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16. Abstract
Results from two sets of full-scale post-tensioned specimens after four and six years of highly aggressive exposure tests are summarized. The study was funded to assess corrosion resistance of both the current state of the industry and possible future developments in strands, ducts, couplers, and anchorages. Non-destructive monitoring was performed throughout the testing, followed by full autopsies of the specimens.

The project also served to highlight a new, smaller test specimen and to investigate how the new specimen was able to better isolate design variables. The main focus was durability of galvanized steel ducts in comparison to plastic ducts. While the galvanized duct certainly showed much worse physical behavior, with large sections of the duct being totally breached by corrosion, the plastic duct jointing techniques failed to completely prevent chloride ingress into the grout and therefore to the tendon. Future testing of post-tensioned systems should be conducted with this new procedure and specimen since it was much more cost effective.

The project results showed plastic ducts weren't subject to corrosion as a result of chlorides but were subject to minor internal gouging damage caused by threading of the strands. Both coupled and uncoupled ducts contained grouts with elevated chloride content. Regardless, the strands showed little physical damage. Additionally the project served to highlight the importance of grouting procedures and the need for proper implementation of the Post-Tensioning Institute grouting standards. Failure to address workmanship issues provided the largest contribution to corrosion damage. These results were considered in a cost analysis which demonstrated how upfront decisions and small initial cost increases can substantially increase performance life and limit corrosion issues.

17. Key Words Galvanized ducts, plastics ducts, encapsulated system, autopsies, corrosion, post-tensioned concrete tendons, epoxy-coated strand, stainless steel strands, stainless-clad strands, hot-dip galvanized strand, copper-clad strands, accelerated corrosion testing	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161; www.ntis.gov.

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A.L. Kilduff
K.L. Moyer
G.E. McCool
M.E. Ahern
J.E. Breen

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Center for Transportation Research
The University of Texas at Austin
1616 Guadalupe, Suite 4.202
Austin, TX 78701

www.utexas.edu/research/ctr

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Project Engineer: John E. Breen
Professional Engineer License State and Number: Texas 18479
P. E. Designation: Research Supervisor

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William M. Kittleman	Rodney T. Davis	Homer R. Hamilton III
T.T. Tran	Jeffrey S. West	Charles J. Larosche
Bradley D. Koester	Andrea J. Schokker	Rene P. Vignos
Rueben M. Salas	Andrea F. Kotys	Tanya Luthi
Jeffrey R. Diephuis	Juan J. Icaza	Gregory P. Turco
Ryan D. Kalina	Sean Mac Lean	Michael E. Ahern
Gregory E. McCool	Kevin L. Moyer	Andrew L. Kilduff

The project was greatly assisted by suppliers who provided both materials and advice. The major contributors with contact information are shown in the following products table.

Materials and Suppliers

Material	Supplier	Contact
Bearing Plates	VSL USA	Jordan Stephenson jstephenson@vsl.net 817-545-4807
Galvanized Steel Duct		
PT Plus Plastic Duct and Couplers		
Hot-Dip Galvanized Strand*		
Wedges		
EIT Systems*	VSL Switzerland	Hans-Rudolph Ganz hansrudolph.ganz@vsl.com
76mm One-Way Ribbed Plastic Duct*	GTI	Joe Harrison joe.harrison@gti-usa.com 281.240.0550
76mm Couplers		
85mm Two-Way Ribbed Plastic Duct*		
85mm Coupler*		
Stainless Strand*	Techalloy	Jim Beitz jbeitz@techalloy.com 815.923.2131
Stainless-Clad Strand*	DSI	Ron Bonomo Ron.bomono@dsiamerica.com
Copper-Clad Strand*	Copperweld	Milton Lamb mlamb@copperweld.com info@copperweld.com
Epoxy-Coated Strand*	Sumiden Wire	Steve Yoshida stevey@sumiden.com
Type V Epoxy*	Unitex	Susan Wintz 816.231.770
Epoxy-Coated Rebar	ABC Coating	Mary Boyette 972.937.9841 orders@abccoatingtx.com
Concrete	Capitol Aggregates	Ron Taff

*Material donated to research project
All contact information current as of August 2012

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Chapter 1. Introduction

1.1 Background

The increased popularity of post-tensioned bridge construction in the United States has led to concerns about corrosion and its impact on the life cycle of these bridges. Although the vast majority of post-tensioned bridges in the U.S. have performed satisfactorily[18], corrosion problems in a small number of bridges have raised concerns about durability of these types of structures. Problems in coastal and deicing regions of the U.S. have highlighted the importance of controlling corrosion, including the use of new materials and construction methods. Commercial manufacturers have produced new materials that are being used in post-tensioning systems, including strands, anchorages ducts, duct couplers, and grout. New construction methods include improved grouting procedures developed by the Post-Tensioning Institute[1,2] (PTI) and taught at PTI and American Segmental Bridge Institute (ASBI) certification programs and workshops.

However, not all of these materials and methods have been evaluated adequately for their effectiveness. While techniques used in construction procedures and material selection can limit corrosive action and increase durability of the system, weak links do exist. Concrete permeability and cracking can lead to aggressive exposure to corrosive agents early in a bridge's design life and reduce the effect of cover. One of the major problems that agencies face today is the difficulty of providing good monitoring and inspection techniques for bonded post-tensioned structures. Condition surveys are often limited to visual inspections for signs of cracking, spalling, and surface rust staining. This limited technique can often overlook the deterioration of prestressing steel and thus fail to detect the potential for very severe and sudden collapses.

1.2 Corrosion and Durability of Post-Tensioned Concrete

Corrosion problems are a significant source of increased repair cost and can shorten the useful life of a structure[3,4]. The concrete bridge structures that typically corrode the most frequently are in aggressive environments where they are subjected to either tidal spray or deicing salts. Cracks allow early penetration of these agents. Once their concentration is high enough around the reinforcement, corrosion can initiate. (Another TxDOT report, 0-4562-3, provides a more detailed explanation[5] of the corrosion electrochemistry and its effect on prestressing strands, offering additional context to this report.)

Corrosion becomes an issue when chlorides are able to penetrate the concrete and initiate corrosion of the post-tensioning system. Grouting has been thought to be a significant corrosion barrier. However, the grouts are not post-tensioned and have been shown to crack in the ducts, as discussed throughout TxDOT project 0-1405[6], the precursor to project 0-4562. Concerns about chloride content within the grout itself were addressed within project 0-1405, resulting in updated testing procedures for future projects. The previous project focused on corrosion in a more general sense. Project 0-4562 evaluated the current state of the industry, including newly manufactured and possible future products and systems, and focused more on specific variables.

1.3 Project Objective

This project began in 2003 and was conducted at the Ferguson Structural Engineering Laboratory under sponsorship of TxDOT and the FHWA. After the completion of 0-1405, new products from industry manufacturers became available. A new set of specimens was required for highly aggressive exposures to consider the performance of these new products, which include flow-filled epoxy strand, electrically isolated tendons, and new duct couplers. Full details of the previous series of specimens are available in the Project 0-1405 reports online at no cost from the Center for Transportation Research[19]. Using the recommendations from 0-1405 and associated research, the development and design of the new specimens by Ahern[21] considered the more specific variables and ways to better isolate them. Epoxy-coated, non-prestressed reinforcement was used to eliminate expansive stresses due to reinforcement corrosion within these new specimens. Corrosion of uncoated bars had resulted in significant damage in previous projects.

The current project used a series of specimens with galvanized ducts as a control set to compare the efficiency of different plastic ducts. Please note that the continued use of galvanized duct is not encouraged in aggressive corrosive environments. In the study of the four-year autopsies, McCool concluded the galvanized ducts performed poorly, with substantial pitting and area loss, as anticipated. These were used as control specimens, as stated, and further analysis was not the intention. The plastic ducts were intact but elevated grout chloride levels indicated that moisture penetration into the ducts at couplers and vents was a major concern. Despite this, strand corrosion was minor and mostly uniform along the length. This result suggested that chlorides traveled along strand interstices. Among the samples, the stainless steel strands were nearly corrosion-free. The pourback quality was found to protect anchorages more than galvanization of bearing plates. To this extent, the workmanship was most important and is now considered within the PTI procedures for grouting. Finally, the electrically isolated tendon did not completely prevent chloride penetration and subsequent strand corrosion. The system did result in lower chloride concentrations along the tendon than the conventional systems.

The six-year autopsies conducted by Moyer had results in line with those of McCool with some differences, as expected over the longer exposure period. Damage to the galvanized ducts was consistent with the early damage over four years. The plastic duct also showed some limited damage. As with the four-year pattern, grout in both galvanized and plastic ducts was high in chloride content but the strands still showed only minor corrosion. One strand did present a significant area of mild pitting that occurred due to a hole in the duct at that location. Backfill quality was good but it did not bond well with the base concrete, allowing moisture and chlorides to enter through the anchorage region. The efficacy of the electrically isolated tendon noticeably decreased. The grout chloride content and corrosion damage was on the same level as that found in the more conventionally protected specimens.

Chapter 2. Test Specimens

The protection strategies implemented within the test specimens are intended to offer different options in providing adequate protection levels (PL). While the Post-Tensioning Institute (PTI) mentions no explicit categories, fib Bulletin 33 provides three separate PLs as shown in Table 2.1[8]. The basis of the corrosion protection at its core is that the provided level should be greater than the environmental aggression or attack levels to which the structure will likely be subjected. Also taken into account is the level of importance of the structure that is being considered. The basic protection, PL1, involves a duct with filling material capable of providing durable corrosion protection. This would include galvanized duct grouted using proper procedures as specified by PTI[1,2] with cement grouts. The table shows that high levels of in-place structural protection, such as adequate concrete cover and waterproofing membranes, coupled with basic PL1 protection are adequate for very low aggresivity exposure levels.

Further levels of protection increase those of the PL1. The PL2 requirements include all of those in PL1 with additional consideration for an envelope, enclosing the tensile element bundle over the full length, and a permanent leak-tight barrier. This would be associated with plastic duct and proper testing procedures given by PTI[1,2] to ensure the system is adequately leak-tight, such as pressure testing. These additional levels of protection are required when the in-place structural system does not include all of the design details that can limit corrosion issues or when increased aggresivity of exposure (i.e., moderate salt water or deicing salts) are present.

The most stringent level of protection, PL3, includes all components of PL1 and PL2 while adding requirements for monitorability and inspection of the structure or specimen. This includes electrically isolated tendons (EIT) that are included in Project 0-4562. At this time, these systems are rarely used in U.S. bridges so their reliability has not been extensively verified. All three levels of protection were implemented in the current testing process, although each specimen was subjected to the same highly aggressive environments. It is also important to note that pressure testing was not performed in construction of the test specimens as is now recommended by PTI[1,2].

Table 2.1 – Protection Levels for Post-Tensioning Tendons Based on Aggressivity/Exposure[8]

		In-Place Structural Protection Layers		
		High	Medium	Low
Aggressivity / Exposure	High			PL3
	Medium		PL2	
	Low	PL1		

Low corrosion exposure or aggressivity is highly uncommon in post-tensioned bridges. Only interior exposures in buildings could qualify. For TxDOT and the FHWA, this level of exposure is not considered applicable. For coastal and deicing locations, the aggressivity of chloride exposure is considered medium or high, indicating a serious concern with integrity. For both conditions, the fib specifications classify cyclical wetting as the most susceptible to corrosion.

2.1 New Specimen Concept

The previous specimens used in Project 0-1405 were very large, used a lot of material, and required reaction beams. The new test specimens were designed for compactness, controlled cracking, isolation of the corrosion of the post-tensioning elements, and the ability to produce results on an accelerated schedule. The comparison between the two is visible in Figure 2.1. The older specimens in the background appear twice as large as the newer specimens in the foreground. The older specimens also require the beams resting below them to yield just one specimen available for autopsy. Both McCool[3] and Moyer[4] reviewed the design and demonstrated that the new specimens don't need reaction beam because they are self-equilibrating. These new specimens use less material and more samples can be therefore cast with the same amount of raw material. The quantities of post-tensioning elements in the exposure zones are similar. This means that these specimens were expected to yield similar results to the specimens in 0-1405 but use 1/8th the material. The design process presented by Ahern[20] is intended to allow for comparison between the first series of specimens and the new ones. Since the original fabrication of the new specimens, improved PTI standards for ducts and grouting were developed. Unfortunately these procedures came too late to be used in these specimens. Further testing performed using the smaller specimens should follow the new procedures and should consider PTI procedures when comparing different sets of results.

Figure 2.1 – New Test Specimen Compared to Old Specimens

2.2 Specimen Description

In a major change from 0-1405, epoxy-coated, non-prestressed reinforcing bars were used to reduce corrosion induced surface cracking and performed very well. There was little to no corrosion issues with them and secondary cracking was greatly reduced. This meant that exposure of strands and ducts was more uniform across the 0-4562 strands than that of the 0-1405 strands. The new specimen with its epoxy-coated reinforcement had only small amounts of corrosion even after the full six years. The only areas of bar corrosion were those that could have been damaged in the handling process, such as locations of bends and any place that the reinforcement was tied together. The equipment used at the dead and live ends to apply the external force is shown in Figure 2.2.

Figure 2.2 – Live End (right) and Dead End (left) Stressing Assembly

The only reoccurring or systematic issue found with the new specimens has been with their eventual unloading. Future testing should use *epoxy-coated* Dywidag bar to induce flexural load. This would allow them to be adjusted periodically to maintain the load and easily unloaded at the end of the exposure period. McCool's attempt to unload the specimens showed the Dywidag bar had corroded and required a torch to cut the bar[4]. Lubricant was applied to the corroded hardware but this step did not yield any benefits. The unloading was therefore very sudden and extra precautions had to be taken. A large concrete block was placed at the live end of each bar to prevent any explosive action from occurring. After the six-year exposure Moyer[4] followed the same procedure as McCool and did not even attempt to unload by using the Dywidag hardware. The specimens, however, showed no damage from this process. A full plan and elevation of the new specimens is shown in Figure 2.3, identifying the locations of each section of the new specimens and the self-equilibrating external force.

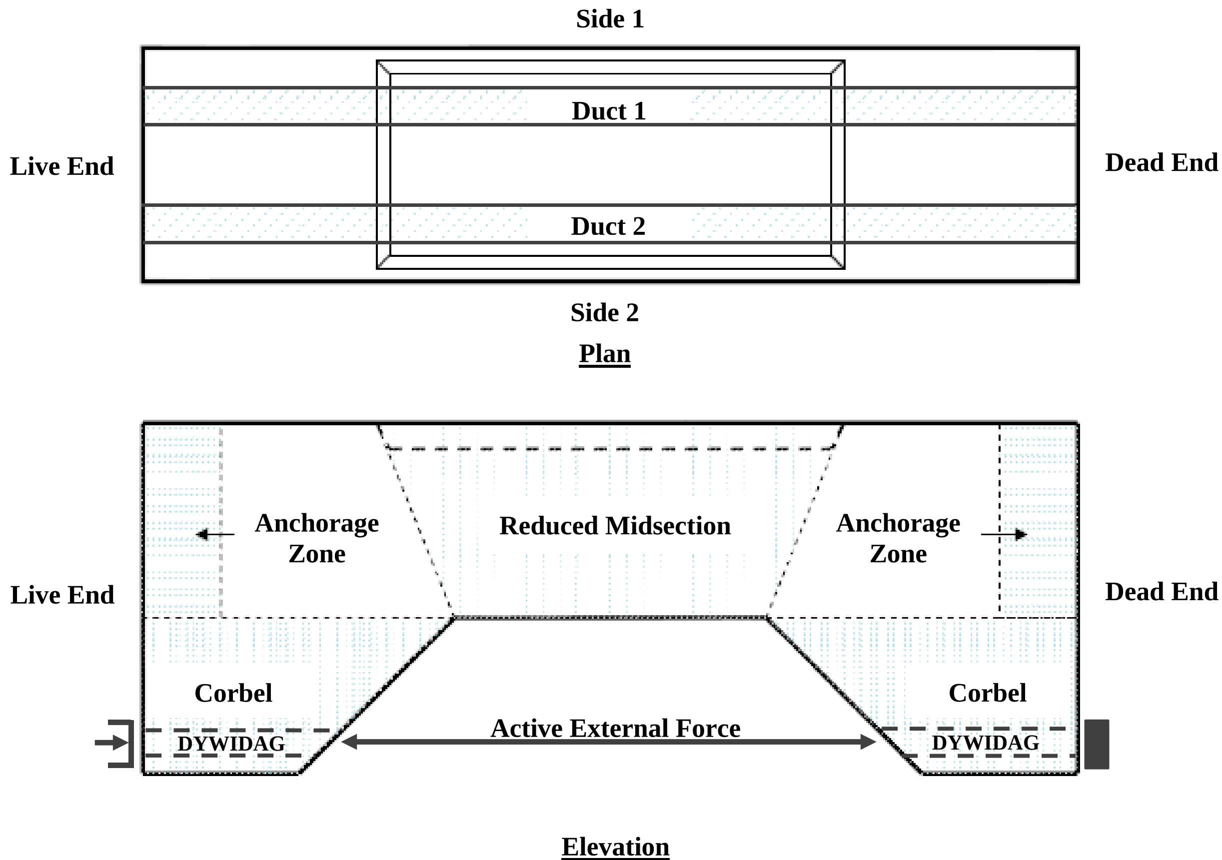


Figure 2.3 – Plan and Elevation of New Specimen with Self-Equilibrating Force Shown

The dimensions of the main autopsy region were chosen to be comparable to the ones used by Salas[7] and Turco[22] in the autopsies of TxDOT Project 0-1405 specimens. The new specimen is shown in Figure 2.4 with the full dimensions. Only the total length of the main autopsy region below the ponding region was shortened by 30 inches due to the new specimens' shorter overall length. No major downsides to shorter specimens are apparent. The results have shown that there is enough of a variation in chloride content and corrosion along the specimen. This shows how chlorides from the ponded area penetrated and traveled within the specimen as intended.

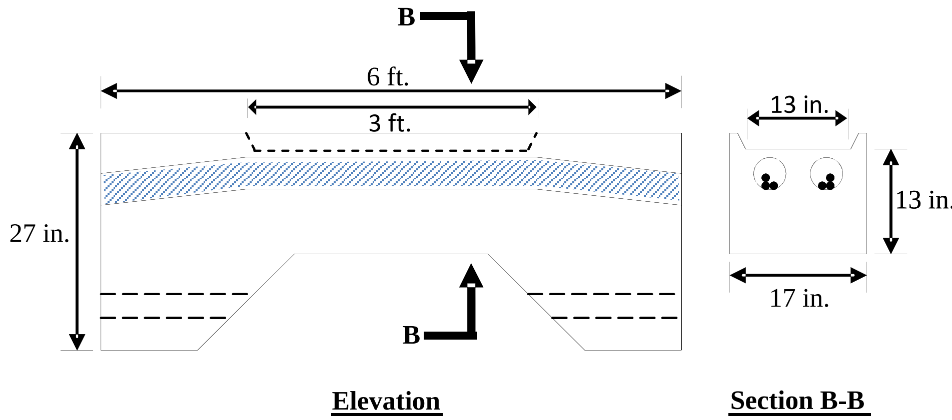


Figure 2.4 – Elevation and Cross Section of New Specimen

2.3 Variables

Previous work by West[11], Schokker[25], Salas[7], and Turco[22] on Project 0-1405 determined that contemporary industry standards for internal bonded post-tensioned construction were inadequate. Project 0-4562 was conceived as a means of examining the corrosion performance of new and upcoming materials and systems that might result in better corrosion protection of post-tensioning tendons[23]. A conference with members of industry and academia was held at FSEL in 2003 to identify which new post-tensioning materials to study. Although some of the materials were unavailable in the United States, a specimen matrix was developed that included several types of new and upcoming post-tensioning components.

The number of specimens produced was a function of the variables that were tested. Some specimens were autopsied early to get useful information for implementation. The dual tendons in each specimen allowed both coupled and non-coupled ducts to be tests. The couplers could be directly compared as all other variables for each specimen remain the same. Specific variables included were either different ducts or different tendons. These were mixed and matched and their combinations are shown in Table 2.2.

Table 2.2 – Table of Specimen Variables

Duct	Prestressed – Strand Type						Non-Prestressed
	Conventional	Hot-Dip Galvanized	Copper-clad	Stainless-clad	Stainless	Flow-Filled	Conventional Rebar
Galvanized	G – 1.4 NG – 1.1 G – T.2 NG – T.1	NG – 2.2	NG – 1.2	NG – 1.3	NG – 4.1		
One-Way Ribbed Plastic	NG – 2.3	NG – 3.4	NG – 2.4		NG – 4.2		
Two-Way Ribbed Plastic	G – 5.1* NG – 3.1*	NG – 3.2*	NG – 3.3*	NG – 5.2*	NG – 5.3*		
Fully Encapsulated	NG – 7.1* NG – 7.2*	NG – 7.3*				NG – 7.4*	
None							Black – 4.4 Epoxy – 4.3

G = Galvanized Bearing Plate, NG = Non-Galvanized Bearing Plate

= Autopsy performed in March 2010

= Autopsy performed in March 2012

* = Dead end anchorage exposure

NOTE: For each specimen with plastic ducts one duct was coupled and the other was continuous

2.3.1 Strand Type

Six types of strand were used to construct the test specimens:

- Conventional (see Figure 2.5)

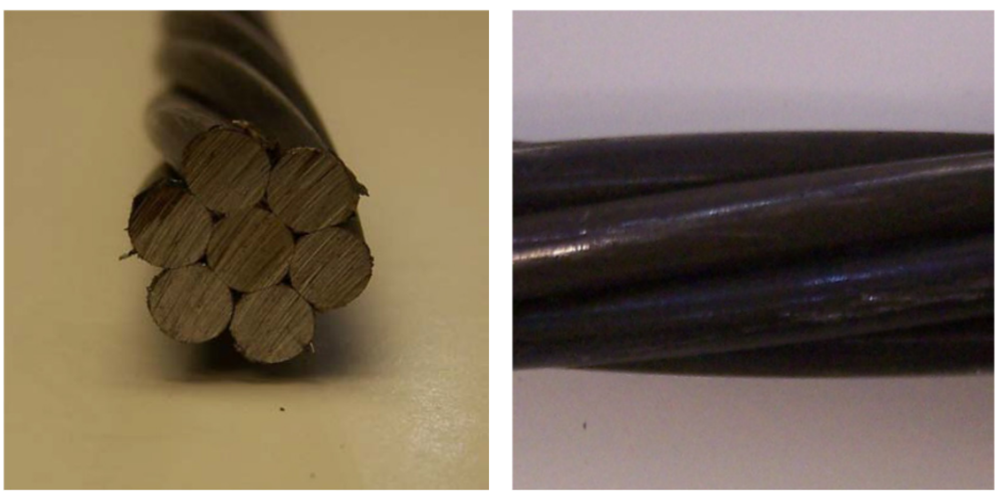


Figure 2.5 – Conventional Strand Cross Section and Exterior

- Hot-dip galvanized (see Figure 2.6)

Figure 2.6 – Hot-Dip Galvanized Strand Cross Section and Exterior

- Stainless steel (see Figure 2.7)

Figure 2.7 – Stainless Steel Strand Cross Section and Exterior

- Copper-clad (see Figure 2.8)

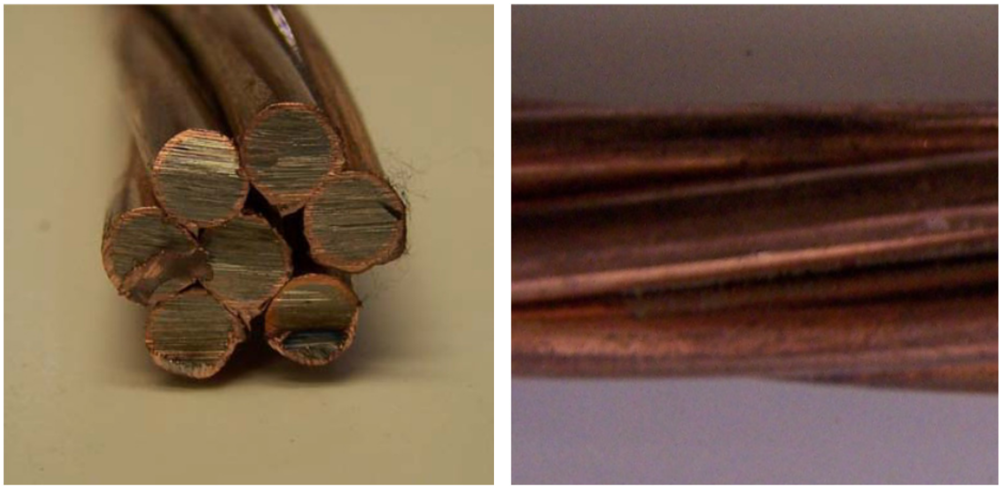


Figure 2.8 – Copper-Clad Strand Cross Section and Exterior

- Stainless-clad (see Figure 2.9)

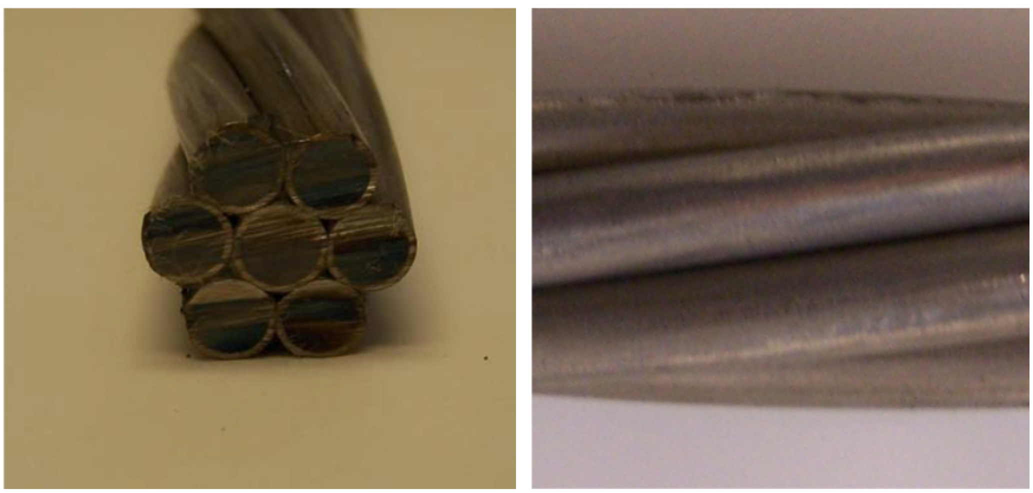


Figure 2.9 – Stainless-Clad Strand Cross Section and Exterior

- Flow-filled epoxy-coated (see Figure 2.10)

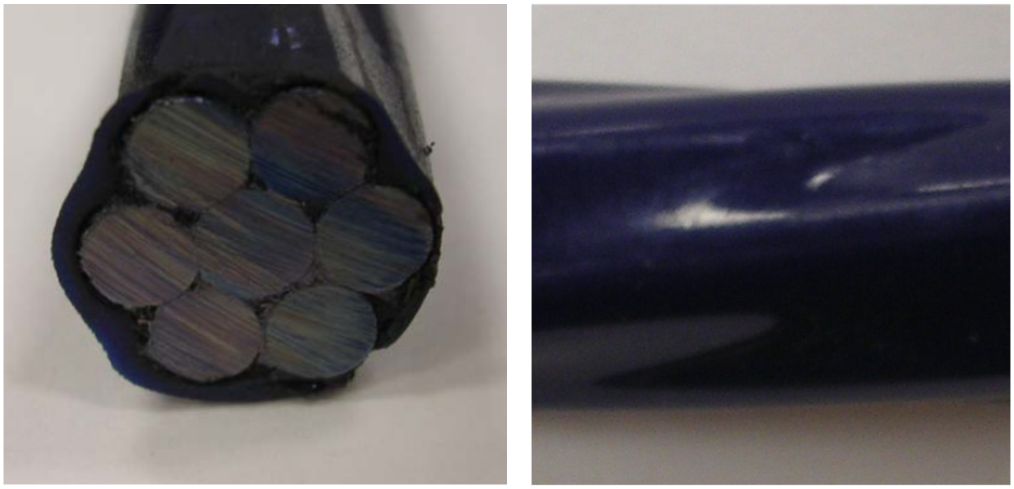


Figure 2.10 – Flow-Filled Epoxy-Coated Strand Cross Section and Exterior

All strands were 0.5-inch seven-wire except for the stainless steel and stainless clad, which were 0.6-inch diameter. Special anchor heads were obtained to accommodate the larger strand size. Special wedges were used with the epoxy-coated strand to ensure good seating during stressing. The galvanized strand was galvanized after being wound, which means that much of its interstitial space is bare steel.

2.3.2 Duct Type

Several types of duct were used in the test specimens:

- Galvanized steel (see Figure 2.11)

Figure 2.11 – Galvanized Steel Duct

- GTI plastic 76 mm one-way (left) and 85 mm two-way (right) (see Figure 2.12)

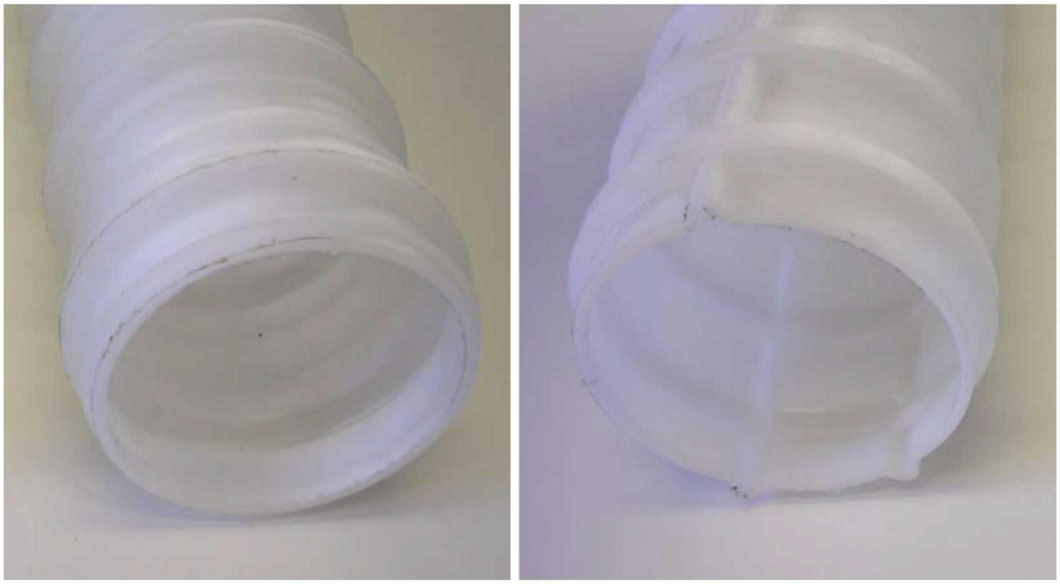


Figure 2.12 – GTI Plastic Duct One-Way (left) and Two-Way (right)

- VSL one-way plastic (see Figure 2.13)

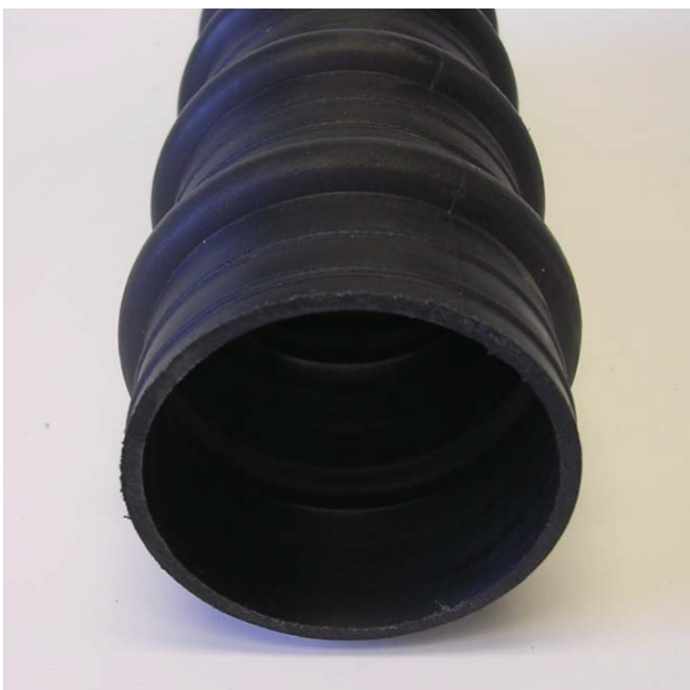


Figure 2.13 – VSL One-Way Plastic Duct

Each type of duct had a different diameter. For each type of plastic duct, the diameter was chosen based on the smallest available coupler style for that duct.

2.3.3 Coupler Type

Because the specimens of Project 0-1405 had shown that coupling methods for galvanized ducts are quite inferior, the research team decided to use continuous galvanized ducts in all specimens. For one tendon per specimen with plastic ducts, the ducts were cut in half. A coupler was placed at midspan to connect the halves. Three different types of coupler were used, each corresponding to one type of plastic duct:

- GTI slip-on 76mm (left) and 85mm (right) (see Figure 2.14)

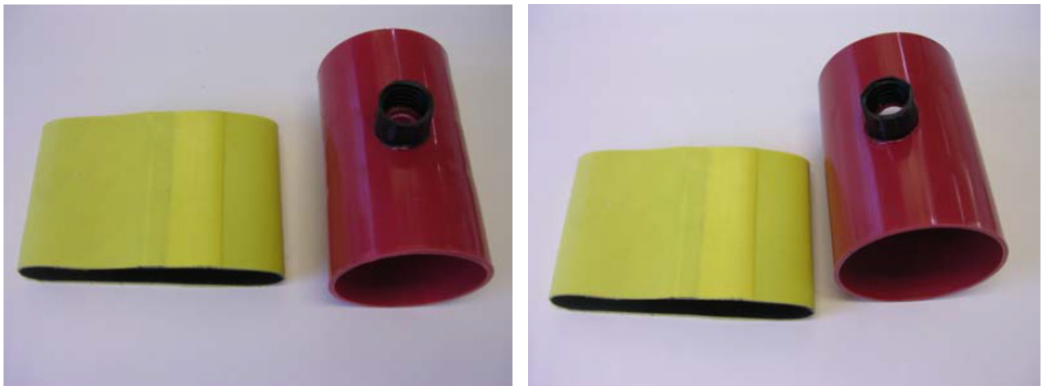


Figure 2.14 – GTI Slip-On Couplers 76 mm (left) and 85 mm (right)

- GTI snap-on (GTI one-way) (see Figure 2.15)

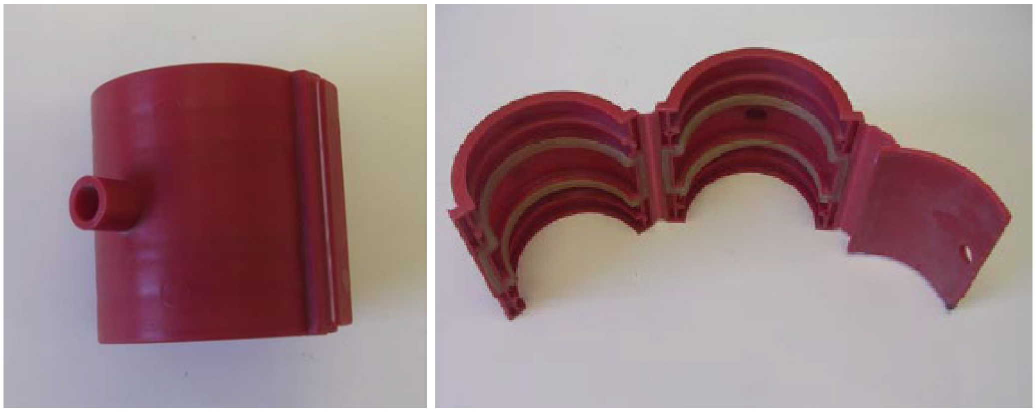


Figure 2.15 – GTI Snap-On Coupler

- VSL snap-on (VSL one-way) (see Figure 2.16)

Figure 2.16 – VSL Snap-On Coupler

The GTI two-way duct allows only a slip-on coupler due to the longitudinal ribs. The slip-on couplers were sealed against the duct with heat-shrink sleeves. The VSL one-way duct did not have grout vents pre-installed at the time of casting so the project team had to fabricate vents. The VSL one-way couplers also had heat-shrink sleeves installed.

2.3.4 Anchorage Type

Due to availability issues, the original anchor head, VSL E5-3, was not used. Instead, a VSL E5-7 anchor head was used. The VSL E5-7 is a seven-strand anchor head while VSL E5-3 is a three-strand bearing plate. Therefore, the four unused holes had to be filled with epoxy. The encapsulated tendons did not use this type of anchor head. Both hot-dip galvanized and non-galvanized versions of the anchorage plate (as seen in Figure 2.17) were used.

Figure 2.17 – Non-Galvanized Anchorage (left) and Hot-Dip Galvanized Anchorage (right)

2.3.5 Fully Encapsulated System

The encapsulated specimens were constructed such that the tendon is electrically isolated from the remainder of the specimen. This is achieved using special anchorages, an isolating insert between the bearing plate and anchor head, and robust, watertight connections between the plastic duct and the plastic bearing plate trumpet. A permanent grout cap was installed over the anchor heads to further protect the tendons. See Figure 2.18[21] for an example detail of an EIT system from fib Commission 5 (2004). The materials for the EIT specimens provided by VSL Switzerland are shown in Figure 2.19 and Figure 2.20.

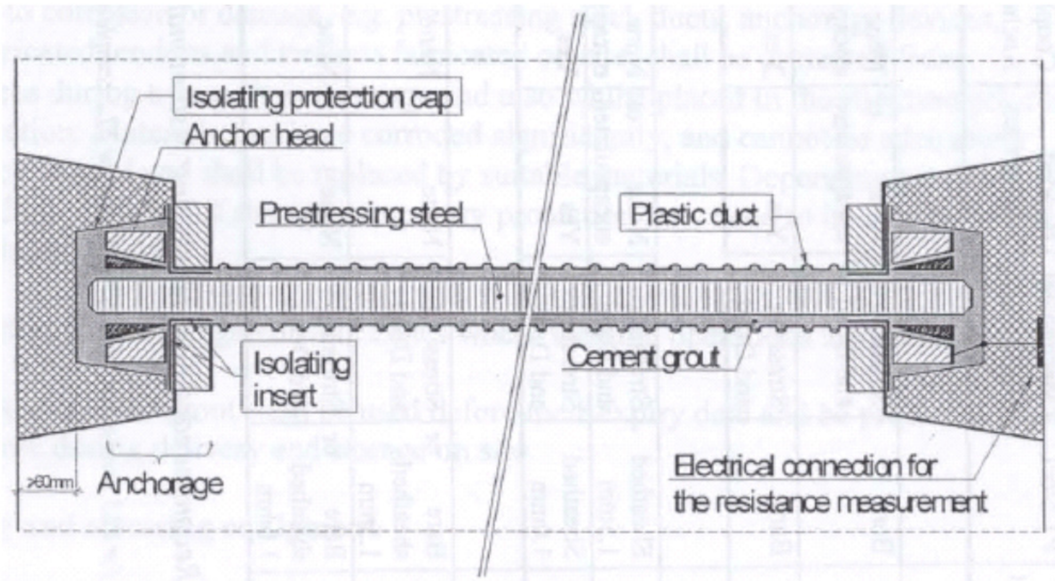


Figure 2.18 – Schematic of Electrically Isolated Tendon[21]

Figure 2.19 – EIT Anchorage

Figure 2.20 – Electrically Isolating Bearing Pad and Anchor Head

2.4 Construction

All specimens were fabricated at FSEL by Ahern[20] and a detailed description of the process is found in his thesis. A more basic procedure is given by both McCool[3] and Moyer[4] as adapted from Ahern's work. TxDOT procedures were followed throughout the fabrication process. This only really came into effect with the use of Class C concrete as well as the requirement that grouting was completed within 48 hours of stressing. Since the fabrication of the specimens, the PTI has come out with new grouting procedures in the guide specifications[1,2] that were not available at the time of grouting of these specimens. Pressure testing of the ducts should be implemented going forward to check couplers and connections. The new PTI *Guide Specification for Grouted Post-Tensioning* states "duct and duct connections installed and cast into concrete prior to prestressing steel installation shall be capable of withstanding 10 ft of concrete fluid pressure."[1] Additionally, air-pressure testing shall be used to locate any potential grout leaks. It is important to note that the air-pressure test shall not be used to assess the air tightness of the system but rather just to see if there are leaks.[2] These two new procedures are excellent ideas and should be fully utilized in any new post-tensioned construction.

During fabrication, epoxy-coated ties were used in place of conventional ties in order to reduce the damage to the epoxy coating of the bars. A small amount of such damage ultimately did occur at some of these locations. Additionally, chairs used to maintain proper cover were plastic. To create the desired crack width of 0.010 inches, a guaranteed ultimate tensile strength of 15% was used. The ability for the new specimens to be easily monitored and have the live loading adjusted demonstrates the success of Ahern's design for the initial procedures. The assembled forms are shown in Figure 2.21 just prior to casting specimens.

Figure 2.21 – Specimen Reinforcement Cage Prior to Concrete Placement

Chapter 3. Companion Testing

Strand samples were tested on their own to evaluate tensile capacity and corrosion resistance. This provided a baseline to judge the ongoing non-destructive testing as well as final autopsies. These tests also helped to identify what problems may have occurred during the construction process. Cracked and uncracked grouts were included to ensure both scenarios were accounted for.

3.1 Tension Mechanical Testing

A new apparatus, seen in Figure 3.1 was used to prepare specimens for tensile capacity testing of coated strand. Distributed loading was important and needed to make sure that the end failures weren't occurring which had previously been an issue.

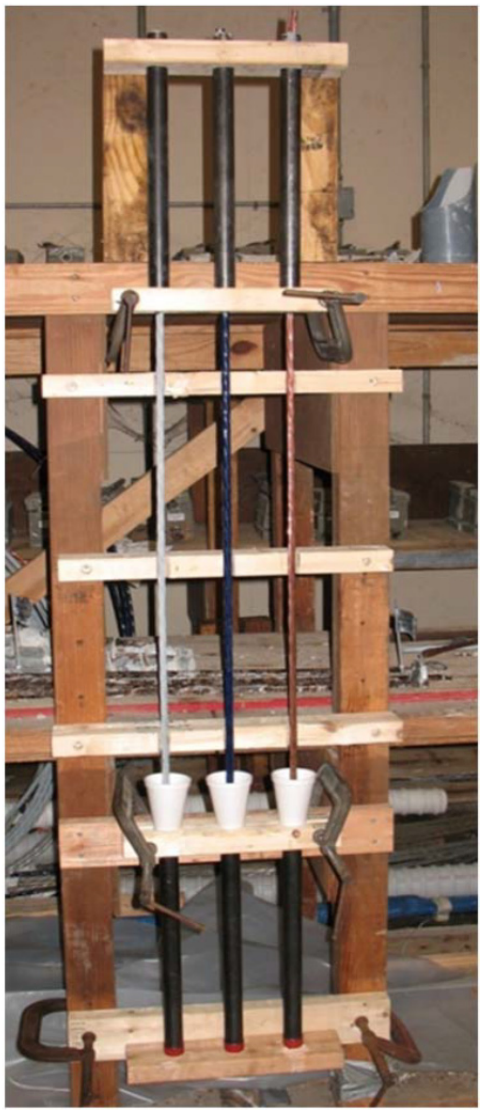


Figure 3.1 – Companion Testing Set Up

A full testing methodology was established by Mac Lean[5] in 4562-3 that was easy to repeat and "universal" or easily used for the different types of strands. An abridged explanation of the preparation and loading procedure is included in Moyer's thesis[4]. Of the three strands tested, one was taken to failure to get a better understanding of behavior and to compare to the ASTM standards. Table 3.1 presents the full testing results.

Table 3.1 – Mechanical Properties of Strand Types

	Yield Strength					Ultimate Strength		
Strand Type	**Nominal Diameter (in.)**	**Area (in.^{2})**	**Yield Strength (kips)**	**Met Gr. 250 Requirement**	**Met Gr. 270 Requirement**	**Breaking Strength (kips)**	**Met Gr. 250 Requirement**	**Met Gr. 270 Requirement**
Conventional	0.6	0.217	56.1	Yes	Yes	61.5	Yes	Yes
Conventional	0.5	0.153	37.3	Yes	Yes	43.0	Yes	Yes
Epoxy-Coated	0.5	0.153	37.8	Yes	Yes	43.7	Yes	Yes
Hot-Dip Galvanized	0.5	0.153	34.5	Yes	No	40.9	Yes	No
Copper-clad (Nominal Area)	0.5	0.144	22.3	No	No	25.9	No	No
Copper-Clad (Steel Area)	0.438	0.108	22.3	No	No	25.9	No	No
Stainless-Clad (Nominal Area)	0.6	0.217	50.6	Yes	No	57.5	Yes	No
Stainless-Clad (Steel Area)	0.5	0.153	50.6	Yes	Yes	57.5	Yes	Yes
Stainless Steel	0.6	0.217	39.8	No	No	48.9	No	No

These results are from Kalina[5]. While quite a number of the improved corrosion resistant strands did not meet tensile test requirements, manufacturers stated that they could produce strand that would pass the ASTM standards given substantial demand. In the end, this set of testing does not represent the strand that would likely be used in a project except for those marked *Yes* in Table 3.1 that are readily available and would not need special consideration.

3.2 Active Corrosion Testing

The series of tests were carried out with the strands encased in grout to simulate the conditions that the strands might experience in the field. To further consider field conditions, a prepackaged grout was used. Potentiostatic accelerated corrosion testing for different strands was ruled out by Kalina and Mac Lean[5]. Linear polarization resistance (LPR) corrosion testing and potentiodynamic testing was used instead to provide better results. Their report details why these monitoring techniques were used. Since polarization resistance and time to corrosion are related, the values for each strand type obtained from the LPR testing were used to obtain a comparative time to corrosion. These tests were done on both cracked and uncracked grout. The cracked specimen was created using a pre-cracking device that induced damage only in the grout encasement and not the strand itself.

3.2.1 Uncracked Grout

Ten potentiodynamic tests and 10 LPR tests were performed on each of the six strand types. To ensure the epoxy-coated strand would yield results, the epoxy coating was intentionally damaged with a chuck. Without small breaches in the epoxy the strand results would not have been measureable or on the same order of magnitude as the other strand types. The comparative results of the polarization resistance values show that, even with induced damage, the epoxy-coated strand performed the best, as expected, and the conventional strand performed the worst. Figure 3.2 shows the polarization resistance normalized to conventional strand. The epoxy strand is nearly 10 times more resistant than the next closest strand and over 90 times more resistant than the conventional strand.

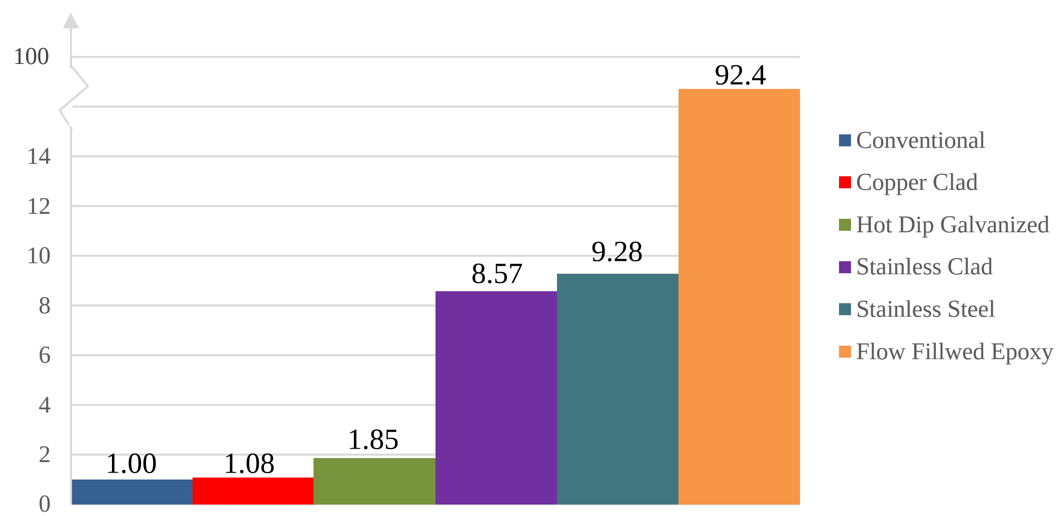


Figure 3.2 – Time to Corrosion for Uncracked Grouted Companion Tests

3.2.2 Cracked Grout

Three potentiodynamic tests and three LPR tests were performed on each strand type. Unlike Mac Lean's[5] flow-filled epoxy-coated specimens, Kalina's[5] flow-filled epoxy-coated specimens were not intentionally damaged and are not included in the results below. Based on the strand properties, the hot-dip galvanized strand had the most active corrosion potential and the stainless steel had the most noble corrosion potential. According to the comparative results of the polarization resistance values, the stainless-clad strand performed the best while the hot-dip galvanized strand surprisingly performed the worst, even below the conventional strand. As with the uncracked strand, the results in Figure 3.3 are normalized to conventional strand.

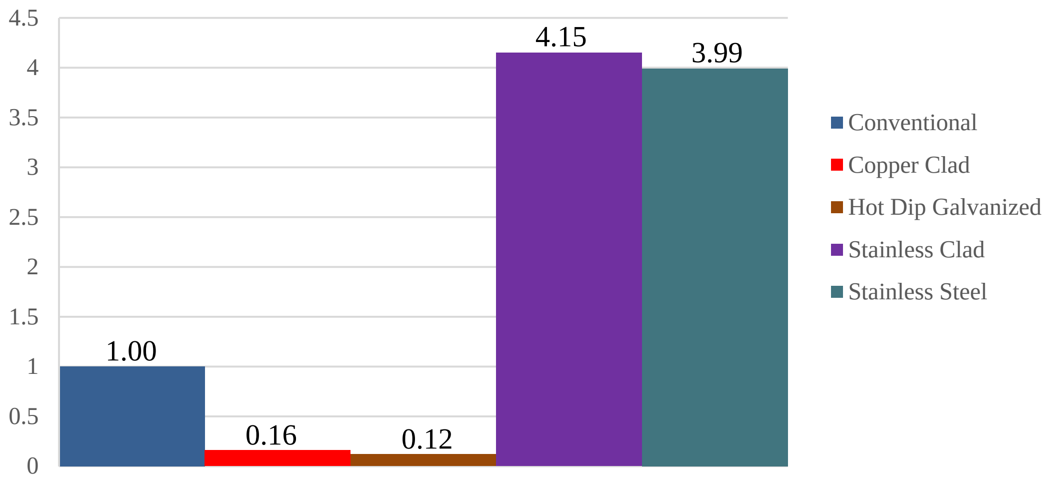


Figure 3.3 – Time to Corrosion for Cracked Grouted Companion Tests

3.3 Passive Corrosion Testing

The passivity tests depended on recording the electrical impulses rather than applying an impulse as is performed in the active corrosion testing. Like the active corrosion testing, two series of tests were performed. These series compared ungrouted strand to fully grouted strands and are reported in CTR Report 4562-3[5]. The first method exposes the strands to wet and dry cycles while the second set of specimens were immersed in a chloride solution and monitored over several months.

3.3.1 Exposed Strand

Corrosion was calculated by comparing the weights of the strand before and after exposure. Results were unsurprising and are given in Table 3.2. All the results are normalized to the epoxy-coated strand, which performed the best. Any result of 1.00 indicates a corrosion rating equal to that of the epoxy-coated strand while a rating of 2.00 is twice as bad, 3.00 is three times worse, and so on. Both the weight loss and the visual inspection rating are included in the calculation of corrosion rating. Table 3.3 includes ratings over time to show the increased corrosion of conventional strand and to show the rates of all the strands. The results of the more qualitative corrosion rating and the more quantitative weight loss are normalized to the epoxy-coated strand as it performed the best in both metrics.

Table 3.2 – Companion Test Results for Each Strand

	Epoxy-Coated	Stainless-clad	Stainless Steel	Galvanized	Copper-clad	Conventional
	EC	SC	SS	GV	CC	CN
Avg. 6 Month Rating	1.50	1.50	1.70	2.00	3.00	7.00
vs. EC	1.00	1.00	1.13	1.33	2.00	4.67
Avg. Weight Loss	0.60	1.07	1.10	2.03	1.03	10.13
vs. EC	1.00	1.78	1.83	3.39	1.72	16.89

3.3.2 Grouted Strand

Rather than connecting the strand to an electrode as in the active corrosion tests, the ends of the strand were encased in epoxy and a small copper wire was attached to one end in order to take readings. After curing, the specimens were immersed in a chloride solution. Initially, one month of exposure before data collection was necessary to develop constant corrosion potential. This caused some error, however, as the potential became more noble instead of more active. The baseline was therefore changed to one week instead of one month. From the results of the grouted strand test, the specimen that performed the best is the stainless-clad strand. The corrosion potential is a measure of the corrosion tendency of the material with a smaller corrosion potential representing more noble behavior. Therefore, Table 3.3 indicates that the best strand type is the stainless-clad strand and the worst is the hot-dip galvanized.

Table 3.3 – Companion Test Results for Grouted Strands

	Conventional	Copper-clad	Galvanized	Stainless-clad	Stainless Steel
E_{corr} (mV_{SCE})	-875	-370	-1025	-360	-475

3.4 Strand Recommendations

The overall rankings in Table 3.4 present the final order of strand types in terms of corrosion resistance. As was expected, epoxy-coated strands performed the best and conventional strands the worst. The next cluster present in all the trends is the stainless-clad and stainless steel strands, with stainless-clad performing better than stainless steel. The final cluster of copper-clad and hot-dip galvanized was also paired together throughout the trends with copper-clad performing better.

Table 3.4 – Strand Rankings Based on Corrosion Resistance

Test	Best 1	2	3	4	5	Worst 6
Half-Cells	SS	SC	CC	GV	CN	N/A
Accelerated (Normal)	EC	SS	SC	GV	CC	CN
Accelerated (Pre-Cracked)	EC	SC	SS	CN	CC	GV
Exposed Strand	EC	SC	SS	CC	GV	CN
Grouted Strand	SC	CC	SS	CN	GV	N/A
Overall	EC	SC	SS	CC	GV	CN
SS = Stainless Steel; SC = Stainless-Clad; CC = Copper-Clad; GV = Galvanized; EC = Epoxy-Coated; CN = Conventional						

When combining the rankings based on corrosion resistance with the values of ultimate strength, the overall rankings are not the same, as some of the strands are not able to meet the required mechanical properties. This refers to the stainless steel and copper-clad strands, which perform well in corrosion resistance but not in mechanical strength. If Grade 270 requirements are needed, then the only two strands available are the conventional and the epoxy-coated strand. In this case, the epoxy-coated strand is the obvious choice for corrosion resistance. If Grade 250 requirements are needed, then the stainless-clad and hot-dip galvanized strand can also be considered. Again, the epoxy-coated strand is the first choice followed by stainless-clad, then hot-dip galvanized, and finally conventional strand. Therefore, based on all the tests including the mechanical tests, clearly the epoxy-coated strand outperforms the others in corrosion resistance and is the best choice for long life in very aggressive environments in the post-tensioned application. Relative cost comparisons are not considered here but are included in Chapter 4. .

After the autopsies were performed, tests performed outside of FSEL indicated that some commercially available grout products contained elevated chloride content. Unfortunately no chloride tests were performed beforehand on the grouts used in the 0-4562 specimens because the grouts were prepackaged and assumed to have established properties meeting maximum chloride limits. Based on the results from the full-scale specimens, high chloride content in grout samples prior to placement became a concern of both McCool[3] and Moyer[4]. The first couple of non-destructive tests showed that corrosion without exposure was a possibility. Future tests should also consider testing strands while they are stressed. The stressed tendons could potentially have different results in the active and passive corrosion testing. A stressed companion test would better mimic field conditions.

Chapter 4. Experimental Procedure

The project specimens were split into two groups undergoing very aggressive exposure for either four or six years. Variables were selected to provide maximum useful information across these two time schedules as seen in Table 2.1. For both time periods the procedures for monitoring as well as the method for performing the final autopsy were the same. A lapse in monitoring occurred during the first period when personnel were changed so it affected all of the samples equally. The system used to wet the specimens had to be maintained as it began to corrode due to the environment in central Texas. The pump and piping that sprayed the corrosive agent was replaced and/or cleaned. It did not change how the specimens were exposed or treated.

4.1 Long-Term Exposure

Ten of the 24 specimens were autopsied after four years of highly aggressive outdoor exposure in 2010 by McCool[3]. The remaining 14 specimens underwent two additional years of exposure and were autopsied by Moyer[4]. The exposure process consisted of alternating wet and dry exposure periods. The wet exposure period involved pouring salt solution in the ponding area and keeping the salt solution level constant throughout the two week wet exposure period. The dry cycle then consisted of removing the solution and rinsing out the depression before removing any remaining moisture with a sponge. The dry cycle lasted the remainder of the month. The heat in Texas required that these ponding areas were monitored very closely as the chloride content could easily change due to evaporation. In addition, a number of specimens in both the four- and six-year cycle had their dead end anchorage region sprayed with salt solution.

4.2 Monitoring

Throughout the exposure testing period, the specimens underwent non-destructive monitoring. Monitoring was carefully maintained for all but a couple of months during the first period, so both sets of specimens were equally affected. Additionally, some of the procedural specifications regarding the percentage of salt in the wetting solution changed during the long test period in ASTM but the original salt percentage of 3.5% was kept to maintain consistency throughout both exposure time periods[24]. Similar methods were used to monitor the Project 0-4562 as were used to monitor Project 0-1405 specimens. Non-destructive monitoring consisted of visual inspection, half-cell potential measurements, and AC impedance measurements. As a destructive test, chloride penetration readings were only conducted at the end of the exposure period just before autopsies.

4.2.1 Visual Inspection

Periodically during exposure testing, visual examinations were conducted of the specimens. The specimens were checked for spalling, corrosion staining, further or new cracking, and efflorescence on the sides of the specimens. The modified specimens of project 0-4562 used the epoxy-coated nonprestressed reinforcement so the visual checks yielded fewer noticeable external characteristics. Some cracking and staining results could still be seen and show the initiation and propagation phases over the time of the experiment. Visual checks provide good images over time. Representative sample images are included in the report instead of each specimen being shown separately. Complete results for each specimen are given in the

McCool and Moyer theses available online at the FSEL website (http://fsel.engr.utexas.edu/publications/).

4.2.2 Half-Cell Potential

Corrosion is an electrochemical process by which electrons are transferred from an anode to a cathode. Individually, the anodic and cathodic reactions are known as half-cells, and each has its own electrochemical potential. For the corrosion of steel in concrete, the half-cell of interest is the anodic half-cell in which iron is oxidized. This half-cell can be isolated and compared against the potential of a known reference electrode. The difference between the anodic and reference potential is known as the half-cell potential. This can be used to estimate the probability of corrosion and the time to corrosion initiation. ASTM C876 provides the standard methodology for collecting and interpreting half-cell potentials of steel in concrete. The half-cell method is designed for use on uncoated rebar only. However, the method had been implemented on Project 0-1405 with some success, and few other monitoring methods exist for bonded post-tensioning tendons. Therefore, the use of the half-cell method was continued for Project 0-4562 despite the presence of prestressing strand and epoxy-coated rebar.

Measurements were conducted just after the end of the ponding wet cycle each month. This ensured that the pore space of the concrete contained enough moisture to electrically connect the anodic and reference half-cells. The depression on top of each specimen was soaked with a wetting solution consisting of soapy water to better conduct current through the specimen (see Figure 4.1). The tip of the reference electrode was covered with a sponge to serve as a porous medium between electrode and concrete. The saturated calomel electrode (SCE) was used as the reference electrode. Measurements were taken at every point of a regular grid within each specimen's saltwater depression. Each tendon was accounted for separately by measuring three rows of grid points with the voltmeter connected to one tendon wire, then another three while connected to the other. Half-cell potentials were recorded at every point of the grid for every specimen. The separation between north and south tendons was noted in order to obtain data on the effect of the couplers even before the autopsies were performed.

Figure 4.1 – Half-Cell Testing in Ponding Region

4.2.3 AC Impedance

When used properly, the AC impedance method can indicate the presence of defects and chloride intrusion in fully encapsulated tendons. When alternating current is passed from the tendon to the reinforcing steel, the plastic duct acts as a capacitor in parallel with a high resistance. Changes in the resistance and capacitance of this circuit throughout a structure's life can indicate defects in the tendon or chloride intrusion. The tendon in each 7-series specimen (the EIT ones) was designed to be electrically isolated, making this a suitable method to monitor them in addition to the half-cell potential readings.

Each 7-series specimen was constructed with one lead connected to its tendon and another to a pair of additional, uncoated steel longitudinal bars added to increase conductivity. To conduct the AC impedance measurements, a BK Model 885/886 LCR meter was connected to the two leads, as shown in Figure 4.2. Resistance, capacitance, and a loss factor were read from the meter at a frequency of 1 kHz and recorded. This procedure was conducted at the end of each month's ponding wet cycle.

Figure 4.2 – AC Impedance Testing Meter

Due to the odd resistance readings that McCool was getting, McCool contacted Dr. Hans-Rudolf Ganz of the manufacturer VSL International. Dr. Ganz suggested that the readings be taken by one of two methods:

1. Readings taken at the 100 Hz frequency.

2. Connecting a DC voltmeter to the tendon and uncoated steel bars and measuring the voltage, then connecting a DC current source (a battery charger) to the tendon and uncoated steel bars and measuring the voltage and current. The voltage difference was then divided by the current to get the resistance.

Moyer employed both of these methods for six wet/dry cycles and found the readings from method 1 were comparable to method 2, so Moyer continued to take readings using method 1 and discontinued using method 2. Any future testing should adhere to suggestions obtained from VSL.

4.2.4 Chloride Content

Chloride penetration measurements were taken from the concrete and grout of all autopsy specimens after the end of the exposure period. Chloride content was determined for each sample using the CL-2000 Chloride Test System by James Instruments. This system performs a variation of the acid-soluble chloride test procedure outlined in ASTM C115216. Accuracy of the test system was validated by testing a powder sample from 1-inch depth at the top surface of Specimen T.1. Powder from the same depth was sent to the Tourney Consulting Group in Kalamazoo, Michigan, for acid-soluble chloride testing according to ASTM C1152.

Two different chloride tests were administered. First, surface chloride penetration samples were extracted using a hammer drill prior to the full autopsies. At all locations, powder samples were extracted at depths of 0.5 inch and 1 inch from the same hole, taking care to prevent cross-contamination. On each specimen’s top surface, chloride samples were taken at a location 2 inches towards the live end from the beam’s transverse centerline. Samples were also extracted at the dead end anchorage face, 5 inches from the top of the specimen. Additional samples were extracted from the live end anchorage faces of the three dripper specimens at a distance of 6 inches from the top surface. For Specimen 7.1, samples were extracted from both ends at a depth of 6 inches. These locations correspond to the center of the dead and live end anchorage pockets, respectively.

In addition to surface chloride penetration, samples were extracted from the grout in the tendons of the autopsy specimens. Grout powder samples were taken after all post-tensioning elements had been removed from the main autopsy region blocks and the ducts had been cut open. For galvanized ducts, samples were taken every 2 inches along the regions of the ducts with visible external corrosion or area loss. For plastic ducts, one sample was extracted at midspan in each tendon. The samples were extracted using a clean hammer and chisel. Care was taken to obtain a sample that included grout from the entire depth of the tendon. After pieces of grout had been chipped away from the tendon, they were ground with a mortar and pestle. Tests were done on this material.

Chapter 5. Exposure Test Results and Analysis

Results for both the four-year and six-year specimens are presented in this chapter. On March 1, 2006, highly aggressive exposure testing began on all 24 specimens. On March 1, 2010, exposure testing finished for 10 of the specimens, which was 1460 days (four years) of exposure. Autopsy results for these specimens were reported by McCool[3]. On March 1, 2012, exposure testing finished for the remaining specimens, which was 2192 days (six years) of exposure. Autopsy results for these specimens were reported by Moyer[4]. Other than a few gaps in the data due to logistical issues during the six years of exposure testing, readings for the half-cell potentials and the AC impedance generally happened monthly. As mentioned in Chapter 4, concrete and grout samples were removed from the specimens at the ends of the exposure testing periods to test for chloride content. Data comparing the two series of specimens can be used to evaluate the effectiveness of the respective variables as well as the specimen design itself for use in future testing.

This final report will focus on general characteristics and important findings. A highly detailed specimen by specimen break down for the specimens autopsied after four years was given by McCool[3] and a similarly highly detailed specimen by specimen break down for the specimens autopsied after six years was given by Moyer[4]. They are available at no charge on the theses section of the FSEL server. This chapter focuses on the comparison of results from both sets of data, especially for tendons and ducts. It is impossible to directly relate the overall aggressiveness of the six years of exposure testing to real lifetime periods but the research team felt that the nature of the aggressive test environment is representative of multiple decades of intermittent real life exposure.

5.1 Half-Cells

The half-cell potential method used was calibrated for uncoated reinforcing steel. Although half-cell potentials were measured on specimens containing epoxy-coated reinforcing steel and several types of prestressing strand, the method is still useful in indicating the relative extent and severity of corrosion for the test specimens examined here. It should also be noted that the half-cell potential readings could only detect the probability of localized corrosion, not the existence or severity of it. Therefore, readings were taken at multiple points along the specimens. Half-cell values for conventional and flow-filled strands taken from the six-year specimens are shown below in Figure 5.1. The data shows that nearly all of the specimens are at a 90% probability of corrosion within the first 100 days of exposure.

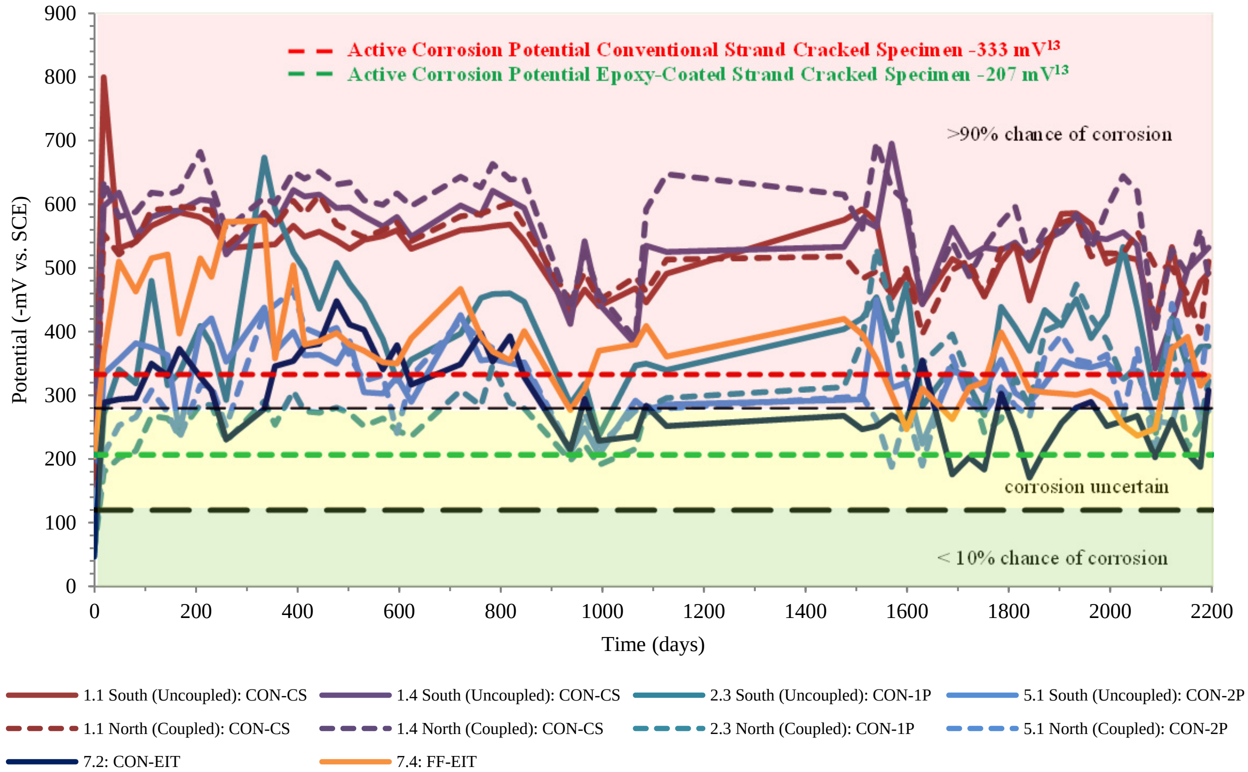


Figure 5.1 – Corrosion Potential For Conventional and Epoxy-Coated Strand

The results from the half-cell potential measurements over the length of the exposure show that regardless of the duct type, the tendons were susceptible to corrosion. Additionally, the results show no discernible difference between north coupled and south uncoupled ducts. While some periods appear to show a noticeable difference between ducts, none of the specimens continue any trend throughout the exposure. While no conclusions can be drawn from the data regarding the couplers, we can conclude that all the specimens are highly susceptible to corrosion, regardless of the materials or system being used. Results from the six-year specimens with stainless-clad and stainless steel strand are shown in Figure 5.2 with results from copper-clad and hot-dip galvanized strand potential over time shown in Figure 5.3.

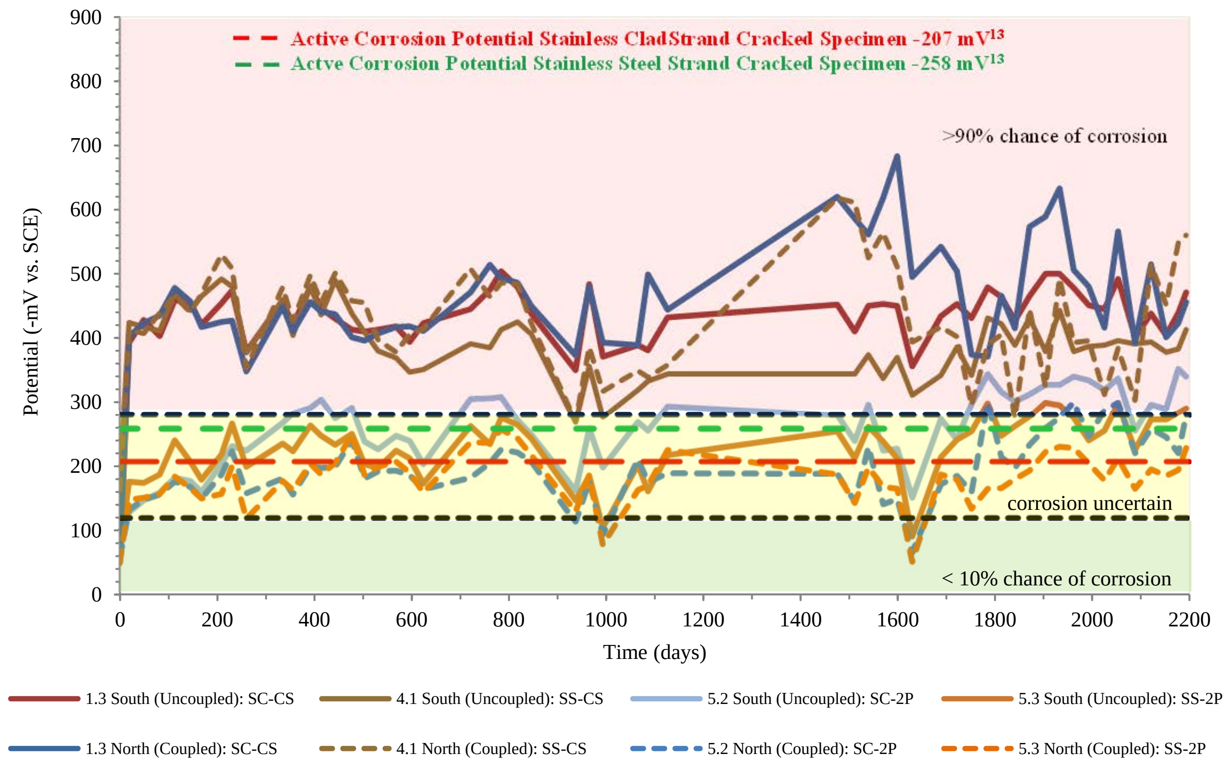


Figure 5.2 – Corrosion Potential for Stainless-Clad and Stainless Steel Strands

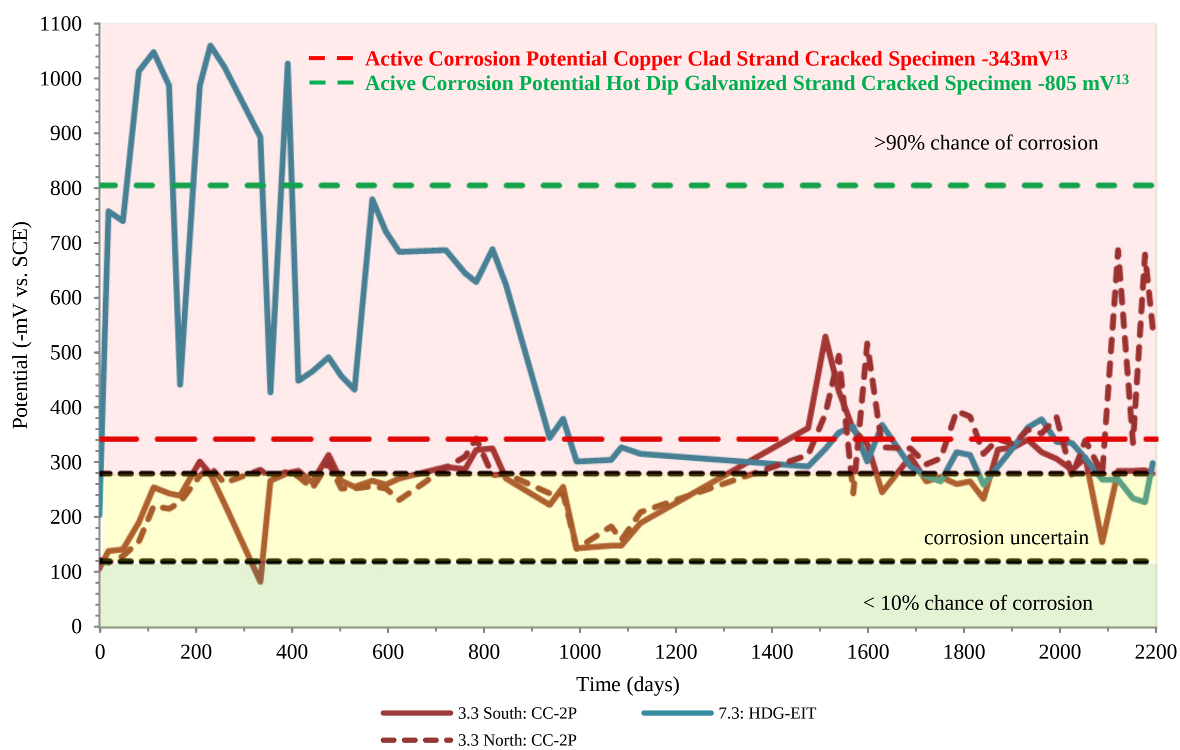


Figure 5.3 – Corrosion Potential for Copper-Clad and Hot-Dip Galvanized Strands

The results from these strands reinforce the conclusions found in the conventional and flow-filled epoxy strand data. After less than 100 days the probability of corrosion is significant in almost all the specimens. The data collected from the six-year specimens show no noticeable change in potential during the two years that separated the two sets of specimen autopsies. Accordingly, the data fails to provide an indication of corrosion initiation and propagation that may occur over a longer exposure period.

Half-cell contour plots are presented in Figure 5.4 for both four- and six-year specimens. These plots represent the final potential readings taken at every point on each specimen just prior to autopsy. Specimens 4.4 and 4.3 did not contain any duct or prestressing tendons and are therefore not included. Note that the contour maps represent an overhead view of the ponding region of the specimens with the live end to the left and the north coupled duct on the top and south uncoupled duct on the bottom. The least negative potentials are shown in blue and green and represent the lowest corrosion potential. The red and purple regions have the most negative potential and are accordingly the most susceptible to corrosion. North and south duct differences were seen in specimens across both exposure durations. However, some specimens such as T.1, 1.2, and 5.2 showed the uncoupled tendons with a more negative potential while others such as 2.2, 3.3, and 5.1 showed coupled tendons with a more negative potential. Both sets of specimens did show some variation between the ends of the ponding region and midspan. Specimens 3.2 and 3.4 from the four-year exposure and specimens 1.4 and 2.3 from the six-year exposure both show a higher corrosion potential towards midspan.

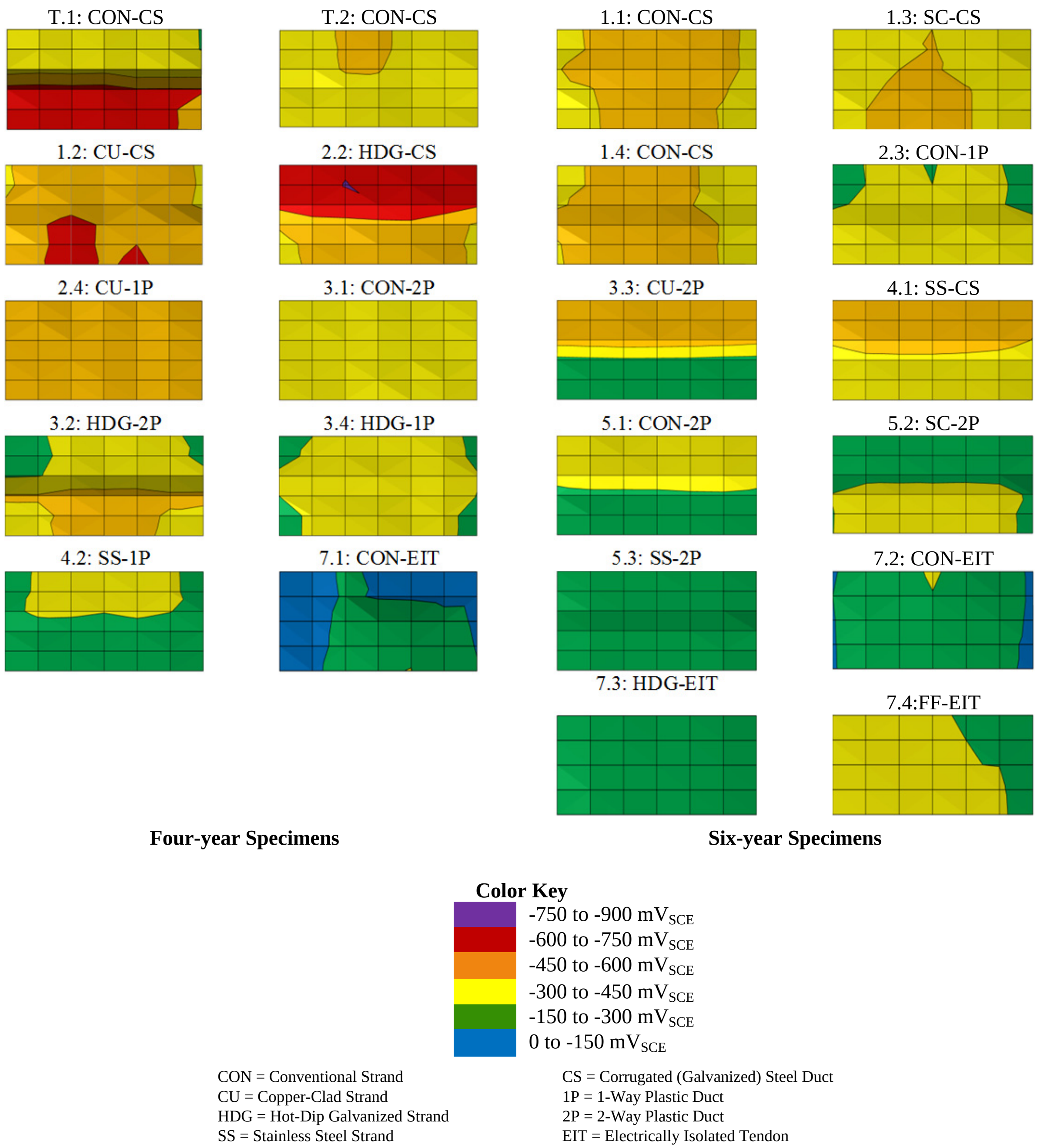


Figure 5.4 – Final Half-Cell Potential Contour Plots

Differences in north and south cannot be attributed to the differences in couplers between the tendons. The differences in the ends of the ponding area versus midspan can be seen in some instances, indicating a greater probability of corrosion at midspan. This is not, however, attributed to greater cover, as the tendon is at a uniform depth across the ponding region. More likely the potential is associated with likelihood of cracks to form near midspan and around the grout vents to promote chloride ingress. As with the half-cell measurements over time, the final contour plots do not show a significant difference between coupled and uncoupled ducts. The stainless steel, two-way plastic duct, and electrically isolated tendons (EIT) tend to have the lowest corrosion potential while the specimens with galvanized duct show the worst behavior and highest corrosion potential.

5.2 AC Impedance

Resistance, capacitance, and loss factor were measured each month on specimens 7.1, 7.2, 7.3, and 7.4. Outliers were omitted from the analysis at 462 and 494 days for specimen 7.1 by McCool. Measured values at these times were several orders of magnitude larger or smaller than the rest of the data. VSL defines the minimum resistance required to assure the absence of a short circuit to be 10 Ω [8]. All resistance measurements easily exceed this value as shown in Figure 5.5. Thus, it is reasonable to assume that no short circuit occurred between the tendon and reinforcing steel.

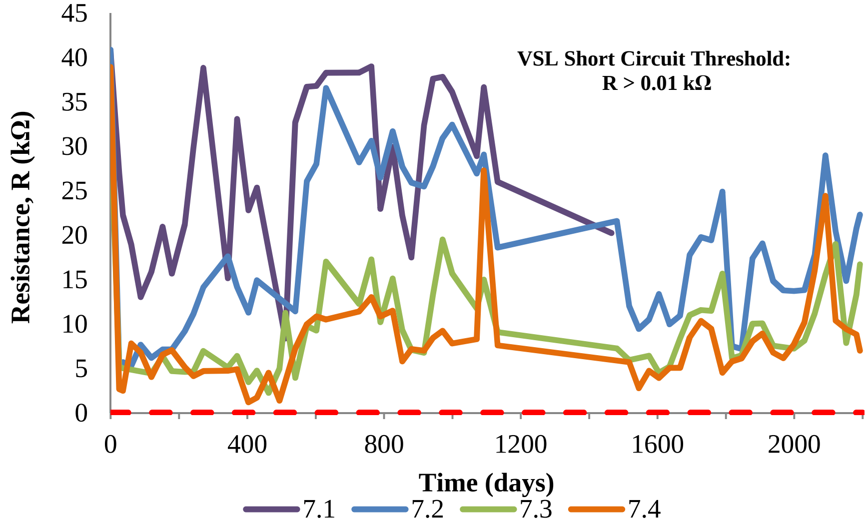


Figure 5.5 – Resistance of EIT Specimens throughout Exposure

VSL also defines a threshold specific resistance of 500 kΩ-m [8], below which a post-tensioning tendon is not considered monitorable in the long term. All of the specific resistance values were well below this value, suggesting that the tendon is not suitable for accurate long-term monitoring. However, ASTRA (Swiss Federal Road Office) gives a much lower threshold[9] for monitorability of 50 kΩ-m. As Figure 5.6 indicates, approximately 60% of the specific resistance values for Specimen 7.1 were above this threshold, with specimens 7.2, 7.3, and 7.4 registering less than that throughout their respective exposures.

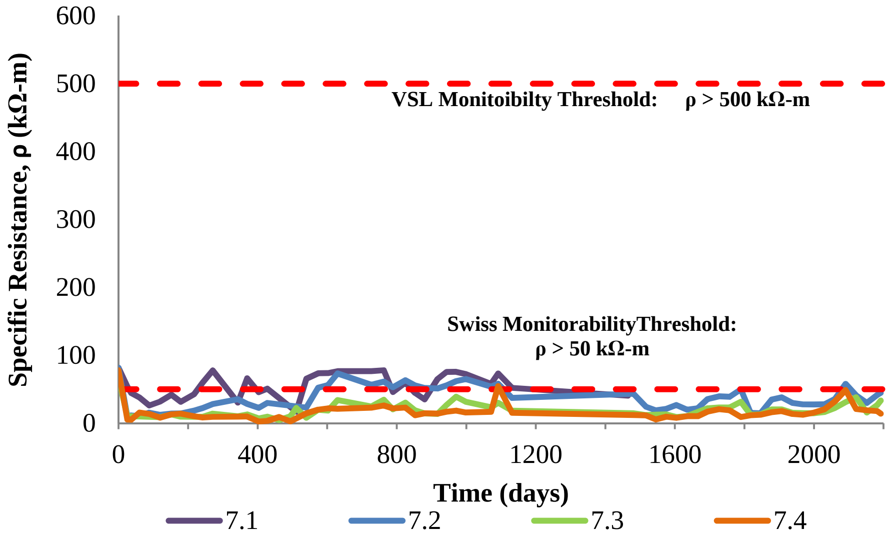


Figure 5.6 – Specific Resistance of EIT Specimens throughout Exposure

The ASTRA standard is several years newer than that which was published in fib Bulletin 33. The specific resistance threshold was reduced after field experience showed that 500 kΩ-m was nearly unattainable. Regardless of which standard is used, the monitorability of the EIT specimens is in question. While Figure 5.5 shows no short circuits, the data shown in Figure 5.6 effectively nullifies whatever conclusions may be drawn from this. The procedure seemed suspect and even called for McCool to contact the distributor and initiate different testing methods.

Analysis of AC impedance data for the specimens does not clearly establish its monitorability. It is certain that no short circuit occurred in any specimens, and it is possible that chlorides entered the duct at some point during the life of the specimen. The extreme variation of the data is also problematic. In a truly encapsulated specimen, readings should vary little from month to month, even in a subtropical climate such as Austin. According to Dr. Hans-Rudolf Ganz, at the time Chief Technical Officer at VSL International, the measuring device that was used does not fully comply with accepted standards for AC impedance measurements. This issue was addressed for the remaining electrically isolated specimens before the final round of autopsies began in 2012. Even with the new measuring program the data did not display a new pattern. This further suggests that the measuring device used does not comply with accepted standards for measuring AC impedance.

5.3 Surface Chloride Content

Chloride samples from the exterior of the specimens were extracted with a hammer drill as described in Chapter 4. . Chloride data from the grouts are considered separately and are found later in Figure 5.20. The threshold for corrosion in the concrete was taken from Salas' work on Project 0-1405[7] and was given as 0.033%. Although the true threshold value may vary by cement content, 0.033% was used for concrete and grout chloride levels to provide continuity with previous corrosion research at The University of Texas at Austin. Surface samples were taken both at the top of the specimen as well as from the anchorage region.

Penetration of chlorides into the top of the specimen occurred in both the 0.5 in. and 1 in. samples taken at four and six years. The maximum chloride content occurred in specimens 2.2 and 2.4 from the four-year exposure and 2.3 from the six-year exposure. While these three specimens are consecutive in the naming process, they represent three different types of strand and two types of duct. Therefore there does not appear to be a direct connection between them. From the data presented in Figure 5.7, only specimen 7.1 does not show a decrease in chloride content as with an increase in depth. Finally, only specimen T.2 is below the corrosion threshold.

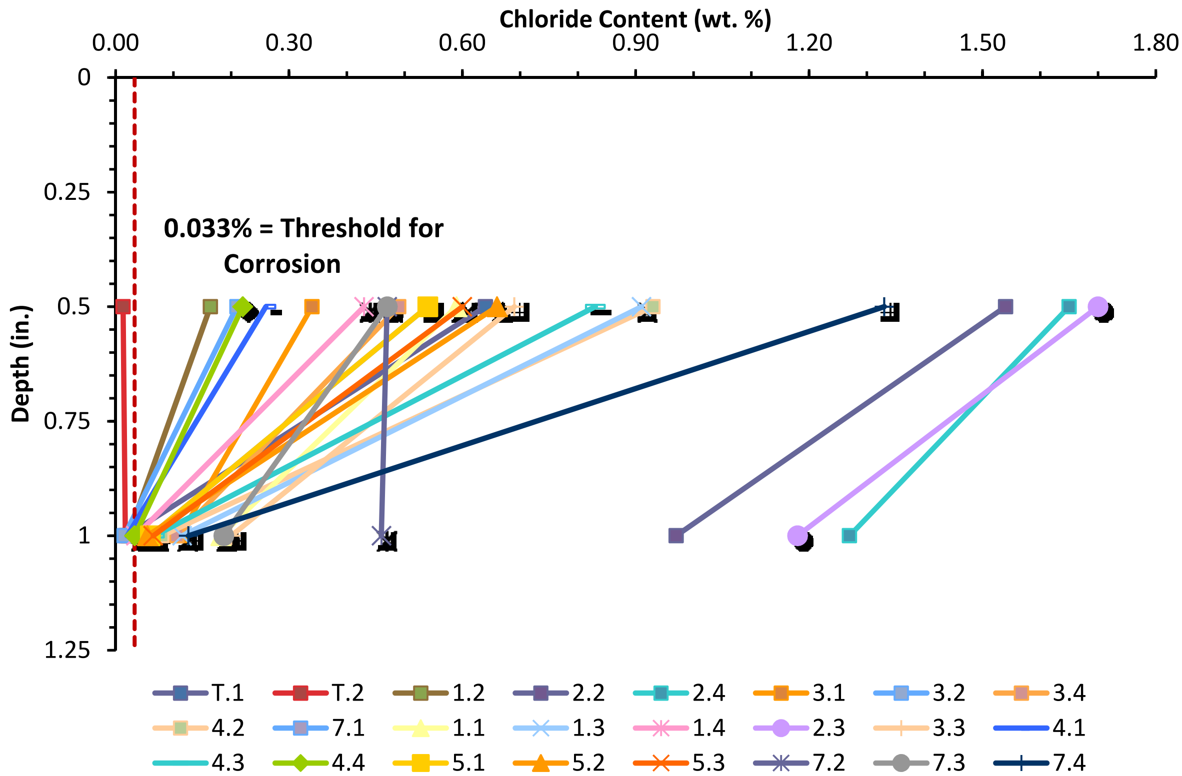


Figure 5.7 – Chloride Penetration from Top of Specimen

The figure shows only six specimens had content below the threshold at 1 inch depth. They are, however, grouped well below 0.30% with outliers for specimens 7.1, 2.2, 2.4, 7.2, and 2.3. The high level of chlorides within the top surface of the specimens may indicate one of two things. Either several samples were extracted from a small crack or the concrete was relatively porous and allowed chlorides to permeate to a depth of at least one inch. The procedures McCool and Moyer adhered to deliberately attempted to avoid the former. The latter is more realistic and plausible. The surface of the specimens' saltwater trays generally appeared to be in poor condition upon autopsy at both four and six years, and the subsurface concrete condition could have been affected as well. Had control blocks been cast alongside the post-tensioned specimens at the start of the project with inert dye to display penetration effectively, there would be a better understanding of the transport of chlorides through the concrete.

The presence of large, deep cracks on the top of all specimens increases the probability of corrosion substantially. Because chlorides can travel so deep into the specimens through the cracks, their movement through the pore space of the concrete is expected to have a nearly negligible effect on corrosion. It should be noted that a portion of the sample from the depth of 0.5 inch into the top surface of Specimen 1.3 (sent to Tourney Consulting Group) had a chloride concentration of 0.542% by weight of concrete for testing in accordance with ASTM[9]. Material from the same sample tested at FSEL had a chloride concentration of 0.67% by weight of concrete using the James Instrument CL-200 Chloride Test System for chloride detection. It can be assumed that the results from the CL-200 Chloride Test System are fairly accurate because these chloride concentrations are in general agreement.

Anomalies in both sets of specimens were noticeable around the anchorages. Samples were taken for specimens that were subject to exposure from drippers as well as unexposed specimens. Chloride contents for the anchorage regions of the dripper as well as non-dripper specimens are shown in Figure 5.8 and Figure 5.9. Note that on the dead end of the specimens, samples were extracted 5 inches from the top surface. On the live end, samples were extracted 6 inches from the top surface. For 7-series specimens, samples were extracted 6 inches from the top surface at both ends. At all extraction sites, samples were taken at depths 0.5 and 1 inch.

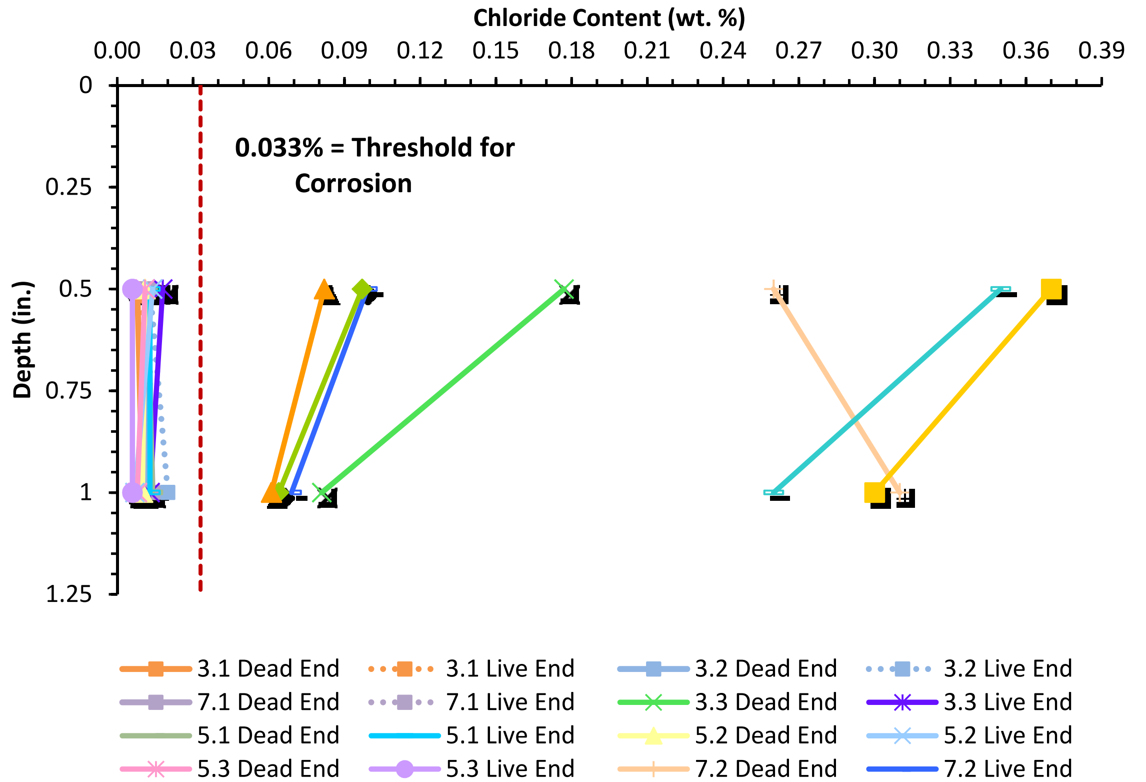


Figure 5.8 – Chloride Penetration at Anchorage Region with Salt Solution Spray

Surprisingly, samples from the dead end anchorage regions of Specimens 5.1, 5.2, and 5.3, which were the ends that received salt solution spray, did not have chloride contents above the corrosion limit. This might be due to the concrete of the pour backs being well consolidated, causing the concrete to have lower permeability then the other dead end pour backs. Another interesting observation is the chloride contents of the live end anchorage regions of the 7-series had chloride contents above the corrosion limit. Moyer noted cracking over the vent spout in the anchorage during the visual inspection before autopsy and this may contribute to the elevated chloride content. Another anomaly is the chloride content of the concrete sample taken from the dead end anchorage region of Specimen 7.2 increased with depth. Again this might be due to the cracking over the dead end anchorage region.

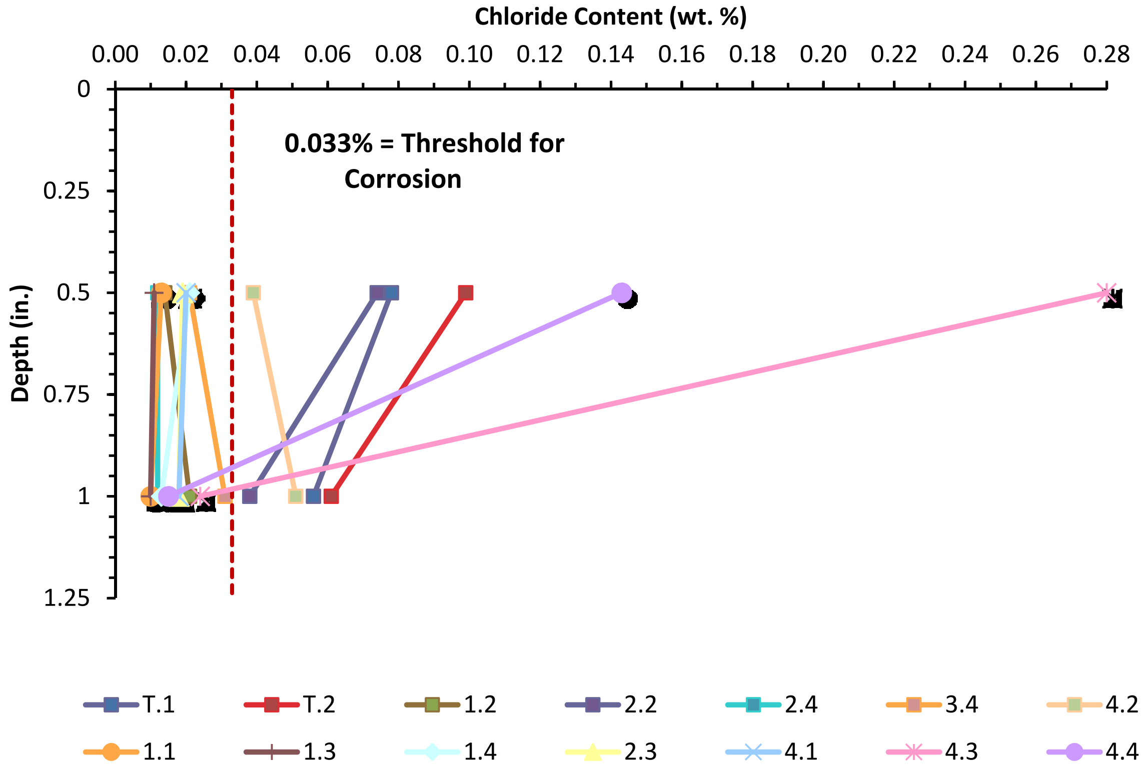


Figure 5.9 – Chloride Penetration at Anchorage Regions without Salt Solution Spray

As expected, many of the concrete samples from both depths had chloride contents below the corrosion limit. Interestingly, the four-year specimens had a greater number of specimens over the corrosion threshold. The two samples in the six-year exposure that were above the corrosion limit were both from a depth of 0.5 inch and were from Specimens 4.3 and 4.4, the non-prestressed specimens. These outliers might be because these specimens did not have pour-backs because they were only reinforced with conventional epoxy-coated and uncoated steel reinforcement and the concrete surface were scaled. However, for McCool the pourbacks were visually in better condition so cracking promoting chloride ingress is not considered a factor. For all four-year specimens, the pourbacks were visually in much better condition upon autopsy than the saltwater trays. Therefore, concrete permeability should not have played a role in the unusual chloride distributions. This is coupled with the factor that samples were not taken from cracks. The strange distributions in Figure 5.9 could be partially caused by inaccuracies of the testing equipment at lower chloride contents.

5.4 Autopsy Analysis

This information is included in depth by both McCool and Moyer in their respective theses. The autopsy procedure was kept the same between both series as Moyer had experience working with McCool. The specimen's isolation of tendon and duct was successful. The data shows that corrosion of the epoxy-coated mild steel reinforcement was not an issue. Additionally, the difference in north and south tendons shows how the couplers can almost be considered a separate variable on their own. The only issue to address is the crack rating in McCool being significantly higher. There is no systematic difference in samples (like plastic which tended to crack) to suggest why this occurred. The explanation may likely be to human involvement. A more detailed analysis is provided in 5.4.2.

5.4.1 Appearance

The surface concrete of all specimens developed scaling in and around the saltwater tray. In many cases, the north and south faces of the specimens were also affected. Shallow surface air voids were visible in the saltwater trays of all specimens. Isolated spalling was found around the surface cracks and pourback joints of some specimens. Corrosion staining as shown in Figure 5.10 was visible on the top surface of several specimens, most often near the base of one or both grout vents.

Figure 5.10 – Staining at Grout Vent

5.4.2 Cracking

As shown in Figure 5.11, most specimens displayed wider and more numerous top surface cracks than had been observed immediately after live load application. Cracks were also found on one or both corbels of several specimens. When present, these corbel cracks shown in Figure 5.11 were longer than had been noted immediately after live load application. Efflorescence or water stains were found around the corbel cracks in most cases, indicating that moisture was present inside the specimens at those locations.

The visual inspection procedures developed by Salas[8] were used to examine the visible surfaces of each specimen for cracking, surface flaws, discoloration and corrosion staining, and efflorescence. Each specimen was photographed before it was unloaded and autopsied. Surface cracks in the ponding area were measured, marked, photographed, and mapped using a crack scope, crack comparator, grid, and camera. The cracks were traced with a marker for visibility and photographed from approximately four feet above the center line of the ponding area.

Figure 5.11 – Cracking across Ponding Region (left) and at Corbel (right)

Crack ratings as proposed by Salas[8] were taken before autopsies were performed for both the four- and six-year specimens. However, the equation's dependence on crack length resulted in a discrepancy between the four-year specimens and the six-year specimens. As the specimens were designed[5] for a specific crack width of 0.010 in., only that metric of width will be considered. The crack data collected by McCool[3] was quite questionable and is not reported herein. The subjective and qualitative nature of crack measurements makes further analysis of the data difficult.

With these considerations, a comparison between crack widths reported by Ahern[20] at the time of live loading and Moyer[4] after six years of aggressive exposure show some increase. Both the absolute maximum crack width on each specimen and the average maximum crack width of the cracks on each specimen are shown in Figure 5.12 and Figure 5.13. The absolute maximum crack widths show that some cracks did expand over the course of the exposure as was expected. Considering the minimal visible staining, expansive forces from corrosion products can only be considered minimal. This is in agreement with the data as the crack widths do not expand significantly. Only Specimen T.2 showed a major increase in the crack width.

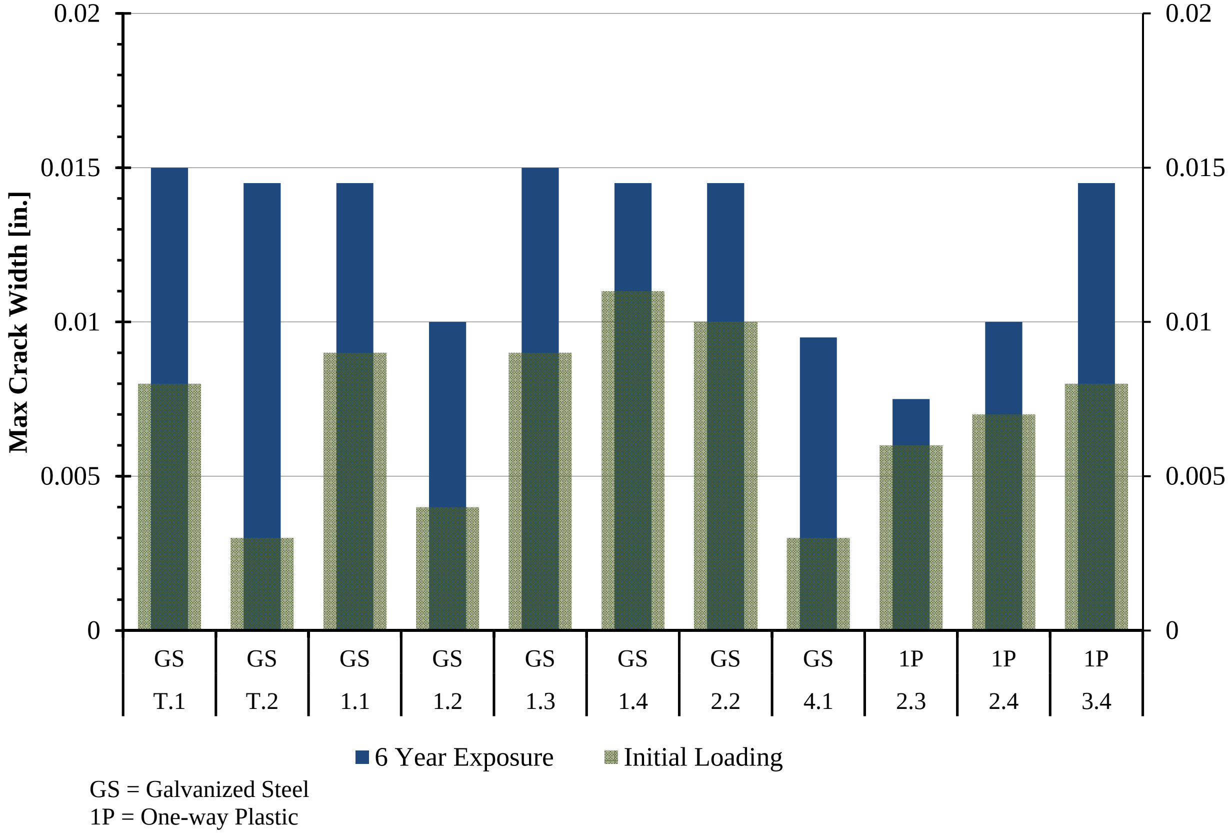


Figure 5.12 – Propagation of Absolute Maximum Crack Width over Exposure

The average maximum crack widths in Figure 5.13 show only small increases. Specimen 1.4 shows a decrease in crack widths; however, this can be attributed to a number of smaller cracks being included in the calculation of the average. Specimen T.2 and 1.2 provide the major increase in crack data.

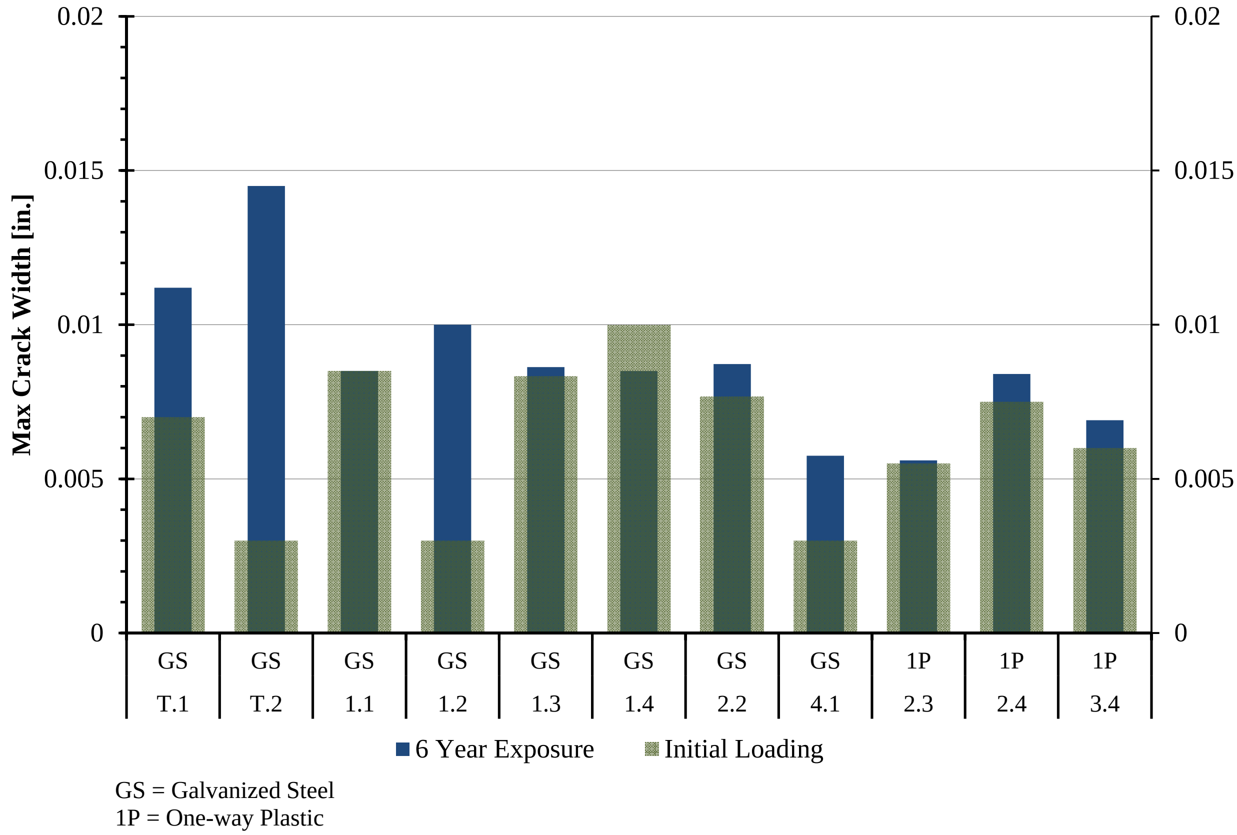


Figure 5.13 – Average Maximum Crack Width over Exposure

5.4.3 Longitudinal Bar and Stirrups

Overall, the specimens' epoxy-coated mild reinforcing elements were in good condition. Corrosion damage was minor and limited to small isolated areas of some bars or stirrups. In between these regions, the epoxy coating was completely intact. Discoloration and corrosion tended to occur at locations where damage to the epoxy coating was likely to have occurred, such as points where the bars had been tied, lifted with a crane, or bent as shown in Figure 5.14. Pitting and area loss were extremely rare. Discoloration was the most common form of corrosion damage.

Figure 5.14 – Epoxy-Coated Mild Steel Reinforcement Corrosion

Both McCool and Moyer plotted generalized longitudinal bar and stirrup corrosion ratings with crack ratings for each. However, due to the discrepancy between the four- and six-year crack rating, this comparison is not given herein. Figure 5.15 compares only the corrosion ratings from the transverse mild reinforcement (the stirrups) and the longitudinal mild reinforcement. As expected, the epoxy coating proved to be a significant factor. The uncoated bars used in specimens 4.4 and 7.1 have the two highest ratings out of any of the reinforcement. The transverse reinforcement in Specimen 2.4 had an unusually high corrosion rating even though it was epoxy-coated. This is attributed to one stirrup that lost over 20% of its cross section over a small length at midspan of its horizontal portion. This damage did not correspond directly to a surface crack location. Of the total corrosion rating given as 590, this single stirrup accounted for 530 of the total, indicating it is a major outlier.

A generalized corrosion rating with a value of 36 is used in Figure 5.15 to indicate when transverse or longitudinal bar was found to have light to moderate corrosion throughout on both the top and bottom of the bar as indicated by the rating system originally developed for Project 0-1405[11].

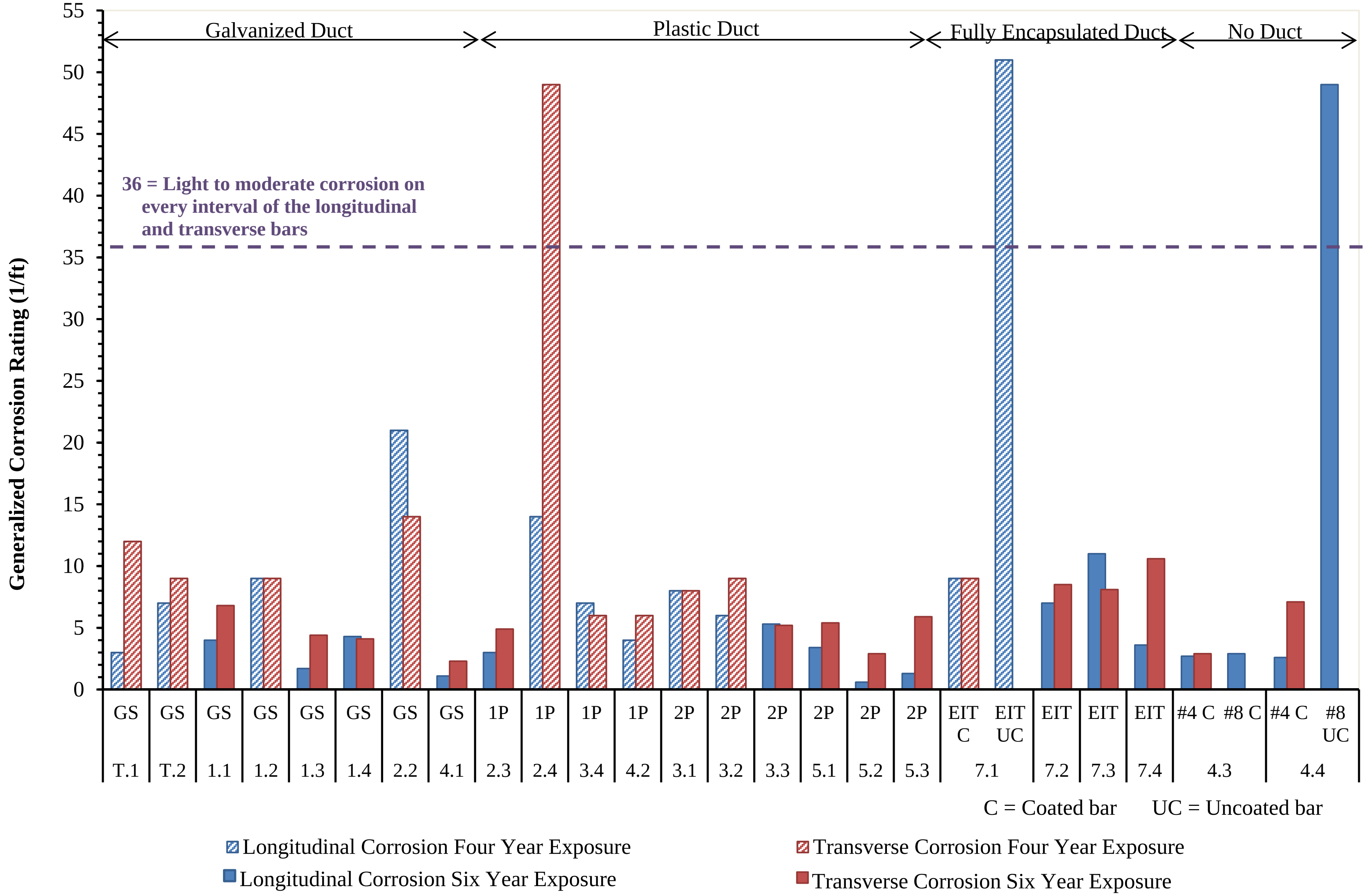


Figure 5.15 – Longitudinal and Transverse Corrosion Rating of Four- and Six-Year Specimens

The EIT series specimens had the highest corrosion ratings for coated longitudinal and transverse bars in the six-year study. This might be because the specimens were larger and therefore the reinforcement cages were larger. More likely, the difficulty in fabricating the isolated tendon system resulted in a less well constructed specimen. When comparing the EIT specimens with the rest of the specimens, the results are not significantly different. Specimen 2.2 had a much larger corrosion rating for the longitudinal bars due to a particularly bad north bar. Specimen 2.4 had particularly poor results for the stirrup damage. The specimen contained one heavily damaged stirrup, while the others were not nearly as bad. Excluding these two outliers, the data is consistent across both exposure periods. One would expect behavior that indicates initiation and propagation. This would show itself with a higher six-year corrosion rating. The data does not support this, however, showing both sets of results as roughly equal. It's more probable that corrosion propagated on all areas of corrosion and formed a complete layer of corrosion product. To further reinforce this, the uncoated reinforcement had similar ratings in both four and six years, demonstrating how that particular reinforcing bar had already been corroded and formed a layer of corrosion product. This meant the propagation phase had been fully finished at four years.

5.4.4 Duct

As expected, the results from the galvanized duct and the plastic duct were substantially different. Galvanized steel ducts performed very poorly, with every specimen showing area loss and pitting over a portion of its length. Substantial area loss and pitting were present at locations of grout voids. Corrosion and discoloration were less localized, appearing over larger portions of the ducts' length. Damage was most severe along the portions of duct which were located beneath each specimen's transverse cracks. The smallest cover was underneath the ponding region where most of these cracks were located. This resulted in aggressive corrosion in those regions, seen in Figure 5.16.

Figure 5.16 – Galvanized Duct Corrosion with Severe Pitting

The plastic ducts were found to be only lightly damaged at the time of both autopsies. This damage, shown in Figure 5.17, was caused either by strands scratching the inner surface of the duct while being threaded through the specimen, or by one or more strands gouging into the duct during stressing. In both autopsies, the highest plastic duct damage ratings were in ducts that contained stainless steel strand. The highly curved stainless steel strand scratched interior walls of the ducts during strand placement, resulting in high damage ratings for Specimen 4.2.

Figure 5.17 – Damage Caused by Stainless Steel Strand

Except for specimen 7.2, no holes or leaks were found in any of the plastic ducts, indicating that the ducts themselves did not allow chlorides to enter the tendons. The sole crack was at the location of a dead end grout vent shown in Figure 5.18. The resulting rust staining on the interior of the duct is shown in Figure 5.19. Breaches were observed in the heat shrink or mechanical couplers used to connect the two halves of the north duct on all but one specimen. Also, the epoxy used to seal the grout vent to the south duct was observed to be loose on all specimens in both the four- and six-year specimens. This provided a route for chlorides to enter the tendon and may explain the high chloride levels in all tendons with plastic ducts except for Specimen 7.1.

Figure 5.18 – Crack in Specimen 7.2

Figure 5.19 – Mild Staining of Plastic Duct

Correlation between crack rating and duct corrosion is expected and was generally observed across both autopsies. However, this measurement was ultimately disregarded as a quantitative measure because of the marked discrepancy in crack ratings. The correlation between the appearance of cracks and duct corrosion rating is still considered an indicator of possible damage to galvanized duct. Crack locations and grout voids are equally important, with the latter considered highly dependent on the quality of workmanship. Concerns over workmanship were expressed in both sets of autopsies and will be addressed on its own later in the report.

As seen in Figure 5.20, chloride content was not an indicator of duct corrosion. Significant chloride penetration into the grout occurred within all specimens, showing that impermeability was not achieved with any system. Only Specimen 7.1 had chloride content below the corrosion threshold. The other EIT specimens had chloride content on the order of the other specimens, including the highly corroded galvanized duct. While the purpose of the experimental procedure is not to compare galvanized duct to plastic duct, the values comparing the two do demonstrate that while the plastic duct does not corrode nearly as much, the value of it as a barrier to corrosion penetration is greatly reduced if duct couplers or grout attachments are not perfectly sealed.

The ducts themselves were not permeable; instead, the location of the couplers and the grout vents proved to be the means of ingress. Except for Specimen 7.2, none of the plastic ducts had observed holes or cracks in either the four- or six-year intervals. This indicates that the high chloride levels found in the grout of the plastic ducts did not come from a defect in the duct. This is further reinforced by Figure 5.20. The seal of the heat shrink-wrap to the duct and the mechanical couplers were observed to be inadequate to keep out contaminants in the north ducts and the 7-series specimen's duct. Also, the couplers used to connect the two halves of the north ducts and to connect the sections of the 7-series specimen's duct did not provide an adequate seal to keep out contaminants. McCool and Moyer both noted the silicone or epoxy used to attach the grout vents to the south ducts was found to be loose on all specimens. All of these factors would have provided a path for chlorides to enter the ducts and explain the elevated chloride concentrations that had been observed in the grout from the specimens with plastic duct.

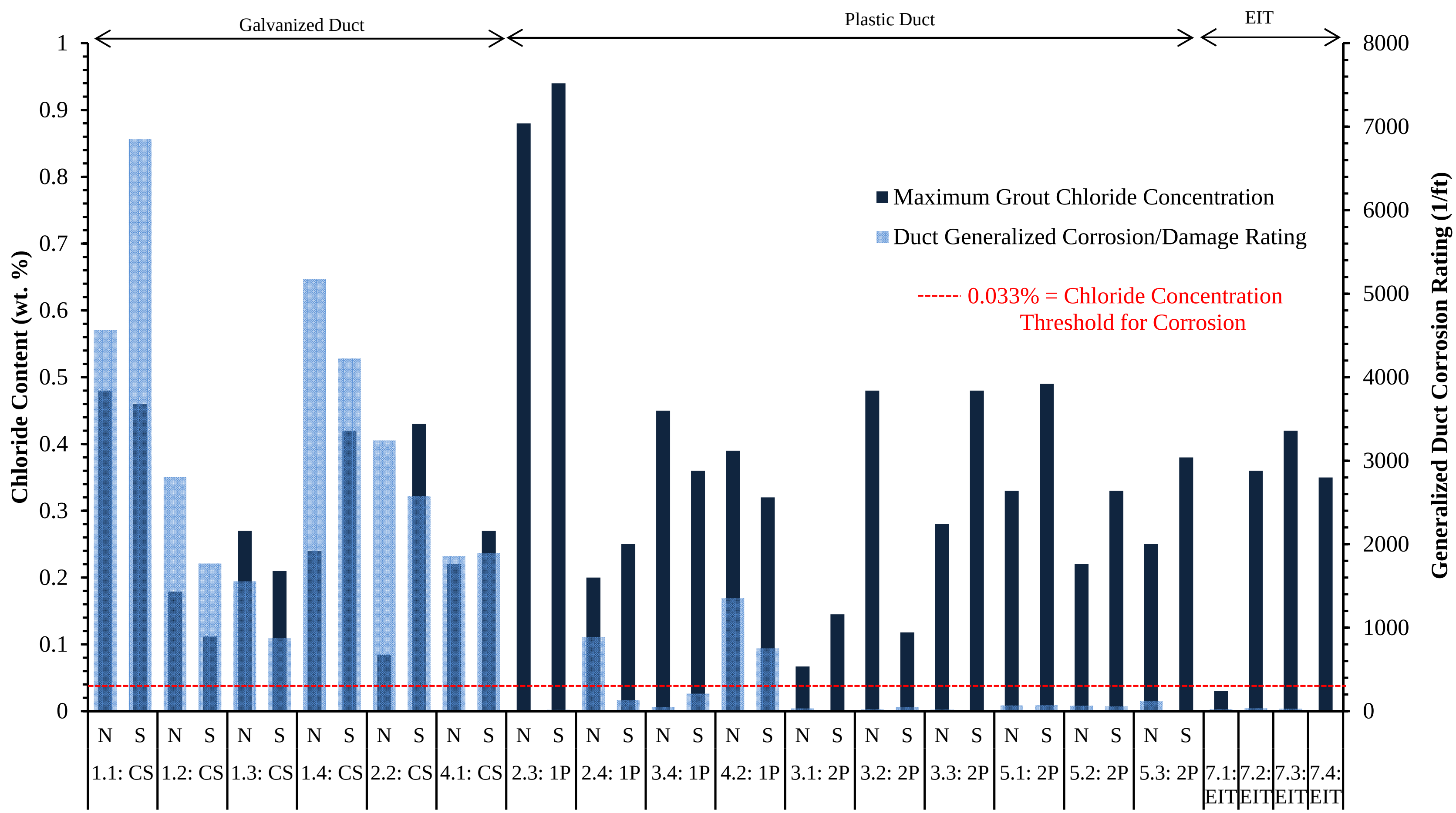


Figure 5.20 – Grout Chloride Content and Generalized Duct Corrosion Rating

5.4.5 Grout

As mentioned in Chapter 4. , grout samples were taken from anchorage plates of each tendon at both dead and live ends. For tendons in galvanized duct, additional samples were taken every 2 inches in regions where the galvanized ducts had deteriorated. For tendons in plastic duct, except for the 7-series specimens, grout samples were taken at midspan of the tendon. For the 7-series specimens, grout samples were taken from the regions where grout vents were located and at midspan of the tendon. It should be mentioned there is an unconfirmed possibility that the grout used in Project 0-4562, SikaGrout 300 PT, might have been contaminated with chlorides to a level very near the chloride limit before the grout was even placed in the tendons. The chloride concentration of SikaGrout 300 PT is limited to 0.04% by weight of cementious material[12]. Assuming 65% of the SikaGrout 300 PT is cementious material, the limit for chloride concentration would be 0.026% by weight of grout. This is below but close to the limit of 0.033% by weight of grout used in this report. It should be noted that chloride concentration limit for corrosion of conventional steel from Reference 5 might not be the chloride limit for corrosion of the non-conventional stand types.

The failure to test the prepackaged grout that was used throughout the experimental procedure, both in the companion testing and the fabrication of the specimens, is a major error. Such acceptance testing was not common at the start of this project. Several cases of high chloride content in grouts have been alleged in field applications. The Post-Tensioning Institute (PTI) has now included grout testing in their new specifications. As emphasized throughout this report, adherence to these new specifications is considered extremely important in reducing the number of variables that may cause corrosion. Future testing that does include initial grout testing will be able to more accurately determine where the chlorides tend to gather within each specimen.

Figure 5.21, Figure 5.22, Figure 5.23, and Figure 5.24 show the chloride concentrations of tendons that contained galvanized duct, one-way plastic duct, two-way plastic duct, and EIT systems, respectively. All tendons had chloride concentrations along the whole length of tendon above the corrosion limit of 0.033% by weight of grout. This is consistent with the average half-cell potential readings at the end of exposure testing being more negative or close to the greater than 90% probability of corrosion half-cell potential readings that these tendons had. As expected, the chloride concentrations were greater at midspan than in the anchorages except for the EIT specimens. Because the couplers failed to prevent ingress and there was no major difference between coupled and uncoupled ducts, this is not unexpected. This might be because the chlorides would take longer to get to the anchorages because the chloride ions would have to travel through the interstitial space between the gout and the duct and/or interstitial space between the grout and the strand. The chloride concentrations at the anchorages were all somewhat equivalent. The stainless steel and clad specimens did have higher live end concentrations, but the magnitude is not considerably different.

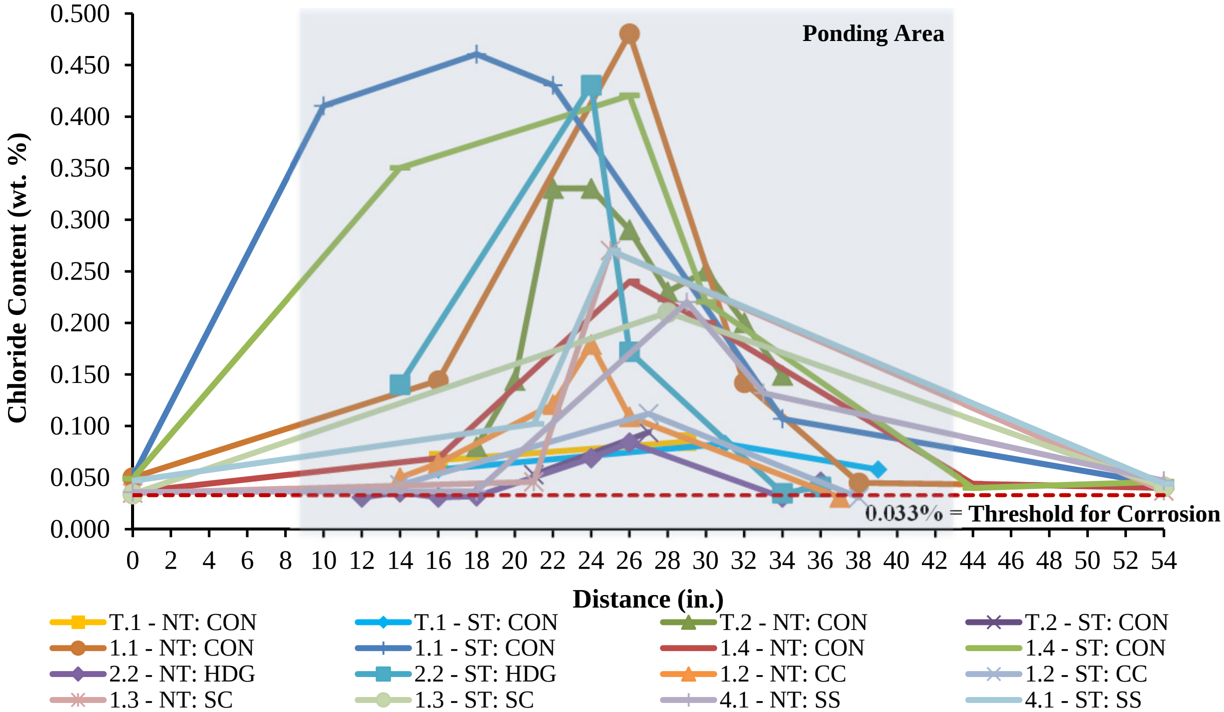


Figure 5.21 – Grout Chlorides for Galvanized Duct Specimens

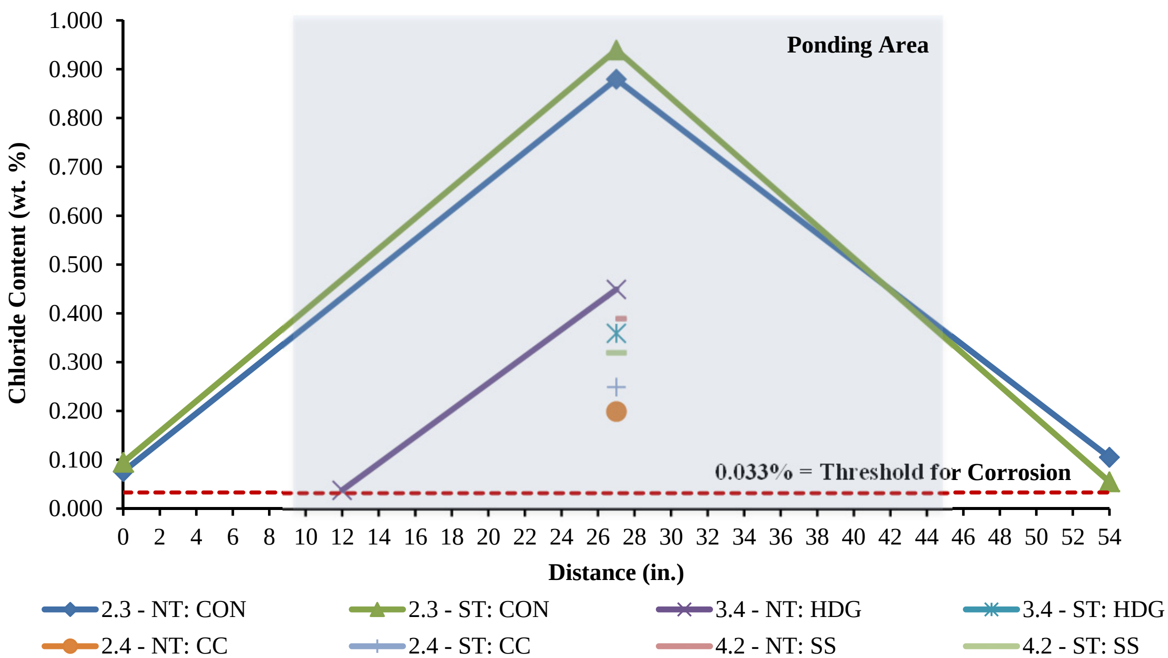


Figure 5.22 – Grout Chlorides for One-Way Plastic Duct Specimens

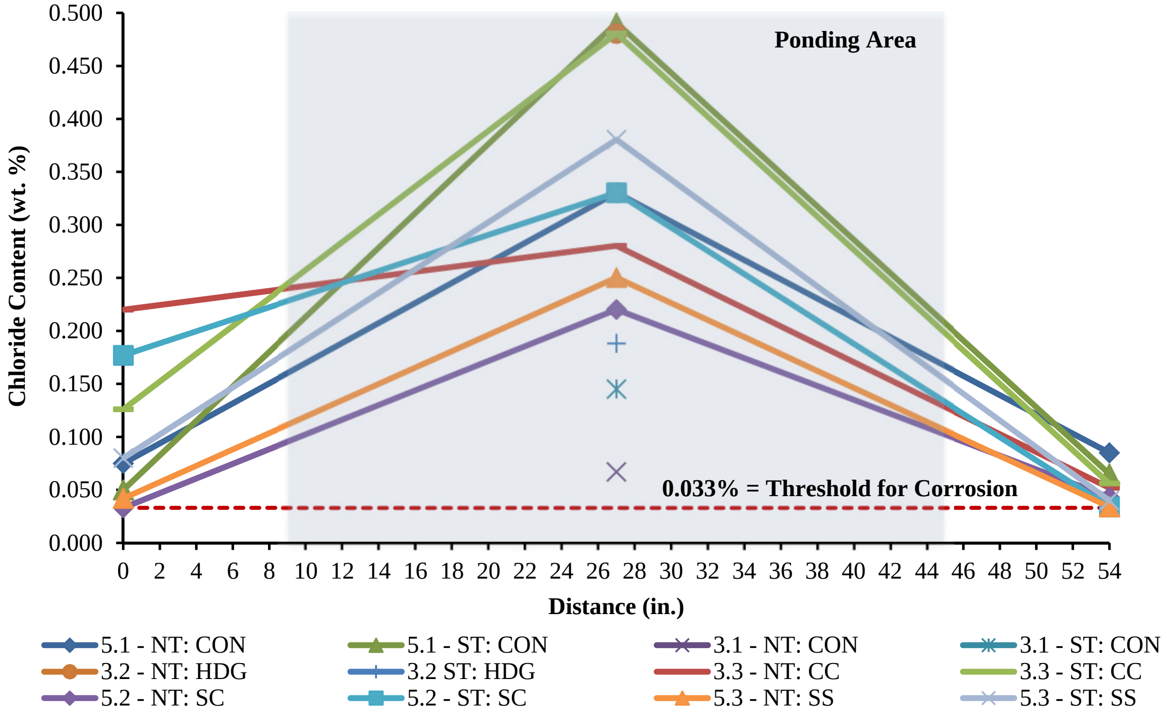


Figure 5.23 – Grout Chlorides for Two-Way Plastic Duct

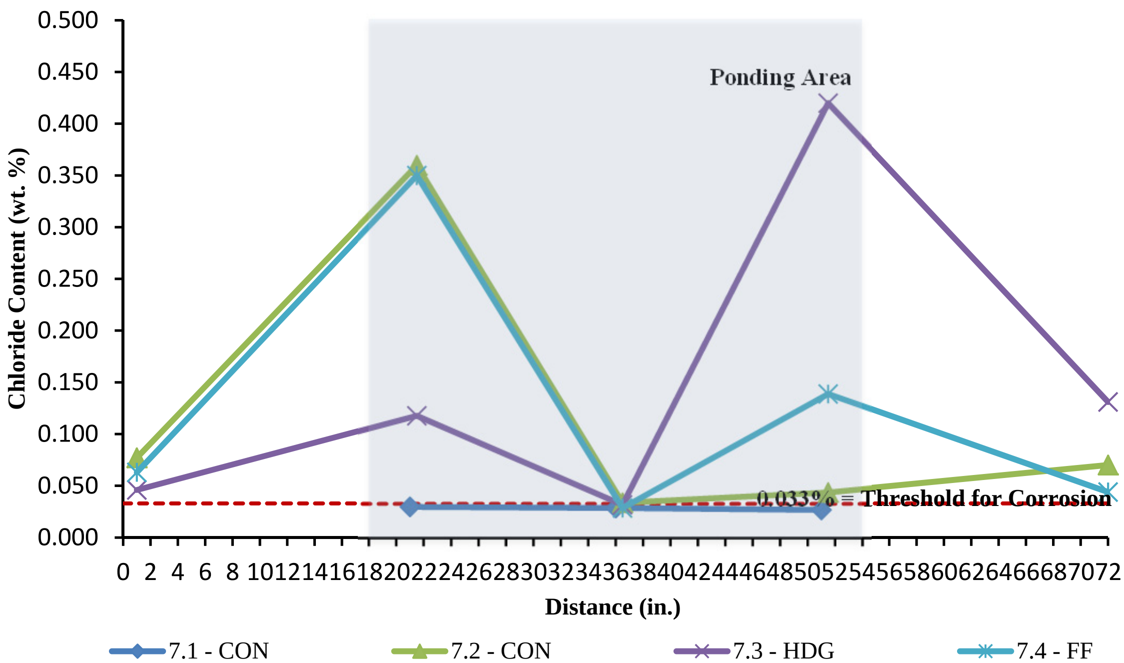


Figure 5.24 – Grout Chlorides for EIT Specimens

Surprisingly, the tendons from Specimen 2.3 had the highest chloride contents despite being two-way plastic ducts. This might indicate that the ducts are not watertight and allowed chlorides to enter the tendon earlier than the other ducts. Another interesting observation is the tendons from Specimen 5.1 had chloride concentrations comparable to the chloride concentrations from the tendons in galvanized duct. The ducts that encased the tendon in Specimen 5.1 were two-way plastic duct, as well. Again, the watertightness of the couplers and grout vents of the plastic ducts are in question. The north tendon of Specimen 1.4 had the lowest chloride concentration at midspan. The disparity in the average final half-cell potentials between the north and south tendons of Specimen 5.1 do not correspond to the difference in chloride concentrations at midspan of the same tendons. The south tendon had chloride concentrations greater than the north tendon and midspan, whereas the average final half-cell-potentials suggest that the north tendon should have had the higher chloride concentrations. Therefore, the disparity in the average final half-cell potentials might be from corrosion of the epoxy-coated steel reinforcement located closer to the north duct elevating the half-cell potentials.

The live end side of the south tendons in Specimens 1.1 and 1.4 had chloride concentrations that were far greater than the chloride concentrations of the dead end side of the tendons. Specimens 1.1 and 1.4 had tendons with galvanized duct. This difference in chloride concentrations between the live and dead ends of the south tendons of Specimens 1.1 and 1.4 might be from the cracks on the live end over the south tendons of the ponding area in the concrete allowing more chlorides to reach the live end of the tendons then the dead ends. On the other hand, the chloride concentrations of the north tendons of Specimens 1.1 and 1.4 dropped significantly away from the midspan of the tendon. The elevated chloride concentrations of the tendons would make the average final half-cell potentials more negative but the average final half-cell potentials for the tendons with galvanized duct, Specimens 1.1 and 1.4, were more negative than the potentials from the tendons with plastic duct. This would suggest that the corrosion of the zinc in the galvanized duct as well as the chlorides were contributing to the average final half-cell potential of the tendons in Specimens 1.1 and 1.4. The level of chlorides in the tendons is consistent with the corrosion observed during autopsies.

Much of the autopsy analysis actually revolves around voids and poor grout quality. This suggests that pressure was not maintained during the grouting process. This can easily be remedied by the PTI specification for constant pressure. All the ducts and connections should be able to withstand 10 feet of fluid pressure and a continuous flow of grout must be visible out of the vents before grouting can stop. New tests and standards by PTI have pressure suggestions as well as new apparatus that should be used to establish what will need to be done to ensure proper placement. This should be done next time and will help improve corrosion behavior. These specifications and preliminary grout chloride tests should eliminate the doubts that exist in this series of exposure testing.

5.4.6 Strand

Because the different strand types corroded in different ways, direct comparison among them is difficult. Generalized strand corrosion ratings are plotted with maximum chloride content for both tendons in each autopsy specimen in Figure 5.25. Maximum chloride concentrations for all the tendons were above the threshold for all the four-year specimens except for Specimen 7.1 and were well above the threshold for six-year specimens.

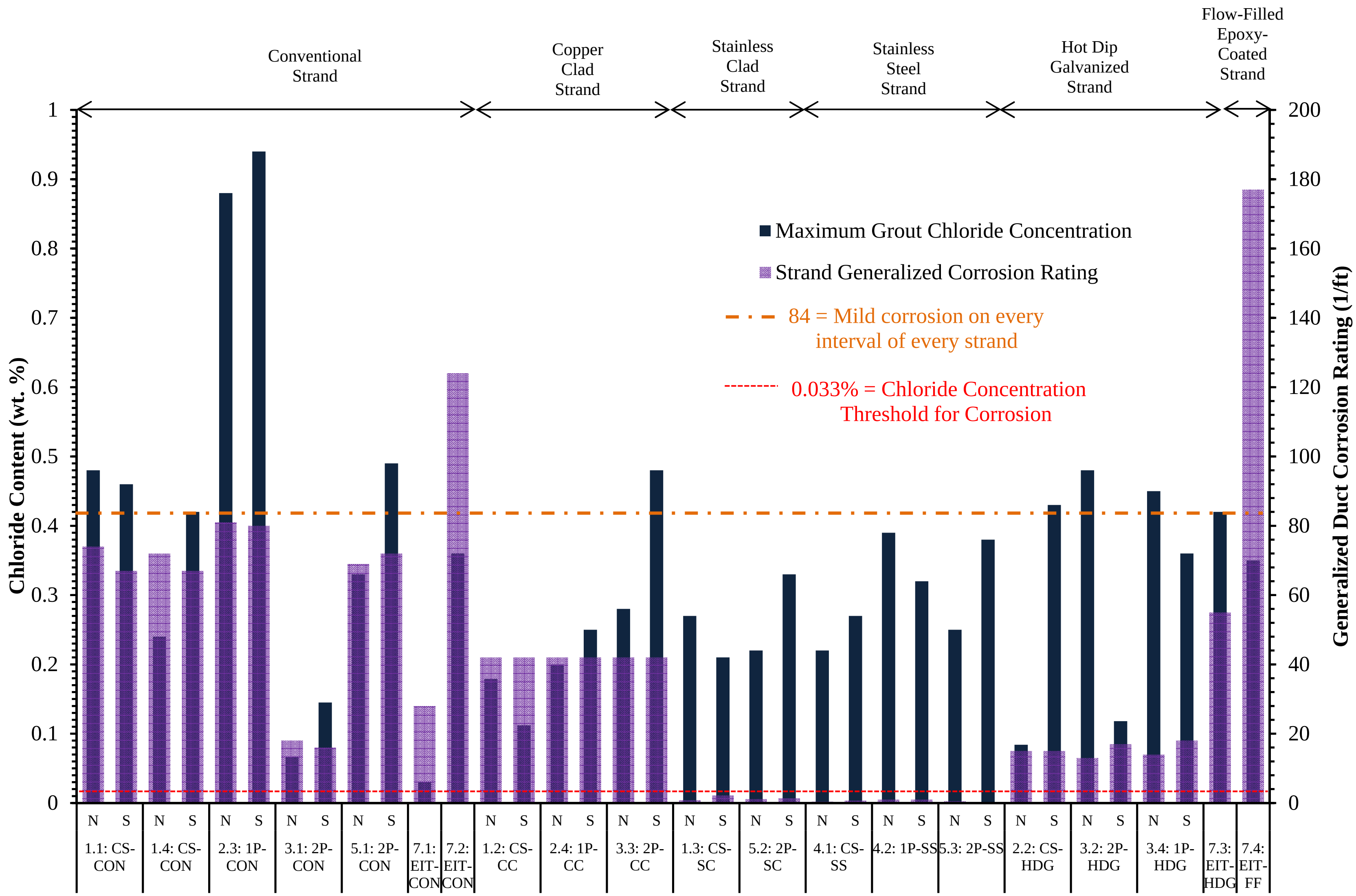


Figure 5.25 – Strand Corrosion with Grout Chlorides

All corrosion was very light. There was only mild pitting in the six-year strands. Corrosion was noticeable where there had been direct contact with the duct. The four-year strands were mainly lightly discolored with some corrosion, mostly on the non-coated inner wires. Stainless steel in the four-year group performed well, as the chloride content was high but the corrosion rating was low. This was reiterated in the six-year autopsy as the chloride content is elevated but the corrosion rating is basically non-registered. Flow-filled epoxy-coated strand did not perform as well in the six-year exposure as anticipated, as the extreme right side of Figure 5.25 shows. Half-cell results suggest the damage may have been present underneath the coating prior to their use and Figure 5.26 shows some corrosion within the bundle of wires once the epoxy is stripped off and the wires are separated. Note the intermittent discoloration that indicates minor corrosion.

Figure 5.26 – Highlighted Mild Discoloration on Interior of Flow-Filled Strand

For the four-year report, only EIT was below threshold. At six years, it did not stay below the threshold. Moyer states the extra cost of EIT is not worth it based on poor chloride resistance. However, this lack of resistance may be due to other issues, such as poor construction. It appears that above chloride threshold, the higher values of the chloride content do not greatly affect the corrosion value. The lack of a connection between the chloride content and corrosion was reiterated by Moyer.

Conventional strands showed discoloration or light corrosion spots on their outer wires in both the four- and six-year autopsies as seen in Figure 5.27. However, mild pitting was observed only on the outer wires of one strand from Specimen 7.2. The pitting was located at the dead end grout vent where a crack in the duct had been observed. Somewhat more severe corrosion spots on the inner wires were apparent in both sets of autopsies as well. The spots were most frequent in the regions that had been in direct contact with the surrounding duct. Galvanized strands showed similar damage. However, most corrosion on the outer wires of each galvanized strand occurred on the zinc coating, while damage to the inner wire occurred on the bare interstitial steel. Again, the second set of autopsies noted the same results as the first.

Figure 5.27 – Discoloration on Conventional Strand

Copper-clad strands were uniformly coated with a black patina, which appeared glossier on the inner wires than the outer wires. The six-year autopsies revealed occasional tiny reddish colored spots on the copper-clad wires. Stainless steel strand was covered with a light coating of grout residue but was otherwise immaculate. Moyer noted there were very few spots of discoloration and corrosion. The stainless-clad strand autopsied after six years had similar results as the stainless steel strand.

The flow-filled epoxy-coated strand did not perform as expected. The inner and outer wires had corrosion ranging from mild pitting to light corrosion over the majority of their lengths. This corrosion might have been from the paint stripper used to remove the epoxy coating in the autopsy process or the corrosion may have existed before the strand was coated. The latter might be the more valid reason because the half-cell potentials taken during the exposure testing suggest that corrosion had already existed before the stripper was applied.

5.4.7 Anchorage

Autopsies from both sets of specimens show only light corrosion issues with anchorages. Corrosion occurred in similar locations for both the galvanized and the non-galvanized bearing plates. The galvanized anchorages show a little bit less corrosion as Figure 5.28 and Figure 5.29 demonstrate. The exposed surfaces of the bearing plates and anchor heads showed patches of light to moderate corrosion. Inside the specimens, corrosion was most prominent on the underside of the bearing plates, suggesting that voids may have formed there during casting and that moisture was able to enter. This occurred in both sets of specimens. Anchorage region ducts showed similar damage to their counterparts in the main autopsy region. Grouts were similar in appearance, but voids were smaller in size. The six-year specimens had chloride concentrations ranging from slightly above to well above the corrosion threshold. Anchorage region strands were most corroded at their outer tips and at the regions which had been located inside the anchor head. Wedges were almost always intact, although many displayed light to moderate surface corrosion.

Figure 5.28 – Underside View of Anchorage with Non-Galvanized Bearing Plate (left) and Galvanized Bearing Plate (right)

Figure 5.29 – Corrosion on Exposed Faces of Galvanized (left) and Non-Galvanized (right) Anchorage Plates

All the anchorage plates had light corrosion on their outer surface where the epoxy coating had not adhered well. On the embedded portion of the anchorage plates, corrosion was most prominent on the underside of the anchorage plate and where duct tape was used to attach and seal the plastic duct to the anchorage plate. This suggests that moisture, oxygen, and/or chlorides had infiltrated to this region where a possible void had formed during casting. On specimens that did not use duct tape to seal the duct to the anchorage plate, no corrosion was evident. The damage to the strands was most evident in the region of the anchor head. The wedges were intact and had either light or moderate corrosion.

The fully encapsulated systems had greater damage to their components than the conventionally post-tensioned systems. In fairness to the system manufacturers who ordinarily install these systems on projects, the EIT systems were installed by the same graduate students who installed all systems. The more complex EIT system might require more care and experience in the installation than the other systems. The steel retaining rings from all specimens had pitting, moderate corrosion, and light corrosion on all surfaces. The anchorage plate had pitting, severe corrosion, and moderate corrosion on the exposed face. The embedded faces were corrosion free. The ducts from the anchorage regions were in similar condition to the duct sections from the main autopsy region. The strands showed similar damage to the strands from the main autopsy region. The wedges were intact and some had either light or moderate surface corrosion. Overall, the complex EIT system probably was not installed well. This could be responsible for the issues with monitoring of the system.

Except for the 7-series specimens, the presence of the dripper system did not seem to have much of an effect on the anchorage components. This suggests that the damage observed in the anchorage regions might be from another source. The path of salt water solution, moisture, and oxygen was more than likely from the cracks that had been observed at the interface of the backfill mortar and the base concrete. The salt water solution could have entered the cracks when the ponding area was emptied after the wet exposure cycle. The 7-series specimens had greater damage to the dead end anchorage region, which was the end exposed to the dripper system. This might be from the cracking observed in the backfill mortar of the anchorage pockets allowing chlorides to infiltrate deeper into the mortar than the uncracked backfill mortar from the conventionally post-tensioned specimens.

5.4.8 Couplers

The specimens with galvanized steel ducts did not contain couplers. In each specimen with plastic ducts, the two halves of the north duct were connected at midspan with one of two couplers for conventional specimens: GTI slip-on or GTI snap-on. The south ducts were continuous within these specimens. The fully encapsulated specimens had VSL snap-on couplers, although the coupler was not located at midspan but at the connection between the anchorage and the duct. Chloride content at all coupler locations is shown in Figure 5.30 while content at midspan of one-way and two-way plastic duct is shown in Figure 5.31.

The highest grout chloride concentration was found inside the GTI snap-on coupler within Specimen 2.3. The lowest concentrations were found in both VSL snap-on couplers inside Specimen 7.1, although these couplers had the benefit of being covered with an additional plastic sheath. Both chloride concentrations in Specimen 7.1 were below the corrosion threshold—the only two values that fell below the threshold. The presence of chlorides within the couplers confirms that breaches had occurred, as observed during autopsies. For each coupler installed in multiple specimens, chloride concentrations vary significantly. This suggests that the integrity of the couplers depends more on workmanship during construction than on coupler type and manufacturer. The inexperience of the project team at the time of construction may have resulted in improper installation of the couplers, which allowed chloride ingress during exposure.

For all specimens with one coupled and one uncoupled plastic duct, grout chloride concentrations at midspan are plotted in Figure 5.31. This figure makes clear that chloride levels at midspan were well above the corrosion threshold in both tendons of each specimen. For the four-year specimens chloride levels were generally higher in the north tendons. Interestingly, it switched for the six-year specimens. Regardless, concentrations were of similar magnitude in the corresponding tendons across both sets of specimens. This is most clear for Specimens 2.3, 2.4, 3.4, and 4.2, for which both chloride concentrations were nearly equal. This trend confirms that the grout vents at midspan of the south ducts were indeed breached by chlorides during the exposure period.

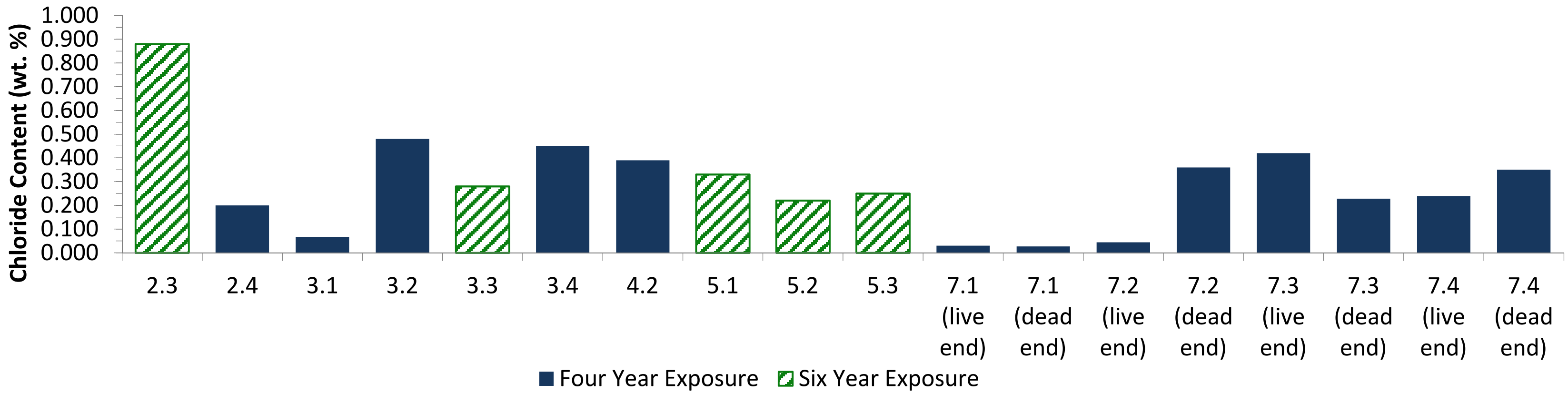


Figure 5.30 – Grout Chloride Content at Coupler Location

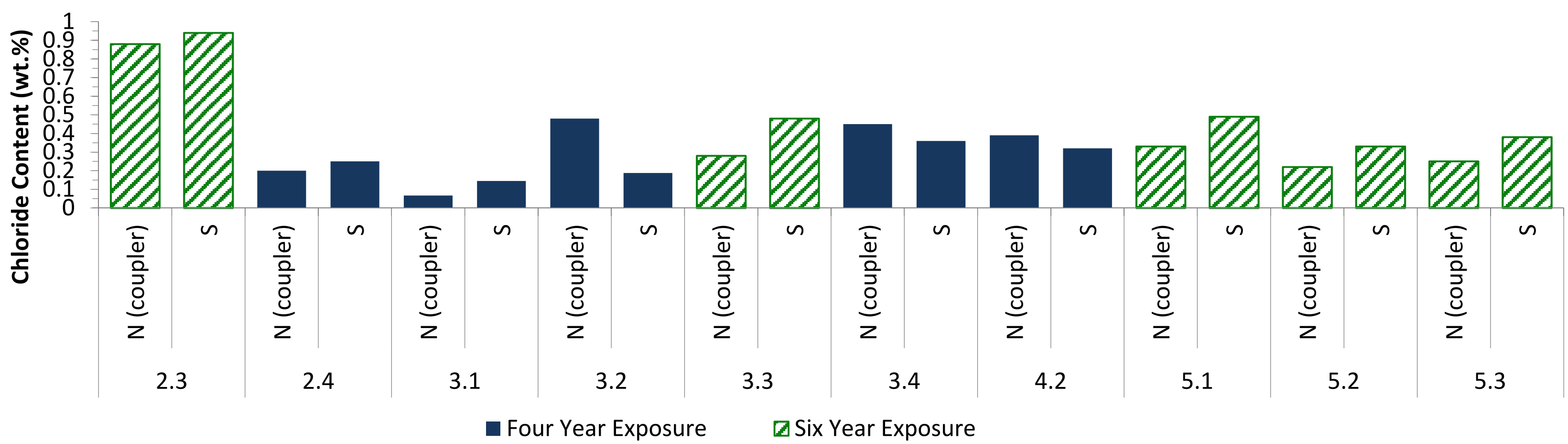


Figure 5.31 – Grout Chloride Content at Midspan of Coupled and Uncoupled Non-EIT Specimens

Chapter 6. Cost Analysis

As part of this project, both McCool[3] and Moyer[4] addressed the cost of improved corrosion resistant post-tensioning systems. However, after final autopsies Moyer[4] also presented a life cycle analysis and compared the cost of galvanized and plastic duct with each type of strand that was tested. However, the values are considered only for an isolated post-tensioned system in an actual bridge, as costs for the full structure may be different.

6.1 Methodology

The new corrosion-resistant post-tensioning materials cited in this report could be capable of extending the service life of a bridge by delaying or eliminating the onset of corrosion if they are implemented correctly. However, designers must understand the additional construction costs that each upgrade incurs. Cost estimates for each of the main project variables are presented. Quantities are based on what would be found in a typical moderate span segmental bridge. McCool selected as an example the FM 2031 Gulf Intracoastal Waterway (GIWW) bridge in Matagorda, Texas. This structure consists of a three-span, 680-foot-long cast-in-place post-tensioned segmental box girder bridge with 19 additional precast prestressed concrete approach spans. Only the cost of the 680 foot segmental bridge was studied. The bridge was opened to traffic in 2009[14]. Post-tensioning material quantities were obtained from TxDOT[15]. To simplify the cost comparison, only quantities of longitudinal post-tensioning materials for the three post-tensioned spans were considered.

Costs for each type of duct and anchorage examined in this report were obtained from a post-tensioning supplier. Strand costs were obtained from the Federal Highway Administration[16] and from estimates of the post-tensioning supplier. Strand and duct estimates were provided in a unit price per foot. Coupler cost estimates were given as a price per coupler. Anchorage estimates were given as a package price per bearing plate, anchor head, and corresponding number of wedges. Because electrically isolated tendons (EIT) were not used in the United States at the time of writing, prices were obtained from a source in Switzerland. These costs were converted to U.S. dollars using the market exchange rate at 5:00 PM EST on Friday, November 12, 2010[17]. All cost estimates exclude shipping, handling, and markup by the post-tensioning supplier. On-site labor costs were assumed to be identical for all materials.

6.2 Cost Comparisons

The official published construction cost of the bridge was $16 million[14]. This price was defined as the baseline cost. Figure 6.1 shows how increases in corrosion protection levels result in increased construction cost when conventional strand is used. Use of plastic duct results in only 0.1% cost increase. Figure 6.2 shows how this percentage increase for each level of protection is further increased when a new type of strand is used. The percent increase in total construction cost for each combination of strand, duct, and anchorage was based on the cost estimates acquired by McCool and Moyer. Figure 6.2 shows a clear correlation between increased protection and the cost of construction. As the level of protection increases the cost of construction goes up. Non-galvanized anchorage plates were less expensive than galvanized anchorage plates. Post-tensioned systems with galvanized duct were more economical than the ones with plastic ducts. The most expensive post-tensioning system was the fully encapsulated (EIT). The cost of the strands increased as the level of corrosion resistance increased. This is assuming that the corrosion observed in the flow-filled epoxy-coated strand in the autopsied specimens was an anomaly and occurred as a result of poor handling prior to fabrication of the specimens. The isolated corrosion tests of various stands reported by Kalina and Mac Lean indicated that the flow-filled epoxy-coated strand was excellent in corrosion resistance[5].

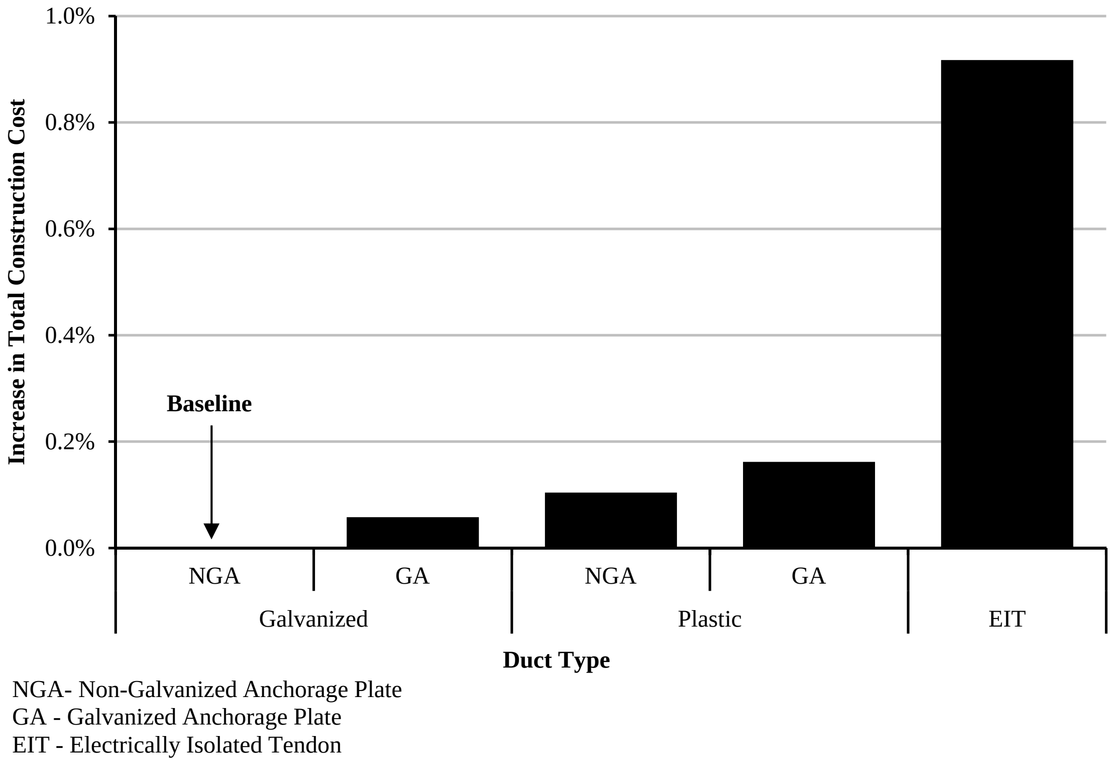
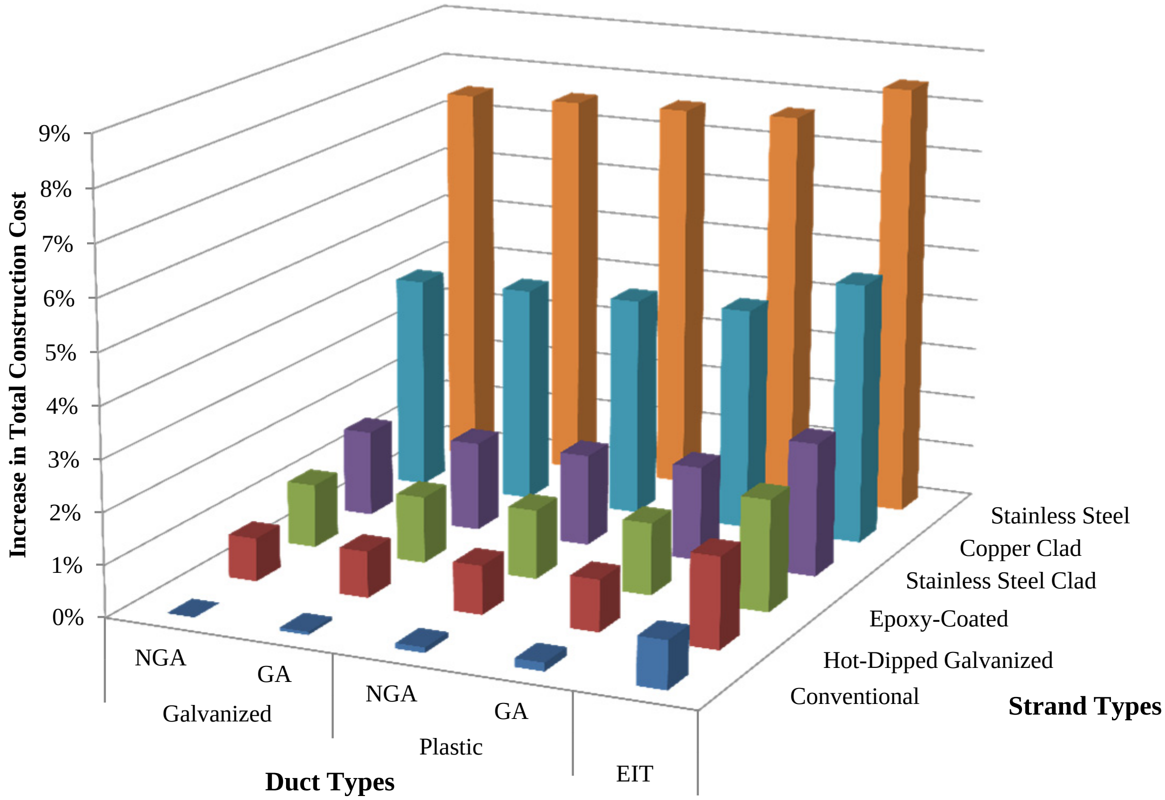


Figure 6.1 – Percentage Increase in Construction Cost with Conventional Strand

To better illustrate the effect of duct and anchorage plates on cost of construction, Figure 6.1 shows the percent increase in construction cost based on conventional strand with different anchorage and duct types. The incremental increase in cost for galvanized anchorage plates and plastic ducts were approximately 0.05% and 0.10%, respectively. Because of the increased number and complexity of components, the increase in construction cost of the fully encapsulated EIT post-tensioning system was substantially higher with an increase in cost of approximately 0.9%.



NGA- Non-Galvanized Anchorage Plate
GA - Galvanized Anchorage Plate
EIT - Electrically Isolated Tendon

Figure 6.2 – Construction Cost with Various Strand and Duct Options

If the Matagorda bridge were constructed with stainless steel strand and EIT, the total increase in construction would have been approximately 8.4%. This was the highest increase in construction cost and acts as the upper bound. Duct and anchorage types had less of an effect than strand type or electrical isolation had on the cost of construction. Figure 6.2 shows this as the change in the construction cost across the different duct options for one type of strand is only 1% while the change between different strands for one type of duct is around 8% when comparing conventional strand to stainless steel.

6.3 Conclusions

Repair and maintenance cost of a bridge over its lifetime are important considerations when considering the total cost of the bridge. Lifetime maintenance costs might be reduced and service life increased if more durable components are used in construction, even though these components would result in marginally higher construction costs. Real costs and the effect of inflation must be considered for a true life cycle cost analysis. More importantly, the question of how post-tensioning materials increase the service life of a bridge needs to be answered. Previous research[12] tried to answer these questions by performing life cycle cost analysis from earlier macrocell corrosion tests[7,11]. Lifetime costs on a random structure were computed by assuming that a decrease in corrosion rate corresponds to a proportional decrease in maintenance cost[12].

Even without a more detailed analysis, solid conclusions can be drawn. Most noticeably, there is a trivial cost increase for much longer lived plastic duct. The autopsies performed showed the good condition of the ducts themselves and the cost increase from this is easily justified if proper jointing to seal out chlorides can be developed. As stated in the project objective, the effectiveness of galvanized is not being evaluated and should no longer be used in post-tensioned bridges. The cost analysis further proves this. In moderately aggressive exposures a combination of plastic duct and conventional strand would probably provide the best cost effectiveness. Autopsies noted only mild discoloration and limited corrosion at locations where the conventional strand was in direct contact with the duct. Good grouting procedures and a limit on initial grout chloride content can prevent this corrosion. In highly aggressive exposures on critical bridges, consider plastic duct with either epoxy-coated, stainless steel, or stainless-clad depending on material tensile strength requirements and availability. The substantial cost increase for stainless steel as compared to epoxy-coated or stainless-clad strand can only justified if the other two strands cannot meet tensile capacity demands or if there is significant concern that the epoxy coating and stainless cladding will be damaged during the construction process.

Chapter 7. Conclusions and Recommendations

This chapter presents a set of conclusions based on the results of the testing procedure and specimen autopsies. Based on very aggressive exposure, these conclusions are useful in deciding the level of resistance that will be required in future bridge fabrication or design. Additionally, the chapter contains recommendations for future practice based on both specimen analysis and the Post-Tensioning Institute (PTI) and fib documents.

7.1 Autopsy Conclusions

7.1.1 Crack Control

Corrosion damage to the longitudinal bars, stirrups, and galvanized steel ducts was most severe at the location of flexural cracks. If a post-tensioned structure is uncracked, chlorides must travel through the concrete pore space to reach any reinforcing elements. This would delay the initiation and subsequent propagation of corrosion greatly. Therefore, we recommend that post-tensioned structures be designed as fully prestressed in aggressive environments and adequate cover should always be used. Additionally, most of the plastic coupled ducts had longitudinal cracking in the concrete above the duct. This was probably from the reduced concrete cover over the coupler and the very different thermal coefficients of the plastic coupler and duct versus that of the concrete. Adequate skin reinforcement for crack control should be used around tendons.

7.1.2 Epoxy-Coated Reinforcement

The use of epoxy-coated mild steel reinforcement greatly reduced the secondary cracking due to expansion of corroding reinforcement. These coated bars should always be used in aggressive environments despite the increased cost. Any corrosion observed on the epoxy-coated steel reinforcement normally occurred at locations where it had come into contact with another component or where the coating had been damaged in some fashion. The epoxy bars should be handled with the knowledge that the coating can be damaged to a point where the underlying steel is exposed. Defects that might arise during handling should be repaired with the appropriate repair compound before the placement of concrete. Instances of coating damage were caused by the epoxy-coated tie wire used to attach bars and duct in assembly or where the bars had been bent. Therefore, to minimize damage to the epoxy coating, we recommend using robust plastic ties to attach components to the coated bars and inspecting the coating before concrete placement. Epoxy-coated steel reinforcement should meet the relevant ASTM standard and the applicable TxDOT standard for thickness.

7.1.3 Chloride Content

Chloride levels were above the corrosion threshold at rebar level in the specimens, and all rebar showed some corrosion at that level. However, chloride content cannot adequately predict the presence of corrosion in epoxy-coated reinforcement. Additionally, chloride content cannot predict the extent of corrosion.

7.1.4 Duct

Galvanized Duct

Although their use is already considered obsolete, we recommend that galvanized ducts never be used in any aggressive environment due to the widespread duct corrosion observed. Every galvanized duct autopsied showed area loss and pitting. These were most prevalent at the locations of grout voids within the tendon, reinforcing the importance of construction quality. Corrosion initiated at the locations where surface cracks intersected with the ducts and spread from there.

Plastic Duct

The greatly improved durability of the plastic ducts prevented the majority of the ducts from getting damaged during casting and post-tensioning or during the highly aggressive chloride exposure. Therefore, it is recommended that they always be used in aggressive environments. It must be noted that the continuous ducts with researcher-installed grout vents allowed chlorides to infiltrate the duct due to the poor workmanship at the point of the vent seal. All grout vents should be installed on couplers where specific provisions are made for the grout hose to have a positive watertight connection. Current grout vents are “welded” to the plastic duct or coupler. As shown in Moyer’s cost analysis, plastic ducts used with conventional strands and non-galvanized anchorages increase the overall bridge construction cost by only 0.1%. The analysis also shows that the service life can be significantly increased when plastic ducts are used with conventional strands. This extra construction cost can be spread over an extended service life while also reducing maintenance costs, thus saving the customer substantial money.

7.1.5 Grout

Because grout was injected with a hand pump, the grout in the autopsy specimens was not always well-consolidated and showed some large voids. It is recommended that anti-bleed and/or thixotropic grout be used for internal bonded post-tensioning tendons. Additionally, grout should be injected using the equipment, personnel, and procedures specified in the TxDOT Standard Specification. The PTI specifications should also be adopted. These include the use of a transparent duct on a test setup to show fabricators where any bleeding, segregation, or air voids may be forming. Good grouting procedure is essential

It should be mentioned that the prebagged grout used in the current study might have been contaminated with chlorides at a level very near the chloride limit before the grout was placed in the tendons. Therefore, we recommend that the chloride levels of any grout used be considerably lower than the chloride concentration threshold for corrosion. If the chloride content of the grout is unknown, the chloride concentration of the grout should be determined before the grout is injected into the duct as a precautionary measure. Note that chloride levels detected in the grout were very high but the good condition of many of the tendons means that the absolute level is not directly correlated to the corrosion itself.

7.1.6 Coupler

In many cases, chlorides entered the plastic ducts through breaches in the seal between coupler and duct. All of the plastic ducts with couplers had grout chloride concentrations well above the corrosion threshold. It is recommended that any duct couplers be installed under the supervision of PTI-certified inspectors or equivalent. Additionally, duct pressure testing should be conducted in accordance with the TxDOT Standard Specification and PTI specifications. For the internal longitudinal ducts of segmental bridges, duct couplers should be installed at segment joints to protect the tendon from chloride intrusion. Alternatively, the segmental duct joints should be swabbed with epoxy to protect them from within. The sealant should be robust enough to maintain a seal during grouting and sufficiently durable in a high alkaline environment throughout the service life of the bridge.

Chloride concentrations were very elevated in the continuous plastic ducts. This suggests that grout vents should be an integral part of the coupler; for utmost watertightness, grout hoses should have a positive attachment to the grout vent. The grout chloride concentration in the coupled one-way duct was approximately twice that of the grout chloride concentrations in the coupled two-way ducts. This indicates that the snap-on coupler on the one-way duct had not been as watertight as the heat-shrink-wrapped slip-on coupler of the two-way ducts.

7.1.7 Strand

All strand types showed a low level of corrosion. Elevated grout chloride levels in many specimens suggest that chlorides were able to travel within strand interstices along the entire length of the tendons. For the four-year autopsies, corrosion was more severe within the anchor heads than in the main autopsy regions. After six years, the anchorage regions and ponding areas had similar levels of corrosion. Some strands did not meet the ASTM yield and ultimate strength requirements. However, manufacturers stated that the proper tensile capacity could be easily produced given enough demand for a particular type of strand.

Conventional Strand

After four years, conventional strands showed discoloration or light surface corrosion spots on their outer wires and somewhat more severe corrosion on their inner wires. The spots were most frequent in the regions that had been in direct contact with the surrounding duct. After six years, moderate corrosion and minimal pitting was apparent on the inner wires. The cost analysis demonstrated that encasing conventional strands in plastic ducts instead of galvanized ducts and anchoring against non-galvanized anchorage plates would result in an approximately 0.1% increase in construction cost of a bridge. However, this combination would result in a substantial increase in service life.

Hot-Dip Galvanized Strand

After four years of exposure, damage to the hot-dip galvanized strand was similar to that of the conventional strand, with some slight staining or discoloration on the outer wires and minimal pitting on the inner wire. On the outer wires of each strand, corrosion was limited to the zinc coating. However, corrosion on the inner wire occurred on the bare steel not covered with zinc during the galvanizing process. The galvanized strand had a very strong bond with the surrounding grout and was very difficult to remove. Small bubbles found in the interstices of some galvanized strand suggest that the zinc may have reacted with the grout chemically. The six-year autopsies showed more extensive corrosion. The exterior wire had signs of corrosion both for the zinc coating as well as the underlying steel. This indicates minor propagation of corrosion that occurred between the autopsies. Cost and life cycle analysis showed that the use of hot-dip galvanized strands encased in plastic duct instead of galvanized duct with non-galvanized anchorage plates would result in an increase of the construction cost by 0.9%. However, with proper construction techniques and grouting procedure this would decrease corrosion concerns and increase the service life considerably.

Copper-Clad Strand

The copper-clad strand in the main autopsy region assumed a glossy black patina on all wires that was noticed by both McCool and Moyer. The patina was darker and glossier on the inner wires than the outer wires and occasional reddish colored spots were observed after six years of exposure. Dezincification may have occurred near the ends of some copper-clad strands. In the anchorage region, the wedges penetrated the copper coating and caused the underlying steel to corrode there. As with the conventional and hot-dip galvanized strands, the cost and life cycle analysis showed that when copper-clad strands are encased in plastic duct instead of galvanized duct and anchored against non-galvanized anchorage plates, the cost of construction would increase by approximately 4.3% but the service life would be lengthened substantially. Further exploration of obtaining copper-clad strand with suitable mechanical properties should be encouraged.

Stainless Steel Strand

The strand in the main autopsy region showed very little corrosion after four years and after six years had only a few spots of discoloration and light corrosion confined to the end regions. For the most part, the strand appeared to be brand new. These strands had a very weak bond with the surrounding grout, which resulted in debonding during autopsy. When stainless steel strands are encased in plastic duct instead of galvanized duct and anchored against non-galvanized anchorage plates, the cost of construction would increase by approximately 7.7% but service life would be greatly lengthened. While the stainless steel strand was responsible for the most damage in plastic duct due to its curvature and gouging concerns, the duct was not punctured and did not influence the corrosion behavior.

Stainless-Clad Strand

The condition of the stainless-clad strands was similar to the condition of the stainless steel strands with a few spots of discoloration and light corrosion. The heat treatment of the anchor heads to remove the strand might have caused the discoloration that had been observed in the strands from the anchorage region. The grout bonded better with the stainless-clad strands with the stainless strands. All the results for the stainless-clad strand were based on six-year autopsies as there were no four-year specimens. Cost and life cycle analysis showed that when stainless-clad strands are encased in plastic duct instead of galvanized duct and anchored against non-galvanized anchorage plates, the cost of construction would increase by approximately 1.8% and significantly increase service life. The stainless-clad strand is nearly 6% cheaper than the stainless steel strand while providing equivalent corrosion protection. This cost advantage is a significant factor in the selection of materials for future post-tensioned bridges. Since the stainless-clad strand met mechanical property requirements for Grade 250 tests, its cost advantage is very favorable.

Flow-Filled Epoxy-Coated Strand

Like the stainless-clad strand, the flow-filled epoxy strand was only autopsied after six years of exposure. Therefore, the poor performance of the strand cannot be attributed to any initiation and propagation behavior. The inner and outer wires had corrosion ranging from mild pitting to light corrosion over the majority of their lengths and did not perform as well as initially expected. There seems to be two possibilities for the origin of this very light corrosion and mild pitting. The first of these is that this corrosion might have been induced by the paint stripper used to remove the epoxy. However, the experiment that was performed on two lightly polished wires from a conventional strand exposed to the paint stripper for seven days showed no further corrosion or pitting on the wires—thus, the corrosion likely existed before the strand was coated. The condition of the epoxy coating was good and showed only a tiny hole, some slight scratching, and slight gouges.

Companion tests performed by Kalina[5] showed the epoxy-coated strands performed extraordinarily well compared to all of the other strand types. When submerged in a chloride solution, either encased in grout or exposed, the epoxy strand exhibited the smallest corrosion rating. The underlying strand is the same as the conventional strand so the mechanical properties were equivalent to the conventional strand and met all mechanical specifications. Cost and life cycle analysis showed that when flow-filled epoxy-coated strands are encased in plastic duct instead of galvanized duct and were anchored against non-galvanized anchorage plates, the cost of construction would increase by roughly 1.4%. However, the service life would be lengthened immensely assuming that the corrosion that had been observed during this study was an anomaly and the strand would have had the same corrosion resistances as indicated in the companion tests[5].

7.1.8 Anchorage

Neither the four-year nor the six-year exposures demonstrated significant difference between the performance of the galvanized and non-galvanized anchorage plates. The quality of the backfill mortar and the bond of the backfill mortar to the base concrete played a more significant role in the protection of the anchorage region than the anchorage plates did. This was noted by both McCool and Moyer.

7.1.9 Electrically Isolated Systems

Strand corrosion in the fully encapsulated tendon was comparable to the non-encapsulated tendons in other specimens over both four and six years. After four years, chloride concentrations were below the corrosion threshold along the entire tendon. It seemed that chlorides did not enter the tendon through the couplers, as was observed on other specimens. However, evidence suggested that chlorides may have entered through the anchorages, likely due to installation problems. After six years, the grout chloride concentrations were well above the corrosion threshold except for the apex of the duct. At the apex of the duct, the chloride concentrations were very near to the corrosion threshold. These chloride concentrations suggest that the poor bond of the heat shrink and poor seal of the coupler had allowed chlorides to enter the duct. When the tendon was being cut from the anchorage plate, Moyer observed moisture. This supports the AC impedance data that suggested that the integrity of the duct had breached in some fashion. Cost analysis showed that using this system on a bridge would increase the cost appreciably depending on the strand type. No analysis was condcuted on how this system would affect the service life of a bridge.

7.2 Monitoring

7.2.1 Half-Cell Potential

The half-cell method was able to predict corrosion in the specimens. However, it could not be determined in which reinforcing element the corrosion was taking place.

7.2.2 AC Impedance

AC impedance measurements indicated that the electrically isolated tendon was barely monitorable, if at all. It did suggest that chlorides may have entered the tendon during the exposure period. Moisture entering the duct was confirmed when the tendon was cut from the anchorage plate and moisture was observed in the duct. AC impedance readings can be used to detect duct defects, but this was not possible for the autopsy specimen due to its lack of monitorability.

7.3 New Test Specimens

An efficient, small-scale specimen was designed and constructed for the corrosion research. The new specimens are much more cost-effective than those used in previous research because 1/8th the amount of material is used for construction while producing quite comparable results. The specimens have been fully autopsied and analyzed after exposure for approximately six years at the time of this writing. Visible signs of corrosion first appeared on some of the specimens during the first year of exposure. Approximately half of the specimens were autopsied after four years. The use of epoxy-coated mild steel reinforcement controlled surface deterioration more effectively than the uncoated mild reinforcement used in the larger specimens. Because epoxy-coated mild steel reinforcement was used for longitudinal bars and stirrups, the corrosion ratings were significantly smaller than the ratings from the larger specimens autopsied after four years. This served to better isolate the duct and strand ratings in the new specimens. The reduced size specimens have been proven to be acceptable and much more efficient exposure specimens, especially in terms of isolated variables intended for inspection.

The new specimens also show the better corrosion protection that was implemented. Figure 7.1 shows that while the strand corrosion was better isolated as a variable, the overall value of the corrosion rating was lower. This can be attributed to multiple different factors. With the new specimens, cracking was controlled and secondary expansive corrosion from the mild reinforcement was limited. More significantly, the grouts and grouting procedure was improved in the time between the specimens were cast. While there are concerns regarding the chloride in the prepackaged grout used in the smaller specimens, the overall placement and coverage of the grout was likely much better. PTI recommendations for grouting were followed, which limited grout voids and segregation that contribute to strand corrosion.

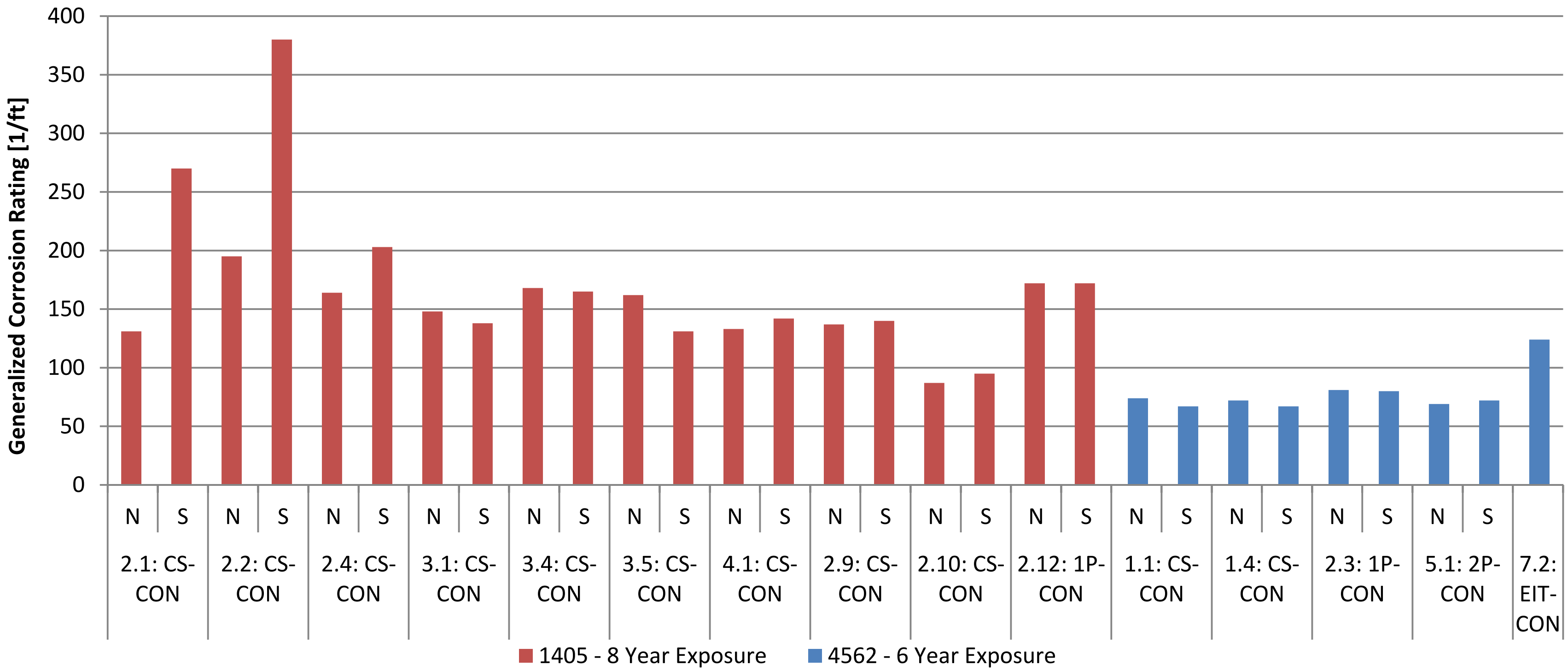


Figure 7.1 – Comparison of Conventional Strand Corrosion at Final Autopsy for Project 1405 and 4562

7.4 Future Testing Suggestions

- The specimen designed by Ahern was successful. However, due to corrosion of the uncoated Dywidag bar used to apply the external loading, it is recommended that the bar be epoxy-coated.
- To track the infiltration of the chlorides into the specimen and possibly into the duct, it is recommended that a dye be used in the salt solution. The dye should not affect how the chlorides react with metals and/or add any additional chlorides to the solution.
- Cracking over to the plastic duct was an issue and should be addressed. Concrete and plastic have different coefficients of thermal expansion. As such, temperature variation may result in gaps between embedded grout vents and the surrounding concrete, providing easy access for chlorides. Study the effect of applying a flexible, waterproof membrane around grout vents at the concrete surface to prevent chloride ingress there.
- Continue developing better grout mixes. Grout voids provide an easy avenue for chloride travel in a tendon, so minimizing grout voids should remain a priority. Ensure that grout chloride content specifications are followed so that chlorides are not introduced to the tendon through the grout itself.
- Develop positively waterproof connection systems for both ducts and vents.
- Test more couplers or test the quality of workmanship in their implementation.
- Non-destructive monitoring was difficult to do and new and existing non-destructive monitoring methods for post-tensioned structures should be refined and developed.

7.5 Recommendations from Literature

The recommendations included in this chapter are based on design flaws or repeated corrosion issues that were noticed and documented in the autopsies but are not mentioned explicitly in the specifications. This includes a requirement for full cover always being used with plastic ducts and always employing epoxy-coated non-prestressed reinforcement for crack control. Another reoccurring concern was with the poor quality in grouting. The older PTI specification did not contain recommendations for pressure testing. The new specification rightly mandates grouting continues until constant pressure is observed across grout vents and duct openings. This report serves to reiterate the importance of this procedure and highlight the issues with not following them.

The fib Bulletin providing suggested protection levels (PL) does not issue recommended uses or limitations. The specifications should limit the use of PL1 to interior uses only based on the low level of protection associated with duct and strand requirements. The fib Bulletin does not mention non-presstressing elements either. Future specifications should include epoxy-coated mild steel reinforcement for crack control.

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