TechBrief

Steel and Concrete Bridge Technology to Improve Infrastructure Performance Program is a cooperative agreement between a university consortium consisting of Lehigh University (lead), the University of Delaware, Portland State University, University of Buffalo, Modjeski & Masters, and Corven Engineering. Its purpose is to advance the state-of-the-art technologies to improve the condition and durability of the nation's bridges and highway structures with a focus on implementable technologies that address high priority needs. The agreement is managed by the Federal Highway Administration Office of Bridges and Structures.

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Designing and Detailing Post-Tensioned Bridges to Accommodate Nondestructive Evaluation

This Technical Brief provides an overview of the work completed under Task 11 of the Cooperative Agreement entitled "Advancing Steel and Concrete Bridge Technology to Improve Infrastructure Performance Program". The objective of this task was to provide guidance for designing and detailing post-tensioned concrete bridges to better accommodate evaluation of the post-tensioning tendons by established or promising nondestructive evaluation (NDE) technologies.

Introduction

Post-tensioned concrete is an important material used for the construction of bridges in the United States. The material is composed of conventionally reinforced concrete with post-tensioning tendons used to induce forces in the concrete to resist applied loads. The components of a typical post-tensioning tendon include prestressing strands, ducts that enclose the strands, grout, and anchorages that transfer forces from the tendons to the concrete. The design details of these components sometimes preclude effective in-service inspection. Recent instances of post-tensioning tendon corrosion have indicated a need to have tendons that can be more readily inspected using nondestructive evaluation (NDE) technology.

The goal of Task 11 was to develop guidance for the design and detailing of post-tensioned bridge superstructures to facilitate NDE technology. The research team considered internal and external post-tensioning systems with cementitious grout as part of this task. Task 11 consisted of five subtasks:

- Subtask 11.1 – Identify promising and readily available
- NDE technologies
- Subtask 11.2 – Review commonly used post-tensioning (PT) systems, components, and details
- Subtask 11.3 – Review commonly used bridge superstructure systems, components, and details
- Subtask 11.4 – Provide design and detailing guidance with regard to favorable NDE technologies
- Subtask 11.5 – Evaluate modified grouts to increase contrast in radiographic images

Research Objectives

Subtask 11.1 – Identify Promising and Readily Available NDE Technologies

The research team conducted a survey of established or promising NDE technologies for post-tensioning tendons. The survey focused on NDE technologies for the assessment of corrosion and its impact on section loss in prestressing steel, the presence of grout voids, the condition of anchorage hardware, a determination of remaining prestressing force, and breeches in the corrosion protection system. The survey identified technologies that can be applied to existing PT systems and technologies that can be integrated into new construction. The research team conducted a literature review of relevant publications for the identified NDE technologies. The research team used the survey and literature review to refine the number of NDE technologies considered.

Subtask 11.2 – Review Commonly Used PT Systems, Components, and Details

Details of common, commercially available post-tensioning tendon systems were collected for review with regard to NDE technologies. The components of these post-tensioning systems reviewed included:

- Prestressing strands and bars
- Metal and plastic ducts
- Anchorages of varying type, size and configuration
- Grout caps placed over anchorages

The research team reviewed the various details for their ability to provide durability, and specifically, for their ability to accommodate NDE technology.

Subtask 11.3 – Review Commonly Used Bridge Superstructure Systems, Components, and Details

Details of commonly constructed post-tensioned bridge superstructures were collected for review with regard to NDE technologies. The superstructure types reviewed included the following:

- Cast-in-place bridges on falsework
- Spliced precast bulb-tee girders
- Spliced precast u-girders
- Precast balanced cantilever segmental box girders
- Precast span-by-span segmental box girders
- Cast-in-place balanced cantilever segmental box girders

Details within these superstructures that were reviewed included the following:

- Profiles of tendons internal to concrete webs and slabs
- External tendon profiles including end diaphragms and deviators
- Anchorage zones

Subtask 11.4 – Provide Design and Detailing Guidance with Regard to Favorable NDE Technologies

Based on the results of Tasks 11.1, 11.2, and 11.3, the research team developed guidance related to the design and detailing of post-tensioned bridges. The guidance developed is presented in the form of six videos available for viewing on the Federal Highway Administration's (FHWA) YouTube channel. This Technical Brief contains descriptions of these videos in a later section, Design and Detailing Guidance Videos.

NDE Technologies

The research team reviewed 11 NDE technologies with regard to evaluating post-tensioning tendons. Each of the NDE technologies reviewed addressed one or more of three primary concerns: locating grout voids, locating strands within the ducts, and evaluating corrosion of the strands. Table 1 lists the 11 NDE technologies reviewed and identifies which of the three primary concerns the technologies are able to address. The subsections that follow Table 1 provide brief overviews of the 11 NDE technologies.

Table 1. NDE Technologies and Applicable Capabilities

NDE Technology	Locate Grout Void	Locate Strand	Detect Corrosion Damage
Acoustic Emission			X
Electrically Isolated Tendons			X
Ground Penetrating Radar	X	X	
Half-Cell Potential			
Impact Echo	X	X	
Infrared Thermography			
Magnetic Flux Leakage			X[1]
Radiography	X	X	X
Time Domain Reflectometry	X		X
Ultrasonic Testing	X	X	X
Visual Inspection	X		X

1 Only for external, plastic ducts

Acoustic Emission Monitoring

Acoustic Emission (AE) monitoring records transient stress waves generated by the rapid release of energy produced by evolving damage in a material. The stress waves propagate through the material and can be detected by surface-mounted or embedded sensors and recorded by a suitable data acquisition system. The location of the evolving damage can be determined by using a network of spatially distributed sensors and applying triangulation techniques.

AE monitoring is limited because the technology is not able to detect damage that occurred prior to the installation of the AE monitoring system. Therefore, baseline conditions and regular monitoring are required because the procedure relies on the detection of evolving damage. With regard to post-tensioning applications, the complete monitoring of a post-tensioning tendon requires a high number of closely spaced sensors due to leakage and attenuation of the transient waves in concrete.

AE monitoring is currently best suited for continuous monitoring of localized areas near sensitive details in bonded post-tensioning tendons. AE monitoring can be used with reasonable success for detecting corrosion-induced failures of prestressing wires in un-bonded tendons and stay cables.

Electrically Isolated Tendons

Electrically isolated tendons (EIT) use a special set of design details to achieve electrical isolation of the tendon from the mild reinforcing steel. The isolation is intended to provide enhanced corrosion protection for post-tensioning tendons. An EIT system has the potential to identify the development of breaches in the corrosion protection system of the tendon throughout the service life of the structure. The EIT system is monitored for changes in the impedance of the grouted tendon, which is indicative of ingress of water into the grouted duct. An EIT system allows for quality control of the post-tensioning system during construction.

EITs differ from typical post-tensioned tendons because the EITs have full electrical isolation from the mild reinforcement in the member, whereas typical post-tensioned tendons are not isolated. This requires the use of electrically isolated anchor heads, plastic ducts, and special care at grout vents. Detailing of EITs is critical to the effective implementation of the system, particularly near the anchorages, to ensure complete encapsulation and electrical isolation. To achieve electrical isolation, a mechanically resistant insulation plate is placed between the steel anchor head and the cast iron bearing plate. This electrically isolates the tendon from the mild reinforcement network. In addition, a plastic trumpet is tightly connected to the plastic duct near the anchorage to isolate the strand from the cast-iron bearing anchorage. Electric terminals must be attached to the anchorage head and appropriately routed to a surface-mounted access box to allow for impedance measurements during the service life of the structure.

The use of electrically isolated tendons for monitoring purposes have been tested in laboratory experiments and have more recently been implemented in a number of post-tensioned bridges in Switzerland and Italy, where data measurements for quality control monitoring have been collected and published. Guidelines for implementing electrically isolated tendons into post-tensioned construction have been developed and published in a Swiss guideline “Measures to Ensure Durability of Post-Tensioning Tendons in Structures” by the Swiss Federal Roads Authority in 2007.

EIT methods are limited to new construction using established details, and cannot be used on existing systems with conventional non-isolated tendon/anchorage detailing. Although the EIT system can identify breaches in the corrosion protection system, the technology cannot currently identify the location of defects along the length of the tendon.

Ground Penetrating Radar

Ground penetrating radar (GPR) is based on the propagation of an impulse of high frequency electromagnetic waves through the material under investigation. When the impulse encounters an interface between materials with different dielectric properties, a portion of the wave is reflected. The velocity at which the wave propagates through the specimen and the amplitude of the reflected waves are a function of the dielectric properties of the material. Therefore, if the dielectric properties of the material are known, then the depth at which the reflection occurred can be determined using the propagation time of the wave.

The most common application for GPR in post-tensioned concrete structures is locating embedded metallic components such as reinforcing steel and metallic tendon ducts. When plastic ducts are used, the GPR technology can be used to locate the strands within a post-tensioning tendon duct and grout voids.

One of the main issues affecting the implementation of GPR is that metal interfaces produce 100 percent reflection of the wave. Consequently, dense placement of mild reinforcing steel can inhibit the accurate location of metallic ducts or prestressing strand within plastic ducts.

Half-Cell Potential

The half-cell potential technology is an established technology for evaluating the corrosion potential of mild steel reinforcement in concrete structures. This technology has been standardized as ASTM C876: “Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete.” When embedded reinforcing steel becomes depassivated because of the intrusion of moisture and chlorides, the electrochemical potential of the steel is reduced and the potential for corrosion is increased. The evaluation of steel corrosion potential is based on the measurement of the voltage differential between an external reference electrode (half-cell) and the embedded steel.

The half-cell potential technology can be applied to concrete structures to detect corrosion potential in mild steel reinforcing and pre-tensioned strands. Difficulties arise when applying the technology to structures with post-tensioning tendons. Metal ducts cause unwanted shielding of the strands, while plastic ducts can create electrical barriers. Embedded half-cell measuring devices are available that allow for local measurement of half-cell potential in a concrete member. These devices could be integrated into plastic post-tensioning ducts during construction at strategic locations along the length of the tendon to assess corrosion concerns.

Impact Echo

The Impact Echo (IE) technology uses mechanical stress waves to detect subsurface features and boundaries of a material under test. The stress waves are generated by mechanical impact of the structure (for example, a hammer strike). The stress waves produced include longitudinal, transverse, and guided surface wave modes (for example, Rayleigh waves). The waves propagate within the material and are reflected from boundary surfaces and interfaces between materials of different acoustic impedance (that is, modulus or density). The waves are detected by sensors (for example, a displacement transducer or accelerometer) placed on the surface of the material. The reflected waves interact within the material to produce resonant vibrational modes. The frequencies of the resonant vibrational modes are determined by analyzing the reflected waveforms. Subsurface features act as reflective boundaries that affect the frequency and mode of the resonant vibrations. Changes in the resonant frequencies are assessed to determine the depth of a defect, the thickness of a plate, or changes in wave velocity.

The IE technology can be used for the detection of subsurface defects (for example, cracking, delamination, and voids) in concrete, and to estimate the depth of the defect. Partially grouted or un-grouted regions of steel ducts ca be detected. In addition, the IE technology can be used to estimate the depth of embedded features such as utilities or to estimate material properties when specimen geometry is well defined.

Infrared Thermography

Infrared thermography (IRT) is used to produce an image of the thermal energy emitted from the surface of a material. The emitted energy is typically presented in the image as surface temperature. Anomalies in the surface temperature are assessed to identify subsurface defects such as voids or delamination, or surface defects such as cracks or spalls. The defects alter the local heat transfer properties of the material, producing an anomaly in the surface temperature at the location of the defect. The contrast in surface temperature between areas where there is a defect and intact areas of material facilitates the detection of the defects. Active or passive heating may be used to induce heat transfer to produce the anomalies in surface temperature. Active heating consists of applying heat to the surface of the material in the area to be imaged with IRT and capturing images during the heating or cooling of the surface. Passive heating typically consist of diurnal weather patterns that result in heating during the daytime and cooling at night.

IRT has been successfully used for the detection and measurement of surface and subsurface defects in reinforced concrete structures, including cracking and delamination. However, the depth and thickness of the subsurface defect is not easily determined without supporting experimental or numerical calibration data. Conventional IRT technologies are generally ineffective in identifying or quantifying grout and strand conditions for embedded post-tensioning steel ducts, primarily because of the cover depth and relatively small dimensions of the duct.

Magnetic Flux Leakage

Magnetic flux leakage (MFL) is an established magnetic technology that is typically used to detect section loss in steel. This technology can be used to detect the location of mild reinforcing bars and section loss resulting from corrosion. In post-tensioned systems, this technology can be applied to detect wire and strand fracture and section loss due to corrosion. The technology can also be applied to wires or strands in stays, cables, and wire ropes.

MFL is based on the principle that magnetic flux will leak from sudden geometric changes in a ferromagnetic material, changing the ambient magnetic field surrounding the material. When a magnetic field is placed near a ferromagnetic material such as steel, magnetic flux lines are developed in the steel because of its high permeability. The magnetic flux induced in the steel affects the ambient field surrounding the steel, based on the volume of material and its permeability. When discontinuities or defects are present, typically caused by corrosion or fracture of the strand or rebar, the path of the induced flux lines is interrupted, resulting in leakage from the steel into the surrounding area. When the volume of material influenced by the magnetic field changes, the ambient field is affected. The changes in ambient magnetic field produced can be detected by sensors and analyzed to determine the location of section loss and fractures.

MFL can be used to determine strand corrosion and wire breaks in post-tensioned tendons in some applications. The technology has the potential to be used with both steel and plastic duct systems. However, it has only been demonstrated to work well for external tendons in plastic ducts. The appropriate application of this technology given the current technology, is identifying significant corrosion or wire breaks in external tendons enclosed in plastic ducts.

Radiography

Radiography uses photons emitted from a radiation source (either an X-ray generator or a radio isotope gamma-ray source) to penetrate the test material and cause exposure of a photo-stimulable detector or film positioned near the opposite surface. The photons passing through the test material are attenuated and scattered because of interactions with the atomic structure of the material. Consequently, spatial variations in material composition results in spatial variations in the photon intensity captured by the detector or film. Generally, variations in density are recorded as contrast variations on the film or image produced from the photo-stimulable detector. In modern digital radiographic testing, the detector readings are digitized and converted to pixel intensity values through which spatial variations can be visualized on a computer monitor as color or grayscale contrast. The spatial variation in pixel intensity is used to identify and measure defects or structural damage, and to visualize embedded features for repair or retrofit operations.

Radiography has been used to detect grout voids, strand corrosion, and strand fracture in the tendons of post-tensioned concrete bridges. In addition, this technology has been used for the verification of re-grouting operations, the location and sizing of steel reinforcing bars and embedded utilities, and the visualization of unknown construction details. Radiography accommodates a wide range of construction materials (including plastic and metal ducts), embedded features with complex geometries, and both internal and external post-tensioning configurations. Access to the front and back surfaces of the region to be imaged is required for successful NDE.

Portable, high intensity MeV X-ray generators are available that provide sufficient energy to image concrete sections up to 150 centimeters (5 feet) in thickness. Unlike gamma ray-producing isotope sources, which are decaying isotopes and therefore produce radiation constantly, X-ray machines only emit radiation during testing, thereby providing better control over work site safety. In addition, the developments of digital detectors and advanced image reconstruction algorithms have improved imaging capabilities and have enhanced data preservation and manipulation. These technological advances improve the efficiency, portability, and safety of field deployable radiographic testing equipment. The advances have improved the quality of radiographic images, making radiography a viable technology for field applications. For this reason, radiography was explored further in Subtask 11.5.

Time Domain Reflectometry

Time Domain Reflectometry (TDR) involves sending high frequency electrical pulses through a sensing cable. Physical anomalies in the cable or the material surrounding the cable can produce impedance variations that result in partial reflection of the pulse. These partial pulse reflections are observed using standard TDR cable test equipment. In the case of post-tensioning systems, the presence of physical defects in the steel tendon (for example, corrosion damage) or the grout surrounding the tendon can produce impedance variations when the steel tendon is used as the sensing cable.

TDR technologies have been used in laboratory experiments to identify grout voids within the duct and to identify strand corrosion along grouted post-tensioning tendons. TDR can be used for quality control during construction to help detect the presence of grout voids. The technology can be used for long-term monitoring of grout and strand condition within the tendon ducts, allowing for early detection of defects. Unfortunately, there is currently no commercially available TDR system for use in post-tensioned inspection.

Ultrasonic Wave Testing

Ultrasonic Wave (UW) testing of post-tensioned concrete structures involves the propagation of ultrasonic waves in the post-tensioning strand. The ultrasonic waves are introduced into the strand at the exposed ends of the steel tendons at the anchorage. The ultrasonic waves can be generated by a conventional piezoelectric transducer coupled to the end of the strand, or by an electromagnetic acoustic transducer (EMAT) surrounding the exposed end of the strand. The propagating waves are guided by the geometric boundaries of the strand and are reflected by local cross-sectional changes (for example, broken wires or section loss due to corrosion). Assessment of the frequency content and amplitude of the reflected waves (detected by the transducer mounted to the tendon end) enable the detection of defects in the strand. The travel time of the reflected wave can be analyzed to determine the position of the defect along the length of the strand.

It is noted that the UW testing requires that the ends of the post-tensioning steel tendons are exposed and accessible such that the UW can be introduced into the strand. For bonded post-tensioning, leakage of acoustic energy from the strand into the surrounding grout is significant, limiting the length of strand that can be assessed. Other materials surrounding the strand, such as grease, also result in attenuation of the acoustic wave, though less severely than cementitious grout. UW testing technologies are not readily adaptable to the inspection of geometrically complex details such as post-tensioning anchorage and strand coupler regions because reflections are produced from the grips that hold the strand.

Visual Inspection

Visual inspection technologies are the most commonly used forms of NDE for bridge inspection. Visual inspection is used in some capacity in all types of bridge inspections with regard to evaluating corrosion damage. In post-tensioned systems, due to the encapsulated construction details used, visual inspection with the naked eye is limited to cases where significant damage is present. Damage detected by visual inspection can include, but is not limited to, splitting of external PT ducts and external corrosion of anchorage blocks.

Visual inspection typically involves assessing a structural component based on the exterior appearance. Post-tensioned systems can be more difficult to inspect visually because often corrosion of the strands does not result in noticeable external changes until the structure is severely damaged. In grouted post-tensioned systems, the tendon and grout condition cannot be examined visually without performing invasive drilling because they are encapsulated by the duct. Typically, holes are drilled at strategic locations along the tendon duct and a borescope is inserted to obtain images of the internal condition in the duct. Based on these images, grout voids can be identified, and if there is a grout void, corrosion of the strand may be assessed. Visual inspection of grouted post-tensioned ducts tends to be easier to perform on external ducts because the duct is more easily accessible. In the case of internal PT ducts, the location of the duct and potential voids must be known to ensure that the drilling process does not cause damage to the tendon.

Summary of NDE Technologies

The survey and literature review conducted for this project identified 11 promising or already-in-use NDE technologies. These technologies are:

Acoustic Emission Monitoring	Magnetic Flux Leakage
Electrically Isolated Tendons	Radiography
Ground Penetrating Radar	Time Domain Reflectometry
Half-Cell Potential	Ultrasonic Wave Testing
Impact Echo	Visual Inspection
Infrared Thermography	

Table 2 presents summary information of these 11 NDE technologies. The information presented includes applicability of the NDE technology to post-tensioned systems, current limitations of the NDE technology, current usages of the NDE technology, and recommendations for continued use and development.

Table 2. Summary of NDE Technologies

Technology	Application in PT Systems	Limitations	Current Uses for PT Bridge Inspections	Recommendations
Acoustic Emission	• Mainly used for the detection of wire fracture occurrence through continuous monitoring	• Cannot detect existing damage • Produces large amounts of data that can be difficult to interpret • Fractures in grouted tendons are more difficult to detect than in un-grouted or partially grouted tendons	• Not used for monitoring of grouted tendons	• The ability to accurately detect a break in a fully grouted PT tendon has not been adequately demonstrated and therefore is not currently recommended for long-term monitoring
Electrically Isolated Tendons	• Detection of breaches in the corrosion protection system • Provides enhanced levels of corrosion protection of the tendon • Allows for quality control and long-term monitoring	• Requires plastic duct and special isolation hardware for anchorages. • If electrical isolation is not achieved during construction, future NDE monitoring cannot be performed	• Not commonly used in US PT systems • Applications exist in Switzerland (required for most PT systems) and Italy for quality control and long term monitoring of the PT corrosion protection systems	• Appears to be viable for detection of a breach in the corrosion protection system of the duct during service life. • Appears to be viable and should be investigated further for the US market.

Technology	Application in PT Systems	Limitations	Current Uses for PT Bridge Inspections	Recommendations
Ground Penetrating Radar	• External detection of metallic duct location • Potential use in detecting grout voids in plastic ducts • Potential use in external detection of plastic duct location	• Difficult to identify duct/tendon in areas with high reinforcement congestion • Cannot inspect conditions within metal ducts • Accuracy is reduced with increase in embedment depth.	• Widely used to locate metal ducts during inspections	• Provides a well-established tool for locating of metallic ducts and reinforcement • Shows promise for locating plastic ducts in laboratory testing. • Provides the possibly for identification of voids in plastic ducts. Should be investigated further.
Half-Cell Potential	• Detection of regions of high potential, indicative of active corrosion of tendons	• Ineffective for plastic or steel duct tendon systems when applied externally due to the masking effect of the ducts	• External applications not typically used for the inspection of PT tendons	• Not viable for external assessment of corrosion because of the shielding provided by the duct • Half-cell probes internally embedded into the tendons are commercially available and should be investigated
Impact Echo	• Detection of Grout Voids • Strand Location	• Difficult to use in areas with congested rebar • Not well suited for inspecting large areas unless automated systems are used.	• Not typically used for tendon inspection	• Shows potential to be used as a quality control tool to ensure proper grouting of the tendon in known problem areas and is currently best suited for metal ducts. • Not currently recommended as a tool for strand location.
Infrared Thermography	• Grout Void Detection	• Ineffective for steel duct systems • Depth and thickness measurements require experimental or numerical calibration data.	• Not typically used for tendon inspection	• Not currently viable for grout void or strand location assessment based on the current technology and lack of successful applications in PT systems
Magnetic Flux Leakage	• Strand Corrosion • Wire Fracture	• More difficult to use when the duct is embedded in concrete • Presence of rebar can affect the accuracy • Ducts can create a masking effect	• Primarily used for external ducts • Field readings for internal ducts have been found to be less accurate	• Viable for the assessment of external tendons. • Should be further investigated for applicability to internal tendons because of the ability to detect corrosion of the strand

Technology	Application in PT Systems	Limitations	Current Uses for PT Bridge Inspections	Recommendations
Radiography	• Strand Corrosion • Grout Voids • Strand Location	• Requires access to both sides of the specimen • Gamma ray devices use radioactive materials • X-ray and Gamma ray require safety precautions during transmission.	• Not typically used for tendon inspection	• May be suited for detecting strand corrosion and grout voids. If verified, would be suited for the inspection of tendon anchorage regions and strand couplers where complex geometries and multi-layer material interfaces present problems for other technologies. • Portable high intensity X-ray machines have improved the efficiency and imaging capabilities of radiography
Time Domain Reflectometry	• Grout Voids • Strand Corrosion	• Best results are obtained with internal sensors which need to be integrated into the duct • Content in voids can affect the accuracy • Pulse generator required can be expensive. • No commercially available system for PT inspection	• Not typically used or currently installed in PT bridge systems	• Appears promising and should be investigated further for internal integration in PT systems. • Should verify the ability to detect corrosion of the strand • Ability to detect moisture levels in grout should be explored further
Ultrasonic Wave Testing	• Strand Corrosion • Grout Voids • PT Tendon Location	• Ends of PT tendons need to be accessible • Signal interpretation difficult for complex geometries	• Not commonly used for tendon inspection. • Has been used for condition assessment of steel strand and prestress monitoring •	• Viable for identifying strand breaks. • Appears to be viable and should be investigated further for the US market
Visual Inspection	• Strand Corrosion • Grout Voids	• Access to the interior of the duct requires invasive drilling • Each access point to the tendon only allows for a small amount of the tendon to be inspected • Location of the tendon must be known	• Currently one of the most typically used methods • Borescopes are widely used to inspect internal conditions of tendons	• Provides accurate information on the condition of the tendon. Because this requires invasive drilling and allows only a small portion of the tendon to be inspected, it is best suited as a tool to verify localized damage identified by other technologies

Literature Review Conclusions

Major conclusions taken from the survey of NDE technology and the subsequent literature review with regard to the applicability of NDE technologies and their application to post-tensioning tendons include the following:

- No single NDE technology is capable of completely evaluating the condition of post-tensioning tendons in existing bridges. Depending on the bridge type, several of the NDE technologies may be combined to produce sufficient review of the tendons.
- Internal integration of NDE technology appears to be the most viable option for long-term monitoring.
- EITs show the most promise for NDE monitoring because of the following reasons:
    - Reasonable cost
    - Availability for implementation
    - Long-term monitoring
    - Monitoring during construction
- Many of the NDE technologies reviewed require validation through research prior to being used to inspect post-tensioning tendons.

Design and Detailing Guidance Videos

Multiple videos have been developed to describe common post-tensioned bridge construction methods and post-tensioning details. Each of the videos then makes recommendations to enhance the ability to inspect the post-tensioning system using NDE technology. The videos can be viewed at the Bridge Technology Series play list on FHWA's YouTube channel.

Subtask 11.5 – Evaluate Modified Grouts to Increase Contrast in Radiographic Images

This subtask evaluated the effect of adding high photon attenuating materials to the cementitious grout components on the resulting grout properties, including compression strength, bleeding, and X-ray attenuation. The two high attenuation materials treated in the study, referred to as photon attenuating inclusions (PAI), were barium carbonate ($BaCO_3$), and iron oxide (Fe_2O_3). Different grout mixtures were tested and compared to evaluate the effect of the PAI on grout properties.

From the compression tests, it was found that adding barium carbonate to the grout did not have an adverse effect on the compression strength of the grout. Strength results for grout containing barium carbonate (10 percent and 20 percent of cement weight) satisfied the compression strength requirements of PTI M55. Similarly, adding iron oxide to the grout did not have an adverse effect on the compression strength of the grout, and the strength results for grouts having iron oxide (10 percent and 20 percent of cement weight) also satisfied the compression strength requirements of PTI M55. Finally, it was verified that adding barium carbonate to grout increases its photon attenuation characteristics, which will make grout more visible in radiographic images, and the absence of grout (that is, a void) more detectable.

Summary

The presented work aimed at enhancing the design and detailing of post-tensioned concrete bridge for NDE. Established and promising NDE technologies were surveyed and evaluated for application in post-tensioned bridges. Post-tensioning systems and post-tensioned bridge types were evaluated with respect to the NDE technology. Videos were developed that present current design and detailing practices and proposed practices to better accommodate NDE technology.

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Contact — For more information, contact:
Federal Highway Administration (FHWA)
Office of Bridges and Structures Reggie Holt — reggie.holt@dot.gov

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