force to address unanticipated future demands. However, most future PT requirements are prescriptive and do not follow a clear design logic in determining the needed future prestress force level and tendon profile. A systematic approach is needed to design for resiliency that meets the challenges of today and is open to the challenges of the future. A few of the uncertainties for future PT design that were discussed included the need to provide additional flexure, axial, or shear capacity and what type or level of anticipated future loading should be considered. All the agencies identified the difficulty in trying to predict future demand and loadings.

Replaceable Post-tensioning to Provide Structural Resilience

A few agencies require replaceable post-tensioning, with most of these agencies only using external PT for this purpose (**Figure 32**). Three possible methods for tendon replaceability were discussed: internal and external flexible filled (grease or wax) tendons, external double-enveloped grouted tendons, and external un-ducted epoxy coated strand tendons. All the agencies indicated that corrosion of the PT is their primary concern and that PT replaceability directly addresses this concern.

A consistent topic of importance was the ability to manage maintenance and rehabilitation needs for PT structures. Agencies strongly supported the need to consider maintenance and rehabilitation (PT replaceability) during the initial design. In addition, a combination of PT replaceability and intelligence was recommended to assist owners in appropriately addressing PT tendon maintenance and rehabilitation needs. Protocols should be included that tie together the intelligence data collected and needed interventions. The concept of inputting bridge condition data into a “digital twin” computer model to assist agencies in identifying maintenance needs was also discussed, and a pilot project implementing this method is currently underway in Germany.

Most agencies agreed that a combined bonded and un-bonded PT scheme would provide the most efficient design. However, design guidance is needed on proportioning the bonded to un-bonded PT to provide sufficient future capacity for unanticipated prestress loss. The risk assessment for PT tendon methodology presented during this exchange could assist in developing this guidance.

Country	De-tensionable	Replaceable	Adjustable(2)
France	X	X	X
Germany	X	X	X
Japan		X	
USA		X(1)	

(1) Florida and Virginia (2) Ability to re-stress the tendon

Figure 32: Use of replaceable post-tensioning to provide structural resilience (Source: FHWA)

Technology to Improve Post-tensioning Installation Quality

There are several items which can be implemented or advanced to improve construction processes and quality of the final product. For grouted ducts, to ensure precise measurement during placement and construction, it is recommended that teams make use of full-scale mock-ups of a single PT tendon prior to construction, vacuum testing of the duct prior to injection, vacuum assisted grouting complimented with a humidity sensor during the process, and in-line grout density meters. Automated grout plants for the production of the grout are also recommended. Additionally, installer training is a vital component of the process and needs to be improved. This includes knowledge of EIT and V/C Sensor installation, training for vacuum assisted grouting (which is a requirement in Italy), and training for the handling and splicing of fiber optic cable in the case of fiber optic implementation. Finally, it is recommended that certifications be provided based on the demonstration of proper installation of these PT technologies.

Three technologies that improve post-tensioning installation quality were discussed along with a summary of the benefit they provide:

- EIT – EITs provide data that identifies contact between prestressed strand and reinforcing steel prior to grouting and quantifies the level of tendon encapsulation after grouting.
- V/C sensor – V/C sensors provide data that identifies voids and incompetent grout immediately after the grouting operation and the onset of corrosion during service. There was interest in investigating the ability to re-inject grout if a poor reading was taken. V/C sensors can also be temporarily removed to facilitate a visual inspection of the grout at the PT anchorage.
- Vacuum Assisted Grouting – Vacuum assisted grouting greatly improves the ability to completely fill a PT tendon during grouting. Many agencies liked vacuum assisted grouting because it provides greater control of the PT grouting quality, with one agency mandating its use.

Many agencies supported increasing the use of technology during PT installation to improve construction quality. Additional promising technologies that were discussed included the in-line grout density meter and automated grout plant. A desire to research technologies that could assess if standing water was in the PT tendon duct prior to grouting was expressed. One thought was to investigate combining a moisture meter with vacuum assisted grouting.

Use of Intelligence to Improve In-service Assessment

For the advancement of the state-of-practice for maintenance of PT bridges, replaceable PT systems need monitoring to trigger either repair or replacement intervention steps. For this reason, easily implemented monitoring technologies building from the EIT systems, V/C sensors, and Fiber Optics systems discussed at the event should be advanced. Monitoring techniques should provide easily interpretable data which can be obtained and analyzed by a typical inspection crew. To obtain this information, designs will need to be amenable to data collection, such as incorporating inspection vaults (discussed by Dr. Naito) into bridge designs. Inspection protocols will need to be developed for these new monitoring technologies. Analysis techniques such as simulations and digital twins (as implemented by the German pilot project) should be considered as viable NDE techniques. Developing a guide on best practices for maintaining PT bridges is highly recommended.

Three promising technologies for in-service assessment were presented at this exchange. These technologies were EIT, V/C sensors, and PT strand with fiber optic technology for in-service force assessment. Below is a summary of the discussions for each of the three technologies presented:

- EIT– This technology provides data on how well a PT tendon is encapsulated (protected) against outside corrosive agents. Agencies liked the maturity of this technology and its ease of installation. Some agencies have been using EITs for over thirty years with one agency mandating EITs for all post-tensioning. Long-term monitoring and installation protocols are still needed for some agencies to assist in its implementation.

- V/C Sensor – This technology provides data on grout voids, grout competency and the onset of corrosion. This technology is young with most of its use occurring in southeast Asia, with one large bridge project using 2,500 sensors. These sensors provide data only at the sensor location and therefore need to be strategically located at locations typically known to experience grout issues such as at anchorages and tendon high points. Use of the V/C sensor can replace the need for post-grouting inspection using a borescope.

- Prestress strand with fiber optic technology – This technology provides a direct stress measurement for a PT tendon along its entire length. This technology works with both bonded and un-bonded tendons. Japan has implemented this technology in a few structures. Many of the agencies liked the accuracy obtained from this technology as well as the ability to assess individual PT tendons independently. Many agencies are using acoustic emissions to identify wire/strand breaks; however, this technology does not provide data on the remaining prestress level in the tendon.

Additional promising technologies discussed included use of a load cell at a PT anchorage to provide force data for unbonded tendons, and a PT duct defect locator using an electro-magnetic field for EITs. Combining NDE technologies to provide a comprehensive assessment was also discussed.

Improve PT Bridge Durability

The agencies overwhelmingly identified durability as the top issue needed to improve PT bridge performance. Poor construction quality and inadequate corrosion protection were identified as the two greatest threats to PT bridge durability. Multiple technologies were presented that address both of these threats and are summarized below:

Epoxy coated (EC) strand generated interest from many agencies. The robustness of the corrosion protection of this system was demonstrated through its passing the aggressive 3,000-hour salt fog test (ASTM B117) and excellent in-service performance of bridges in Japan that use this technology. The epoxy coating protective barrier provides superior protective redundancy compared to the traditional grouted duct protection system. As an example, a breach in the typical grout/duct system would expose all the tendon strands to corrosive agents, whereas a breach in the epoxy coated strand would only expose the wire closest to the breach and would limit migration to the other wires. This corrosion mitigation is due to each wire in the strand being completely encapsulated by the epoxy. In addition, EC strand has better fatigue resistance compared to bare wire strand due to the epoxy coating preventing independent wire movement within the strand.

Prefabricated PT tendons were discussed as a technology that replaces the on-site assembled PT tendon with a factory assembled PT tendon. This factory assembled tendon provides increased quality due to being assembled in a controlled environment. Currently, these prefabricated tendons can be manufactured in lengths up to approximately 170-feet. These systems can provide replaceable and adjustable PT tendons. Agencies recognized that this system could ease the PT installation burden and address the threat of poor construction quality to bridge durability.

Many agencies recognized the value of evaluating the corrosion risk of PT tendons during design to direct the design toward sound detailing decisions. A methodology for risk assessment of post-tensioning tendons was presented that provides guidance for such an evaluation. This methodology also recognizes the benefit of many of the technologies presented at this exchange in its assessment. Many of the agencies expressed an interest in expanding this guidance to include assessment of in-service PT bridge structures.

In France, a durable and watertight duct repair process has been developed to address watertightness defects during construction. This repair consists of welding an oversized HDPE duct around the area of the damaged duct and injecting this duct with wax.

All the agencies recognized the importance of maintaining a well-trained workforce for design, construction, and inspection. Training is needed for both traditional PT design and construction as well as for new technologies and processes. The level of PT installer training and certifications for each agency varied, with a few PT suppliers imposing their own additional training requirements. Most agencies agreed that they could improve their training and certification requirements.

Finally, there were two technologies presented that both improve durability and reduce the burden on the PT installer workforce. The first is un-ducted epoxy coated strand which eliminates the duct installation and filler operations. Japan has reported a 47 percent reduction in tendon installation time. The second is prefabricated PT tendons which move many on-site PT tendon assembly operations to the prefabrication of the PT tendon.

Next Steps

The participating agencies identified several PT bridge technologies and practices worthy of further advancement. The participating agencies recommend the following six technologies or practices be considered for further advancement:

1. **Develop a systematic design approach for the design and detailing of future post-tensioning**. A systematic approach to design future post-tensioning is needed to replace the current prescriptive design practices used by most agencies. Some uncertainties for future PT

design that need to be resolved in the guidance include the need to provide additional flexure, axial or shear capacity, and what type/level of anticipated future loading should be considered.

2. **Develop design guidance for bridge superstructures with combined bonded and un-bonded post-tensioning.** Most agencies agreed that a combined bonded and un-bonded PT scheme would provide the most efficient design. However, design guidance is needed on calculating capacity from this scheme along with guidance on proportioning the bonded to un-bonded PT to provide sufficient future capacity for unanticipated prestress loss or increased traffic loading. This guidance should incorporate findings from the on-going National Cooperative Highway Research Program (NCHRP) research project 112-18 which is investigating capacity provided from the bonded/un-bonded PT combination.
3. **Research of NDE technologies that can provide a comprehensive assessment of bonded and unbonded (replaceable) PT tendon.** An assessment of available NDE methods is needed to determine the maturity and effectiveness of available NDE methods and determine their ability to provide meaningful and accurate data. Combinations of promising technologies need to be investigated to determine the most comprehensive assessment. Protocols should be included that tie together the intelligence data collected and needed interventions.
4. **Research and advance technologies that improve PT installation and grouting quality.** Many advancements were identified in this exchange that improve construction quality. An assessment of the ability of innovative PT installation equipment, methods and NDE technologies to improve construction quality is greatly needed.
5. **Expand guidance on methodology for risk assessment of PT tendons to include in-service PT bridges.** The guidance would help owners to understand which details or locations to prioritize for visual inspections and potentially in-depth areas of evaluations. Potential rehabilitation options would also be discussed.
6. **Expand the use of un-ducted epoxy coated (flow-filled) external PT tendons.** Engage users in Japan to learn more about design, installation, and management practices with this technology. Investigate the need for additional research as well as the possibility of using this technology in a demonstration bridge.

Implementation

In summary, this exchange identified issues that need to be addressed to improve PT bridge performance as well as promising technologies and processes to address these issues. Even though practices may differ in various agencies and countries, they all have similar goals when addressing these issues. The findings and recommendations from this exchange will support ongoing activities for the bridge community. Many of the exchange attendees participate in mutual bridge organizations and committees (both domestic and international). Organizations that were highly represented at the exchange include: American Association of State Highway and Transportation Officials (AASHTO), National Concrete Bridge Council (NCBC), International Federation for Structural Concrete (fib), National Cooperative Highway Research Program (NCHRP), International Association for Bridge and

Structural Engineering (IABSE) and the American Concrete Institute (ACI). It is our hope that we can continue our dialog through these mutual organizations and work collaboratively in addressing the needs of the PT bridge community.

U.S. Department of Transportation

Federal Highway Administration