TechBrief

Advance Concrete Bridge Technology to Improve Infrastructure Performance Program's purpose is to advance the current state of practice for design and construction of post-tensioned bridge structures in the U.S.

U.S. Department of Transportation
Federal Highway Administration

Office of Bridge Technology
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Development of Reference Criteria for Electrically Isolated Post-Tensioning Tendons in U.S. Bridge Applications

This Technical Brief provides an overview of "Advancing Steel and Concrete Bridge Technology to Improve Infrastructure Performance Program." The objective was to research design details of Electrically Isolated Tendon (EIT) technology for post-tensioning systems in concrete bridges to accommodate epoxy-coated mild steel reinforcement and permit post-grouting inspection of anchorages, as are common to U.S. practice.

Introduction

Electrically isolated tendons (EIT) can be used to provide enhanced corrosion protection to prestressing steel elements in post-tensioning (PT) tendons such as that depicted in Figure 1. The electrical isolation prevents the formation of the corrosion circuit that typically originates when corrosive contaminants penetrate the prestressed concrete section, thereby greatly reducing corrosion rates. In addition, the electrical isolation provides the opportunity to electrically monitor PT systems' durability performance.

The Federal Highway Administration (FHWA) previously reported on the ability to identify and localize individual duct perforations in PT tendons using EIT in its publication number FHWA-HIF-18-029. As demonstrated in Switzerland over the past 18 years, EIT has enhanced quality of workmanship and improved durability of prestressed structures by raising awareness of quality in the entire production chain (ASTRA 2007). Furthermore, grouted or encapsulated tendons are inherently difficult or impossible to inspect for signs of active corrosion until wire failures become evident.

Establishing electrical isolation of tendons permits long-term nondestructive monitoring of the tendons in service. Changes in electrical measurements made over time can be used to identify developing breaches in the protective systems or detect ingress of moisture or chlorides through defects in the encapsulation. Early detection of these changes can warn of an elevated corrosion risk and perhaps trigger a more in-depth evaluation of the PT tendon before significant corrosion damage has occurred.

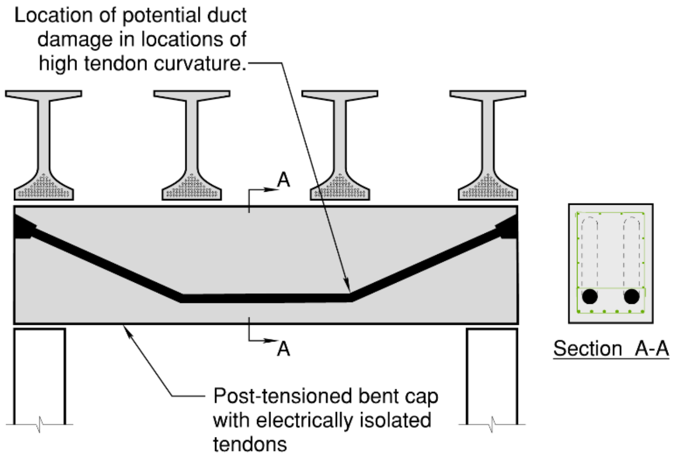


Figure 1. Illustration. Example of EIT in a bridge bent cap.
Source: FHWA

Background

PT tendons are typically composed of a bundle of prestressing strands placed inside a duct that is cast into the concrete section. The strand bundle is inserted into the duct after the concrete has been cast. The strand bundle is connected to the concrete at each end with steel anchorage hardware that has also been cast into the concrete (Figure 2). The strands are stretched and locked to the anchorage to deliver the post-tensioning force to the concrete.

Plastic ducts are now widely used in place of metallic ducts to help remedy the problem of section loss of the duct system itself; however, defects in PT duct systems still occur in scenarios such as the abrasion of the duct system as a result of stressing or improperly sealed duct-coupler systems. A challenge of prestressed concrete, including PT bridge construction, is that the condition of the tendons cannot be visually assessed once the prestressed element is constructed and stressing has occurred.

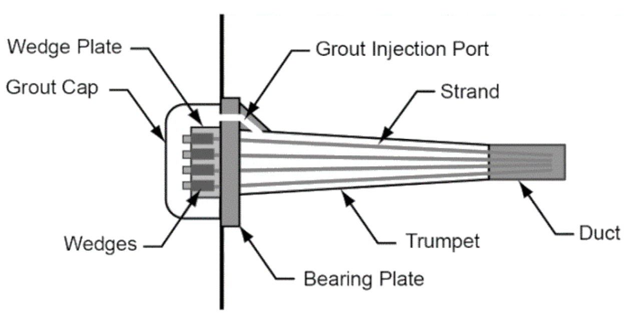


Figure 2. Illustration. Typical PT anchorage components.
Source: FHWA NHI-13-026

Corrosion of prestressing steel located in (PT) ducts may occur when the ingress of deleterious substances such as chlorides occurs from concrete surfaces exposed to harsh environmental conditions in coastal environments or on bridges where frequent application of deicing salts occurs. Once chloride intrusion occurs, defects in PT ducts allow chlorides to contact the prestressing steel located within the duct and thus initiate corrosion of the critical reinforcement of the bridge structure.

Relevant information on bonded tendons can be found in the Post-tensioning Institute's PTI/ASBI M50.3 2019 publication. This nonbinding publication provides information for design professional to consider when preparing design and construction specifications for all PT work, establishing testing criteria, ensuring sound installation, and satisfying durability goals. The PTI's publication is not a Federal requirement; some States do include PTI's publication in their specifications.

Designers select the protection levels for a PT system based on the aggressiveness of the environment and protection provided by the structural element. The non-binding PTI publication lists three tendon protection levels (PL):

- Protection Level 1A (PL-1A)—Duct with filling material providing durable corrosion protection.
- Protection Level 1B (PL-1B)—PL-1A plus engineered grout and permanent grout cap.
- Protection Level 2 (PL-2)—PL-1B plus an envelope, enclosing the tensile element bundle over its full length, and providing a permanent leak-tight barrier.
- Protection Level 3 (PL-3)—PL-2 plus electrical isolation of tendon or encapsulation to be monitorable or inspectable at any time.

EIT technology was introduced as a means of providing construction quality control of PT bridge girders and monitoring the integrity of the isolation system. EIT systems utilize AC (alternating current) impedance measurements between PT strands and the general reinforcement cage of the girder as a means of detecting and monitoring potential sources of corrosion attack of the tendon from sources outside of the PT duct. In the presence of duct damage, electrical current may pass through the defect, which has a much lower electrical impedance than the duct itself.

Acceptance criteria for AC impedance measurements of EIT systems have been developed in Swiss guidelines (ASTRA 12 0010, 2007). Swiss findings may be relevant to the United States; however, differences in construction practices, particularly regarding the use of epoxy-coated reinforcement (ECR) may necessitate adjustment of threshold values. Swiss findings do not reflect Federal requirements in the U.S.

The following summarizes Swiss practice in accordance with ASTRA 12 0010. Immediately after stressing of the PT tendon and before grouting, electrical resistance measurements are taken between the prestressing strands and the reinforcing cage as illustrated in Figure 3. Of particular concern during stressing is the perforation of the plastic duct by the PT strands at locations of high curvature of the PT tendon over duct support bars, allowing for direct metallic contact between PT strand and the reinforcement cage. Metallic contact may also be present at the anchorages as a result of improper installation of the electrically isolating anchorage components. Such metallic contact signifies a short circuit of the EIT system and is indicated by very low resistance measurements on the order of 10 or 20Ω (Angst and Büchler, 2020).

Additional measurements are performed 28 days after the tendon is grouted to determine the quality of tendon encapsulation. Duct perforations that do not result in electrical contact between the prestressing strands and surrounding reinforcement will not be detected by electrical resistance measurements prior to grouting. After grouting, in the absence of direct metallic contact, electrical measurements can indicate the presence of imperfections in the system such as perforations where no metallic contact exists, or confirm general leak-tightness of the EIT system (Figure 3). If metallic contact is present as indicated by the initial quality control measurement, then these AC impedance readings will be dominated by this low resistance, and other defects in the system, such as duct perforation with no metallic contact, will be undetectable. Monitoring of AC impedance measurements over time can give further insight as to ingress of moisture and possible chloride intrusion through defects in the system.

Epoxy-Coated Reinforcement

Effect on electrical measurements

In theory, EIT systems are applicable in the case where epoxy-coated reinforcement is used. Although the epoxy coating provides an insulating component to the EIT circuit like that of the duct, small defects sometimes present in ECR may provide sufficient electrical connection with the surrounding concrete to obtain electrical measurements of the EIT system that are comparable with that of bare reinforcing bars.

There is a concern, however, that the epoxy coating prevents electrical continuity of the reinforcing cage, and thus is not a viable counter electrode for electrical measurements (Angst and Büchler, 2020). This is illustrated in Figure 4 for electrical measurements taken before and after grouting.

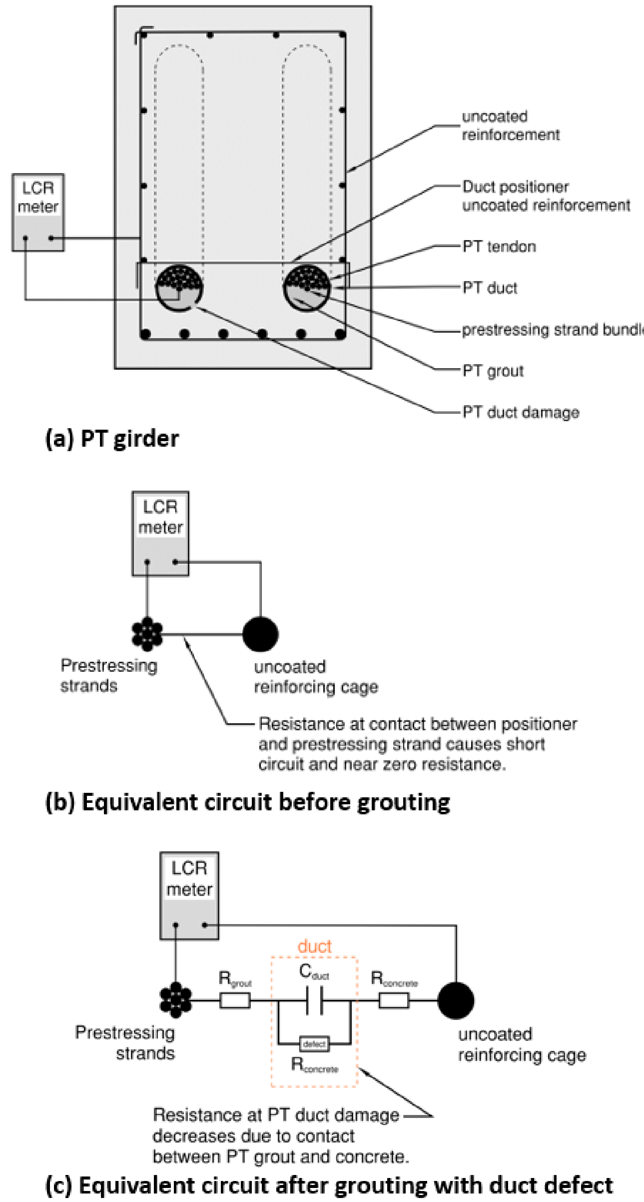
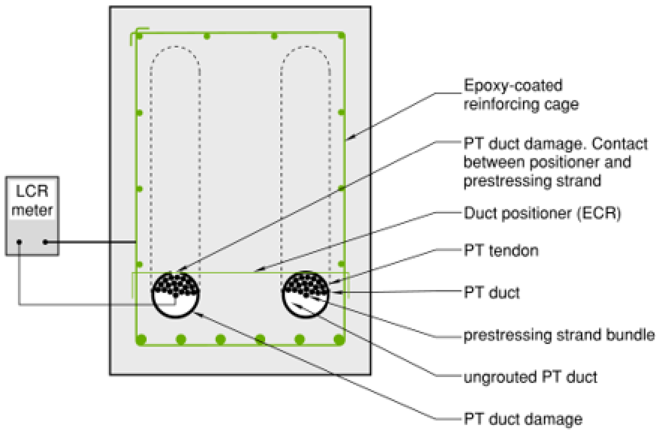
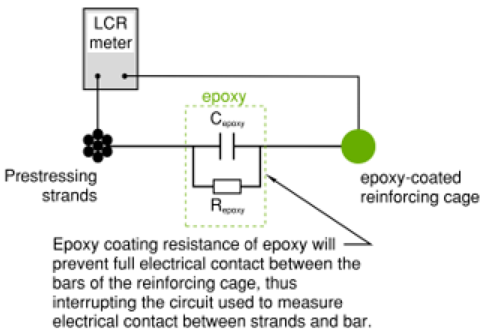


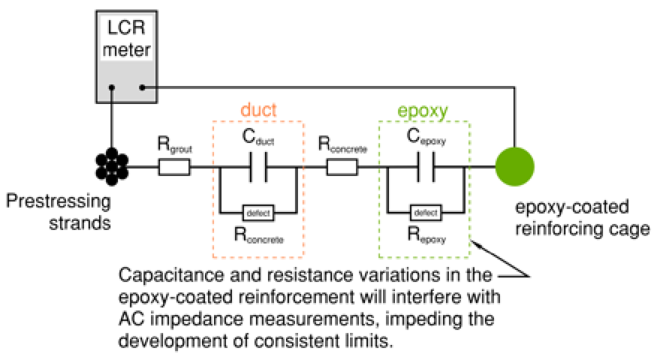
Figure 3. Illustrations. Measurement of AC impedance in an EIT system. An LCR meter measures the inductance (L), capacitance (C), and resistance (R) of an electrical circuit.
Source: FHWA



(a) PT girder with epoxy-coated reinforcement



(b) Equivalent circuit before grouting



(c) Equivalent circuit after grouting with duct and epoxy defect

Figure 4. Illustrations. Measurement of AC impedance in an EIT system surrounded by epoxy-coated mild reinforcement.
Source: FHWA

To avoid the uncertainty regarding the electrical continuity of ECR, Angst and Büchler (2020) suggest the placement of uncoated bars with large surface area in the section to ensure the presence of a continuous conductor for reference as the counter electrode in the electrical measurements. Such a condition can be achieved as shown in Figure 5, where bars are placed longitudinally along the segment and are used as counter electrodes to complete the circuit to measure the AC impedance.

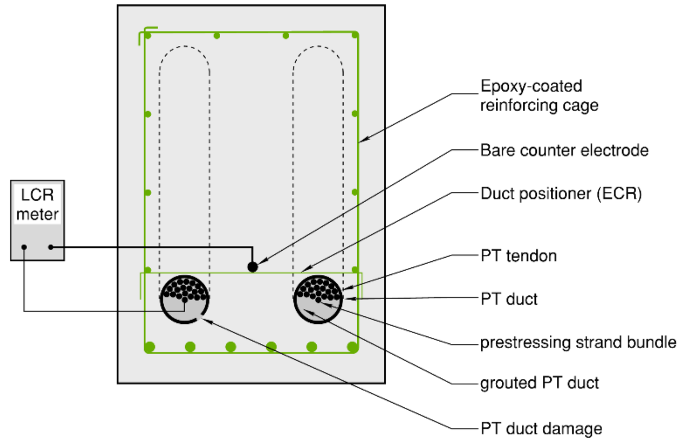


Figure 5. Illustration. Use of bare counter electrode in EIT systems containing ECR.
Source: FHWA

Cylinder test results

To test the effect of epoxy-coated reinforcement on the electrical readings from PT tendons, 6 inch by 12 inch concrete cylinders were fabricated with a simulated PT tendon and counter electrode embedded in the cylinder. The counter electrodes were varied to test the relative change in electrical properties when a coated bar was used in place of a bare steel reinforcing bar. Although the scale of the segments was much smaller than that of PT tendons typically used in practice, the measurements demonstrated the potential for significant variation in AC impedance when using an epoxy-coated counter electrode.

Figure 6 shows the results of cylinder tests that were conducted with two embedded electrodes. The bare prestressing strand was the working electrode, intended to simulate the strand bundle in a PT tendon. ECR was used as the counter electrode, intended to simulate the ECR cage surrounding the PT tendon in the concrete section. Damage was inflicted on several of ECR electrodes to simulate potential damage in the field; square areas of epoxy as indicated in the figure legend were removed. The variation in AC impedance readings was slight among the specimens with damaged epoxy coating; the decline in readings from undamaged to damaged, however, was nearly 90%.

To ensure the integrity and consistency of the EIT readings, if ECR were to be used as the counter electrode, the quality control would need to be such that no damage could be allowed to occur to the epoxy coating. In general, this is not a practical solution. Thus, if ECR is used to protect the reinforcement from corrosion, then an additional bare counter electrode should be used for electrical measurements.

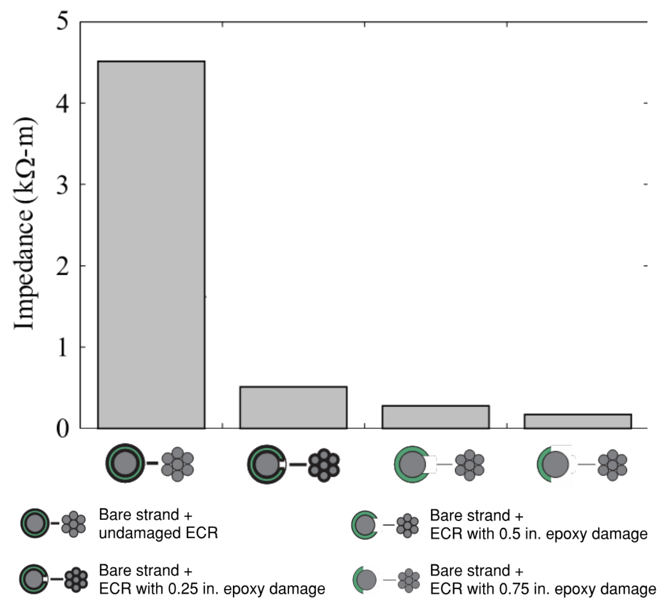


Figure 6. Graph. Effect of epoxy coating damage on electrical readings.
Source: FHWA

EIT Segment Tests

To assess the Swiss technical acceptance criteria, experimental electrical measurements on 1-m long grouted plastic ducts in concrete blocks were conducted. The specimen size and configuration constructed for this research were similar to tests reported in Elsner (2008), which were performed using ducts with 0.07-inch to 1.57-inch diameter holes that simulated duct defects. Those test results were used to develop acceptance criteria for EIT by Swiss Federal Roads Authority and Swiss Federal Railways (ASTRA 12 0010, 2007). The primary purpose of the EIT segment tests reported in this TechBrief was to use a similar test specimen and procedure to assess the applicability of the Swiss EIT design and construction acceptance criteria to materials and systems currently used in the U.S. for PT tendon construction.

Three concrete block segments (designated as S1, S2, and S3) were cast with embedded electrically isolated PT tendons and counter electrodes. The three-foot long segments (Figure 7) were fabricated with two 19-strand tendons and the following counter electrodes:

- Stainless steel rod.
- Stainless steel strand.
- Uncoated reinforcing steel.
- Prestressing strand.

The PT tendons were fabricated with HDPE duct, bare prestressing steel, and prepackaged PT grout. The purpose of these tests was to determine the effectiveness of the selected counter electrodes in providing reliable and consistent EIT measurements when damage was present in the PT duct. The segments were identical in design with the exception of the duct damage size and location as noted in Figure 7a.

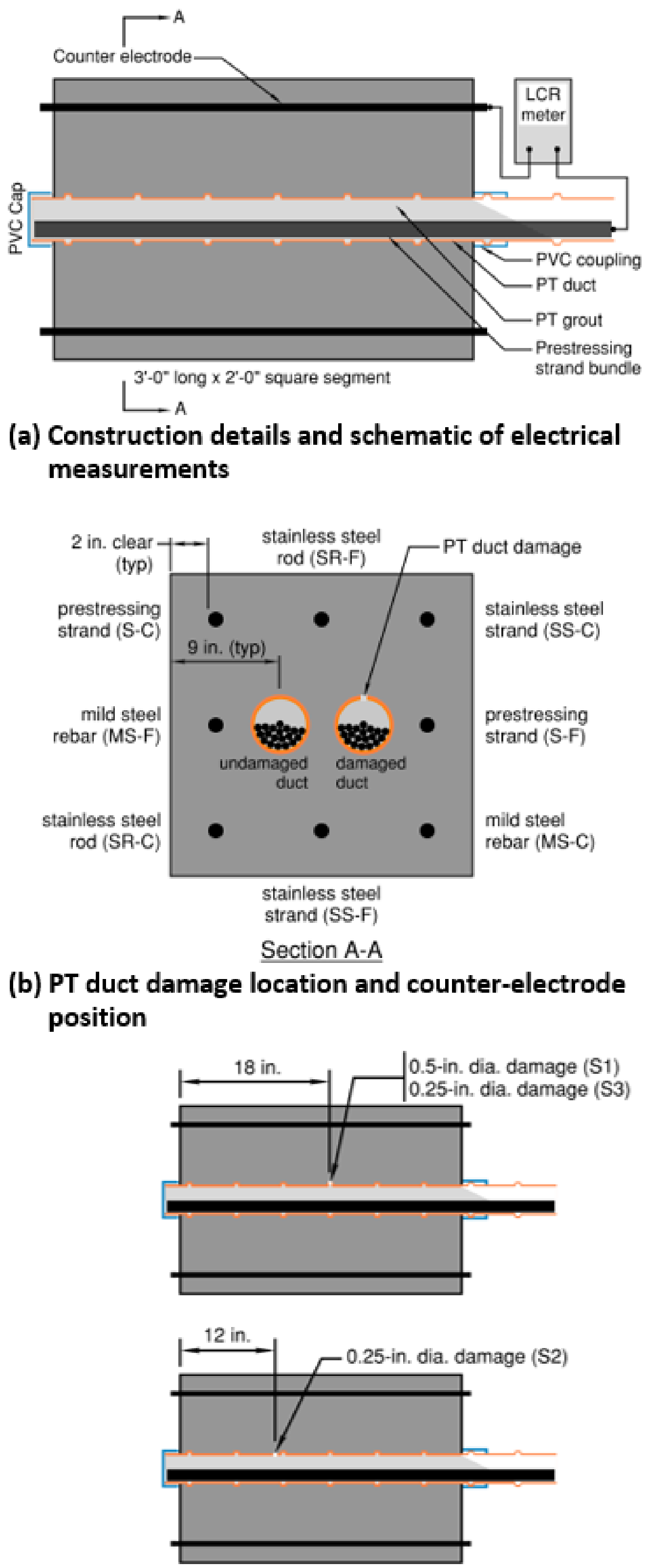
Following completion of the EIT measurements, segment repair tests were conducted on the EIT segments. Holes were drilled through concrete and into the duct to simulate a borescope inspection of grout quality. The purpose was to evaluate the residual effect of these holes on the EIT electrical measurements. Several methods were used to repair the holes to determine if EIT electrical measurements could be restored to levels measured prior to drilling.

Segment design and fabrication

The segment tests were developed as a method to test for the existence of a macro-cell current within the 4-inch polypropylene ducts. Figure 7 shows the design details including specimen configuration, materials, and schematic of electrical measurements. Counter electrodes were placed geometrically around the ducts to evaluate electrode material and relative position on electrical measurements. Electrodes of each material was placed at the corner and side face of the segment cross-section.

Duct perforations of 0.25 in. and 0.5 in. diameter were made in the ducts to simulate prestressing damage and improper storage in the field. Figure 8 shows induced duct damage size and location along the length of the segment. The damage sites were oriented at the twelve o'clock position in the section and were located either at the top of a duct rib or adjacent to a rib. This orientation may have had some influence on the electrical behavior following grouting, which is discussed in a later section.

Concrete was ready-mix concrete typically used to produce Florida I-beam precast prestressed bridge girders. The specified strength of the concrete was 8,500 psi. Cylinder strength at 28-days was 10,300 psi. Specimen S1 was grouted at a concrete age of eight days and specimens S2 and S3 were grouted at a concrete age of 22 days.



(a) Construction details and schematic of electrical measurements

(b) PT duct damage location and counter-electrode position

(c) PT duct damage size and position

Figure 7. Illustrations. Experimental PT Segment Design.
Source: FHWA

Four different counter electrodes were introduced to test whether the impedance and capacitance measurements varied. The electrodes were as follow:

- 0.6-inch prestressing strand (ASTM A416 270 ksi Lo-Lax)
- 0.5-inch stainless steel rod (ASTM 276 Grade 304)
- 0.5-inch deformed mild steel bar (ASTM A615 Grade 60)
- 0.6-inch stainless steel prestressing strand (Grade 2205)

Acting as the working electrode throughout the damaged and undamaged ducts, a bundle of nineteen 0.6-inch diameter prestressing strands was centered in the ducts prior to grouting. Prestressing strand bundles were formed by enclosing them with hose clamps and slipping the bundle into the duct prior to grout placement. Figure 9 (image foreground) shows one such bundle just before insertion into the duct.

The commercial prepackaged PT grout was mixed in a five-gallon bucket and poured through a funnel and into a 1-inch diameter hole in the duct extension at the top of the tendon. Grout was placed in a single lift until the grout line was visible in the duct extension.

Figure 9 shows positioning of the segment on a slope to simulate the slope that can occur due to the variation in tendon position. As shown in Figure 10, this also allowed grout to be poured into the duct from the upper end rather than by injection, which is the customary method of grout placement.

Some leakage occurred around the PVC cap located at the lower end of the duct in some of the segments, which affected the electrical measurements. This will be discussed in a subsequent section.

Electrical Measurements

AC impedance and capacitance measurements were taken between the various counter electrodes and the strand bundle at selected time intervals. Copper ground rod clamps were fastened to each counter electrode and prestressing bundle to provide the connections needed to take AC impedance and capacitance measurements.

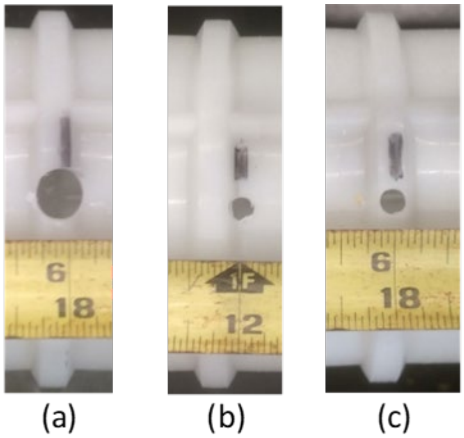


Figure 8. Photo. Damage in segment (a) S1 (0.5 in. at mid-length) (b) S2 (0.25 in. at 12 in. offset) and (c) S3 (0.25 in. at mid-length).
Source: FHWA

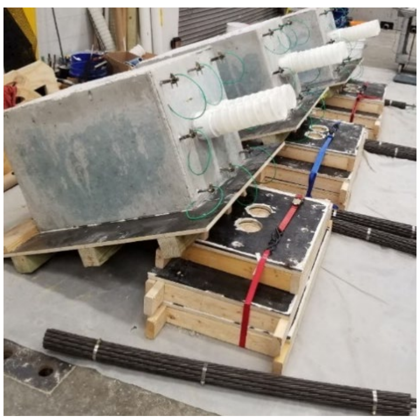


Figure 9. Photo. Segments in sloped grouting position.
Source: FHWA

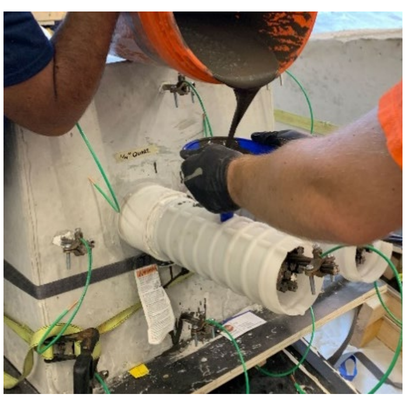


Figure 10. Photo. Grout placement using funnel through opening in top of duct. Copper grounding clamps with #10 AWG copper wire are attached to counter electrodes and tendon strand for electrical measurements.
Source: FHWA

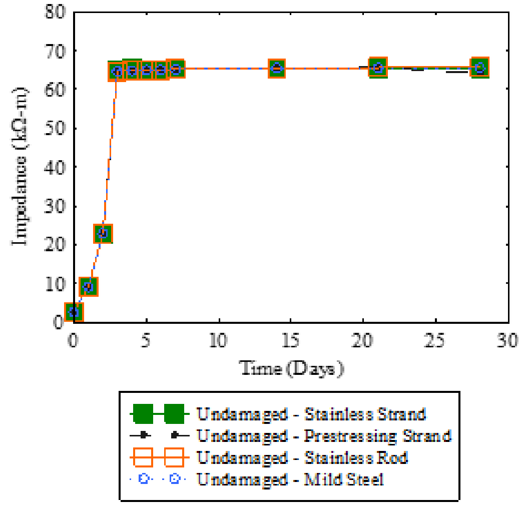
Measurements were taken using an LCR meter with Kelvin clip test leads. LCR indicates electrical Inductance (L), Capacitance (C), and Resistance (R). The meter had a basic accuracy of 0.1% and readings were taken at a frequency of 1 kHz. At this frequency, electrical measurements of grout and concrete are generally dominated by ohmic resistances and plastic duct is dominated by capacitance (Angst and Büchler 2020).

At a measurement frequency of 1 kHz, the plastic duct behaves electrically as a parallel circuit with capacitance and resistance components. Because of its very high resistance, the duct behaves essentially as a capacitor while the surrounding concrete and grout behave primarily as resistors in series with the duct. If defects are present in the duct and the grout and concrete come into electrical contact, then the electrical behavior is changed by a reduction in ohmic resistance at the defect caused by the contact between grout and concrete (Figure 3b), but with almost no change in capacitance at the duct interface. The change can be detected by AC impedance measurements of the tendon after grouting.

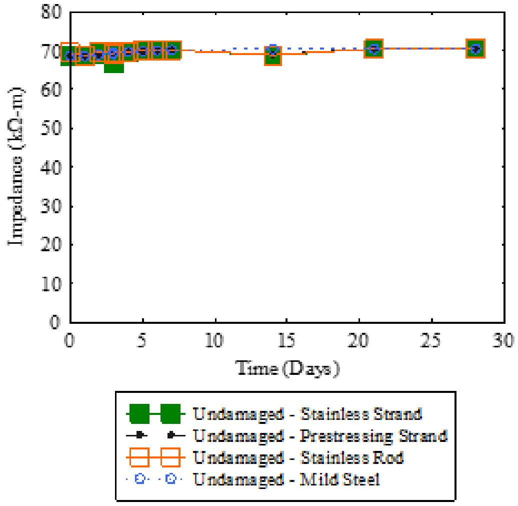
Results and Discussion

Figure 11 and Figure 12 show AC impedance measurements for each segment over the first 30 days following grouting of each segment. Readings were taken within an hour of grouting and then daily for seven days. Further readings were taken weekly until at least 28 days following grouting. The four reference electrode materials are represented individually in the plots and are the average of readings from electrodes of the same material, but in different positions.

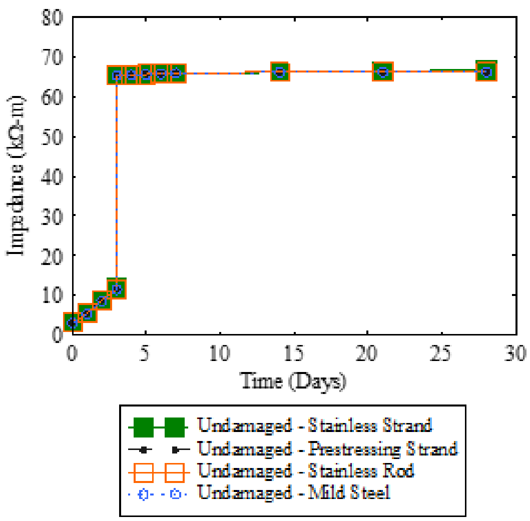
Counter electrodes of varying materials were placed in each of the four corners and four faces of the segment section to evaluate the effect of counter electrode geometry on impedance measurements. Differences in readings, however, varied little for the different electrode materials and electrode positions. For example, the coefficient of variation (COV) of the readings from reference electrodes in the corner or face position of S2 was less than 1 percent, and in most cases less than 0.5 percent. Variation had been expected related to either reference electrode position or material but based on the lack of variation evident in the readings a more extensive statistical analysis of the data was deemed unnecessary.



(a) S1

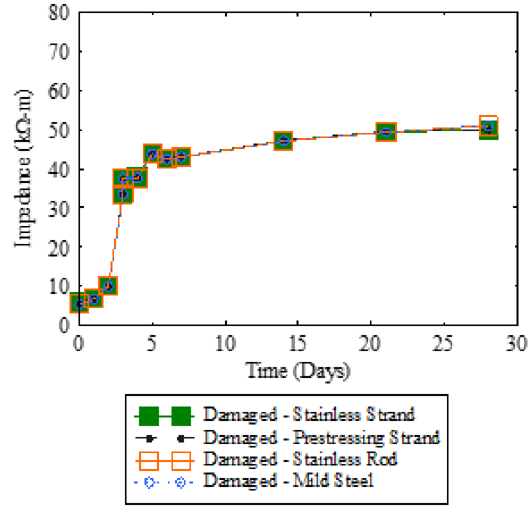


(b) S2

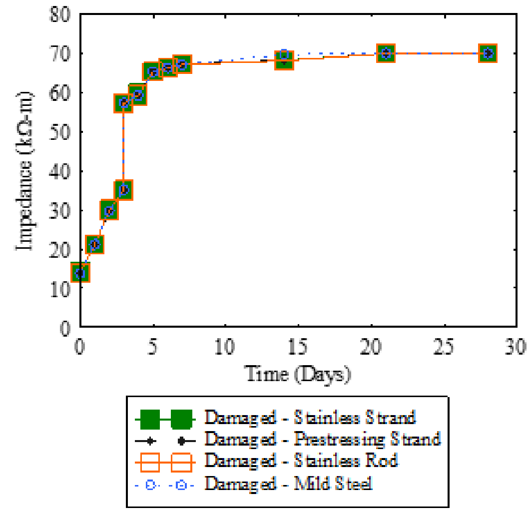


(c) S3

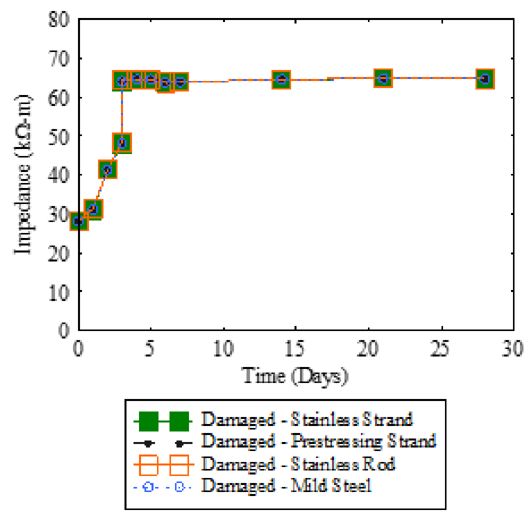
Figure 11. Graphs. Impedance measurements of undamaged ducts in segments.
Source: FHWA



(a) S1



(b) S2



(c) S3

Figure 12. Graphs. Average impedance of damaged ducts in segments using corner and side-face counter electrodes.
Source: FHWA

In conclusion, there was effectively no difference in readings among the selected reference electrodes. Nor were there significant differences caused by the variation in positioning of the reference electrodes in the cross section.

Early-age impedance results for the damaged ducts were low, indicating that the readings were below the minimum value of 50 kΩ-m recommended by Swiss Guidelines (ASTRA 12 0010, 2007). These low values are indicative of the dominance of damage resistance in the reading, which will lead to a lower AC impedance. The increase in AC impedance readings over time indicate that the resistance of the grout as well as the grout-concrete contact point (defect) is increasing. This is likely due to the continued hydration of the cement and the consumption of the free moisture in the grout in the hydration process, thus reducing the overall resistance of the grout.

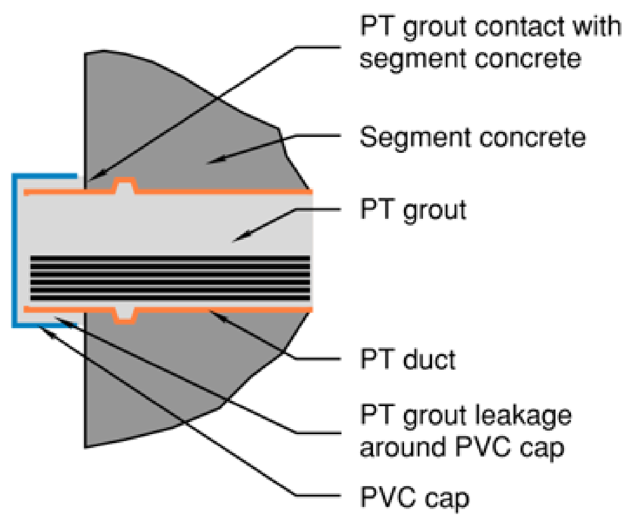
The Swiss guidelines also indicate, however, that readings should be taken after the grout has cured for at least 28 days due to the low electrical resistance of early-age grout. The rapidly changing resistance of the grout was apparent by the significant gain in AC impedance with time immediately following grouting.

If the undamaged ducts provided perfect isolation of the grout from surrounding concrete, then it is expected that the AC impedance readings would be dominated by capacitance and would have an AC impedance of approximately 70 kΩ-m. While S2 displayed this behavior, both S1 and S3 showed depressed AC impedance readings, indicating a possible breach in the undamaged duct system.

In the first few days following grouting, it was not clear why the undamaged ducts showed such distinct differences in readings. During grouting, it was noted that grout had leaked out of one of the end caps and was in contact with the concrete. Upon closer inspection, grout leaks out of the duct were noted on several of the ducts (Figure 13). Following the grout pour of the first duct, a small leak was discovered in the duct coupler at the front of the segment and at the PVC cap at the low end of the duct slope.

To restore the duct integrity, the duct couplers and caps of each duct were removed, and the grout leakage was cleaned. As a result of this action, the AC impedance readings of the undamaged ducts immediately increased to approximately 70 kΩ-m, indicating that the integrity of the ducts had been restored (Figure 11a and Figure 11c).

Caps and couplings were also removed from the damaged ducts, which resulted in sharp increases in readings for all three ducts (Figure 12). S2 and S3 readings increased to levels above the Swiss limit of 50 kΩ-m, which should have indicated an undamaged duct. These readings occurred before the grout was 28-days old and were on the same order as the undamaged ducts. S1, which has the larger damage site, reached the 50 kΩ-m limit but did not surpass it by much. Thus, the AC impedance readings from this segment would indicate damage.



(a) Illustration. Grout leakage through end cap.

(b) Photo. Traces of grout on outside of duct, which resulted in low AC impedance readings.

Figure 13. Effect of PT grout leakage at PVC cap.
Source: FHWA

These results were puzzling given the definite damage that was present in each duct. To ensure that proper procedures were being conducted and that the test equipment was operational, several AC impedance measurements were conducted in which a damp cloth was held against the exposed grout and segment concrete to create an electrical connection. This test resulted in a sharp decrease in AC impedance for all segments to well below the 50 kΩ-m limit.

It was clear from the tests that the damage sites were not making the expected electrical connection between the grout and segment concrete. One possible explanation is that air or water trapped in the duct rib where the damage sites were placed (Figure 14) on two of the three ducts prevented contact between the grout and concrete. All three damage sites had been placed at the top of the duct where air and bleed water will gather and flow before the grout sets. In addition, the segments were placed in laboratory conditions, which provide a relatively dry environment. It is possible that moisture that may have been in the defect area was absorbed by the concrete or grout, thereby effectively breaking the electrical connection. If the segment were exposed to moisture that could penetrate to the defect location, then the electrical connection would be completed, and AC impedance would drop significantly.

The capacitance of the duct is influenced solely by the duct properties rather than the existence of a possible defect in the damaged duct. Capacitance measurements were conducted along with AC impedance periodically during the testing and are presented in Figure 15.

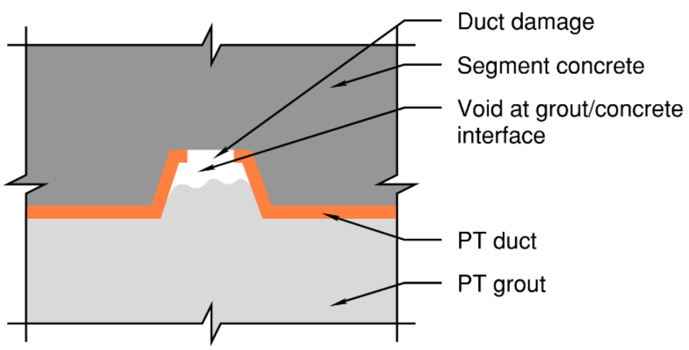
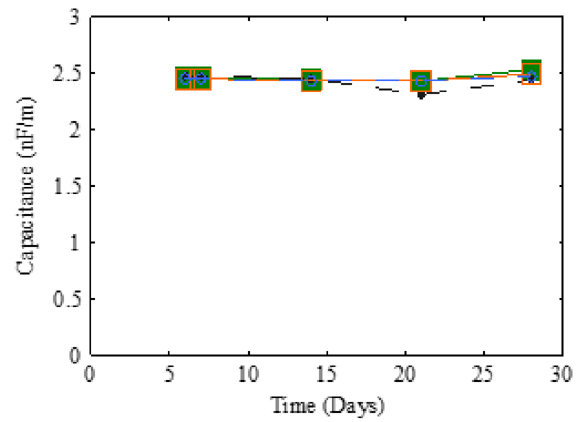
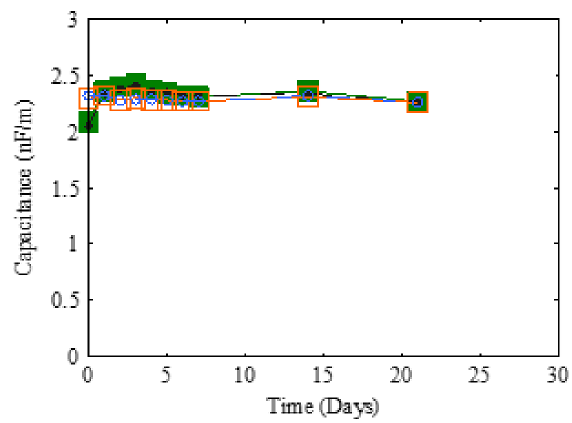


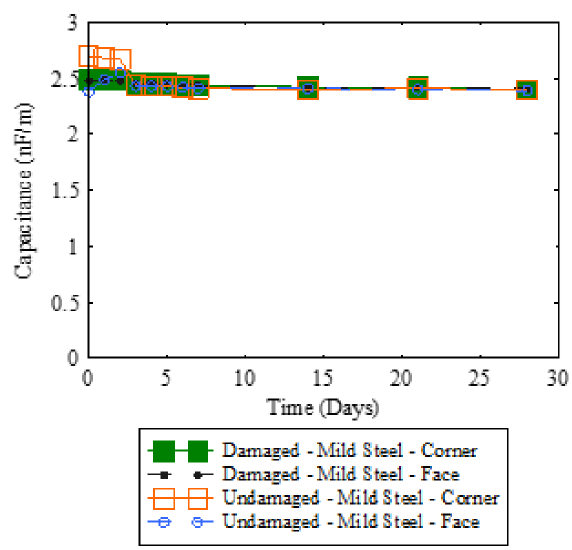
Figure 14. Illustration. Effect of void in duct at damage site.
Source: FHWA



(a) S1 (0.5 in. mid-length)



(b) S2 (0.25 in. offset)



(c) S3 (0.25 in mid-length)

Figure 15. Graphs. Capacitance measurements in test segments.
Source: FHWA

For comparison, Elsener (2008), in experiments on EIT embedded in concrete segments, found capacitance of the plastic ducts measured 2.34 ± 0.04 nF/m, which agrees well with the readings taken in this research.

EIT Segment Repair Tests

Repair approach and design

In U.S. practice, inspection ports are sometimes drilled into the duct to determine if the duct grouting is complete. This action, however, is detrimental to the duct integrity and will likely affect the AC impedance readings used to evaluate quality and long-term performance.

The purpose of the duct inspection hole testing was to determine if an inspection port could be drilled into the duct and then repaired to return the AC impedance readings back to the undamaged state.

Because the procedure was destructive, it was decided to leave one specimen untested to allow long-term monitoring after the completion of the project; segments S2 and S3 were chosen for testing. The simplest repair is to use a cementitious material to fill the hole following inspection. The critical aspect of a repair, however, is to regain the high resistance and dielectric properties of the duct material in the area of the breach. Based on these principles, the repair approaches noted in Table 1 were devised. The S2 undamaged duct was repaired with epoxy only to test the electrical properties of epoxy as a dielectric and the epoxy's capability to bond directly to a polypropylene duct. The S2 damaged and S3 undamaged specimens received a combination of polypropylene duct repair using hot melt glue application and concrete repair with either PT grout or epoxy. The mix of plastic bonding glue, grout, and epoxy was utilized to test each combination's ability to restore the electric integrity of the system.

Damaged ducts were tested because they were both behaving similar to the undamaged ducts with respect to their AC impedance readings. To ensure, however, that they would behave as expected, the drilled opening in the damaged duct in S3 was filled with water after drilling and prior to repair application and then impedance was measured. Measurements confirmed that AC impedance readings dropped sharply as expected.

Table 1. Description of repair types for each segment and duct type.

Segment	Duct condition	Inspection port repair
S2	Damaged	Duct: polypropylene hot melt glue
S2	Damaged	Concrete: PT grout
S2	Undamaged	Duct and concrete: high modulus, high strength liquid epoxy
S3	Damaged	Duct and concrete: PT Grout
S3	Undamaged	Duct: polypropylene hot melt glue
S3	Undamaged	Concrete: high modulus, high strength liquid epoxy

The test procedure began with drilling a single 0.75-in. diameter hole through the concrete and into the duct to expose the grout (Figure 16); the holes were drilled at about six inches from the segment end. Once the holes had been drilled, the selected repair material was applied to the duct at the bottom of the hole and the hole was filled with the selected material; in the case of S2 damaged and S3 undamaged, the same material was used for both (Table 1). A borescope was used to guide the repair process (Figure 17).

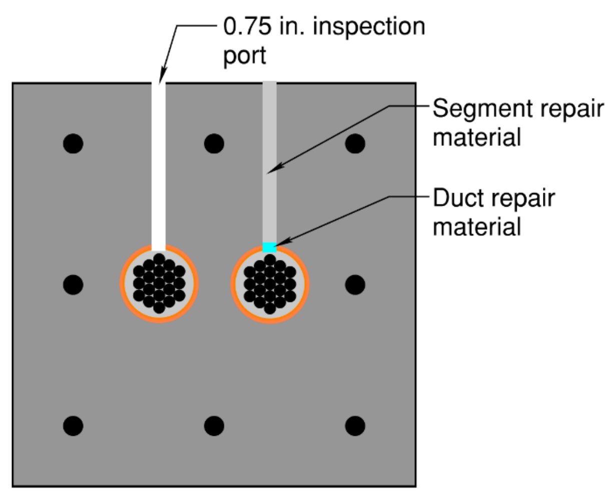


Figure 16. Illustration. Drill locations for borescope inspection.
Source: FHWA

AC impedance readings were taken periodically at critical times during the drilling and repair process as well as over several weeks following the repair. The time variations in readings are shown in Figure 18. As expected, the addition of water to the inspection port in S3 caused a significant drop in the AC impedance. This effect diminished with time as AC impedance readings increased over the next few days. When grout alone was used to repair the hole, the AC impedance dropped further to a low of 15 kΩ-m and did not fully recover, but the impedance trend was increasing as grout cured.

The other repair caused very slight changes between AC impedance readings before and after repair, indicating that the EIT integrity had been restored. Although this procedure appears to have successfully restored the electrical integrity of the EIT, it is unclear if this restored state would remain if the segment is exposed to harsh environmental conditions. Moisture may be able to penetrate the seam between the segment concrete and repair material to the duct and cause a decrease in AC impedance, thus signaling vulnerability of the tendon to potential corrosion. This aspect of the repair process should be fully evaluated before the process is used with EIT in a production environment.

Figure 17. Photo. Insertion of borescope to verify correct placement of duct bonding glue.
Source: FHWA

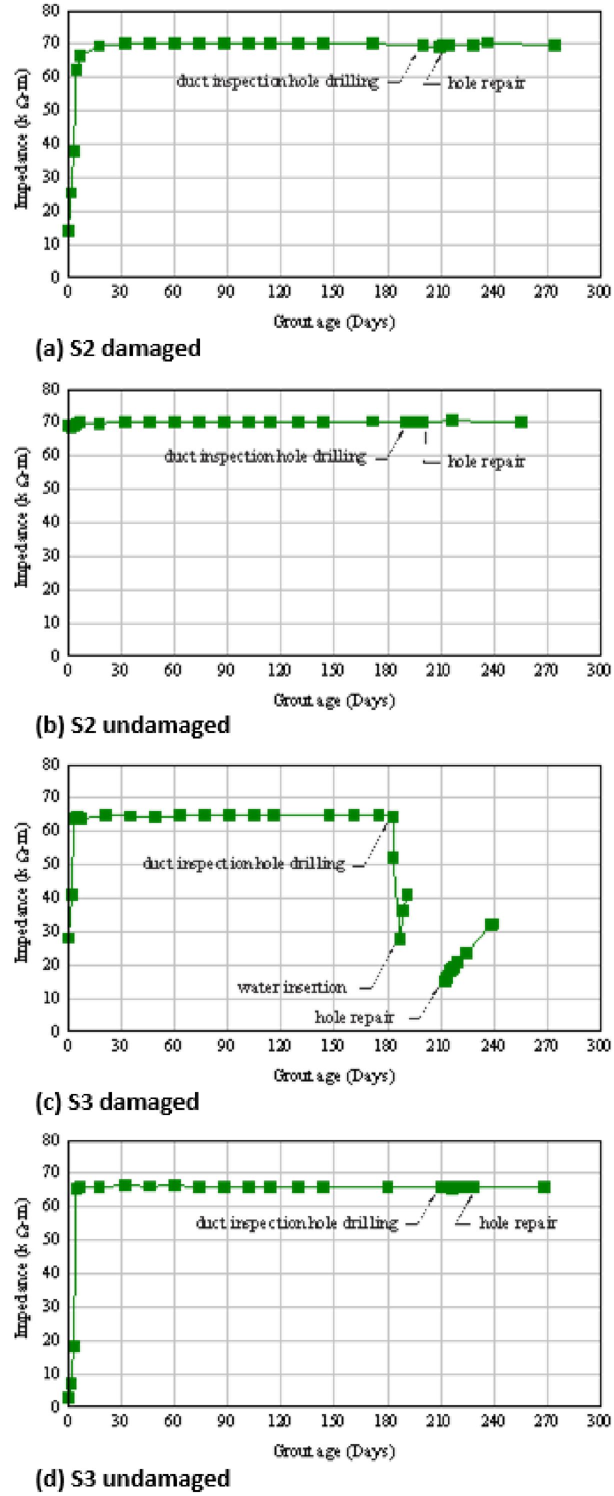


Figure 18. Graphs. Variations in impedance over segment test period.
Source: FHWA

Conclusions

- Use of epoxy-coated reinforcement as a counter electrode resulted in unpredictable variations in impedance readings.
- Variations in AC impedance readings in test segments were found to be insignificant among the selected alternative materials used to fabricate the counter electrodes.
- Variations in AC impedance as a result of counter electrode position within the test segment cross section were found to be insignificant.
- Capacitance measurements of PT duct made in the U.S. was similar to that of duct used in the testing that provided background to Swiss EIT standards for determining damage of grouted ducts.
- AC impedance measurements were comparable to those measured in the development of the acceptance criteria for the Swiss standards.

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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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