

NON-DESTRUCTIVE EVALUATION OF BRIDGE STAY CABLE AND  
EXTERNAL POST-TENSIONING SYSTEMS

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of  
Texas A&M University  
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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December 2014

Major Subject: Civil Engineering

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## ABSTRACT

Non-destructive evaluation (NDE) of bridge stay cable and external post-tensioning (PT) systems is an essential tool to thorough bridge inspections and also eliminates any necessary repair of destructions made during evaluation. Conditions such as corrosion, steel strand and wire breakage, tendon section loss, voids in the grout, water infiltration, and other undesired grout conditions can go undetected in nontransparent stay cable and external PT ducts without proper inspection. In this research, sounding, ultrasonic tomography, infrared thermography, and ground penetrating radar are evaluated for their applicability to identify selected conditions in a mock-up specimen representative of both a stay cable system and an external PT system. A borescope is also used to collect ground truth data for comparison with the NDE results. The conditions are fabricated in the mock-up specimen to closely represent conditions in the field so that the NDE results are directly applicable to bridge construction quality control and in-service bridge inspections. Locations of corrosion, breakage, and section loss are established prior to grouting. These conditions are combined with both foam void locations and an air-filled void in the grout along the top of the duct.

The sounding method was extremely applicable in accurately detecting air voids in the grout and the sounding results matched closely with the ground truth data of the air void extent collected by the use of a borescope. This research concludes that the infrared thermography and ground penetrating radar devices used did not identify any of

the corrosion, section loss, or breakage locations within the specimen. However, both of these methods identified air voids and foam voids in the duct free span during both the quality control testing period and inspection testing period, although GPR did not provide accurate void depth. In addition, infrared thermography was able to identify air voids within the grout caps at each anchorage end. The ultrasonic tomograph used in this research, designed for use on concrete rather than stay cables and external PT, produced inconsistent results when used on the specimen. In future research, a different means of ultrasonic tomography testing may be applicable to identifying voids in the grout.

## DEDICATION

This work is dedicated to my family, whose support throughout graduate school has been tremendous.

## ACKNOWLEDGEMENTS

I would like to thank both my committee chair, Dr. Hurlebaus, and co-chair, Dr. Hueste, for their direction and support. Their advice has been instrumental throughout this research work. Also, I would like to thank my third committee member, Dr. Muliana, for her support and willingness to participate in my committee.

Thank you to the graduate students I have worked closely with on this project for their teamwork and assistance. Thank you also to friends and faculty in the Civil Engineering department at Texas A&M University for greatly enhancing my graduate school experience.

Finally, thank you to both of my parents for their encouragement to work hard in everything I do.

## TABLE OF CONTENTS

	Page
ABSTRACT .....	ii
DEDICATION .....	iv
ACKNOWLEDGEMENTS .....	v
TABLE OF CONTENTS .....	vi
LIST OF FIGURES.....	viii
LIST OF TABLES .....	xiii
1. INTRODUCTION.....	1
1.1. Research Significance .....	3
1.2. Research Objectives .....	4
1.3. Research Outline .....	5
1.4. Thesis Organization.....	9
2. LITERATURE REVIEW .....	11
2.1. Stay Cable Systems .....	11
2.2. External Post-Tensioning Systems .....	13
2.3. Deterioration Conditions .....	15
2.4. Case Studies .....	21
2.5. Prior Fabrication of Conditions.....	34
2.6. Non-Destructive Evaluation Methods .....	39
3. FABRICATION OF CONDITIONS.....	50
3.1. Corrosion .....	51
3.2. Breakage and Section Loss.....	56
3.3. Voids .....	57
4. SPECIMEN DESIGN AND CONSTRUCTION .....	61
4.1. Specimen Design.....	62
4.2. Condition Locations .....	62
4.3. Specimen Construction.....	66

5.	NDE RESULTS AND DISCUSSION .....	73
5.1.	Borescope .....	73
5.2.	Sounding.....	80
5.3.	Ultrasonic Tomography.....	82
5.4.	Infrared Thermography .....	85
5.5.	Ground Penetrating Radar .....	96
6.	CONCLUSIONS AND RECOMMENDATIONS.....	101
6.1.	Applicability of NDE Methods .....	101
6.2.	Recommendations for Future Fabrication of Conditions .....	102
6.3.	Recommendations for Future NDE Research .....	104
	REFERENCES .....	107
	APPENDIX A: QUALITY CONTROL NDE RESULTS COMPARISON.....	112
	APPENDIX B: ULTRASONIC TOMOGRAPHY RESULTS .....	113
	APPENDIX C: GROUND PENETRATING RADAR RESULTS .....	118
	APPENDIX D: FABRICATION OF CONDITION PROTOCOLS.....	124
	Appendix D.1. Fabrication of Corrosion Protocol .....	124
	Appendix D.2. Fabrication of Section Loss Protocol.....	141
	Appendix D.3. Fabrication of Breakage Protocol .....	157
	Appendix D.4. Fabrication of Grout Conditions Protocol .....	164
	Appendix D.5. Fabrication of Voids Protocol.....	171
	Appendix D.6. Fabrication of Water Infiltration Protocol .....	185
	Appendix D.7. Fabrication of Tendon Deterioration in the Anchorage Systems Protocol .....	192

## LIST OF FIGURES

	Page
Figure 1-1: Stay Cable and External PT Specimen.....	8
Figure 2-1: Stay Cable Bridge (Vannemreddi 2010) .....	12
Figure 2-2: Example of External Post-Tensioning System Setup (Lee 2007) .....	13
Figure 2-3: Luling Bridge (Mehrabi et al. 2010) .....	22
Figure 2-4: Luling Bridge Stay Cable Inspection Basket (Mehrabi et al. 2010) .....	23
Figure 2-5: Luling Bridge Corrosion and Sheathing Split (Mehrabi 2009) .....	24
Figure 2-6: General Rafael Urdaneta Bridge (Sarcos-Portillo et al. 2003) .....	25
Figure 2-7: Cable Corrosion in the General Rafael Urdaneta Bridge (De Rincon et al. 2001) .....	26
Figure 2-8: Mid-Bay Bridge (Hartt and Venugopalan 2002).....	27
Figure 2-9: Corrosion of the Mid-Bay Bridge (Corven 2001) .....	28
Figure 2-10: Varina-Enon Bridge (from <a href="http://www.figgbridge.com/varina_enon_bridge.html">http://www.figgbridge.com/varina_enon_bridge.html</a> ).....	29
Figure 2-11: Varina-Enon Bridge External Tendon Failure (Hansen 2007).....	30
Figure 2-12: Close-Up View of External Tendon Failure (Hansen 2007) .....	30
Figure 2-13: Strand Corrosion of the Niles Channel Bridge (Powers et al. 2002).....	31
Figure 2-14: Braidley Road Bridge (from <a href="http://commons.wikimedia.org/wiki/File:Bournemouth,_temporary_traffic_lights_in_Braidley_Road_-_geograph.org.uk_-_1772594.jpg">http://commons.wikimedia.org/wiki/File:Bournemouth,_temporary_traffic_lights_in_Braidley_Road_-_geograph.org.uk_-_1772594.jpg</a> ) .....	32
Figure 2-15: Ringling Causeway Bridge (Paredes 2013).....	33
Figure 2-16: External Tendon Failure of the Ringling Causeway Bridge (Paredes 2013) .....	34
Figure 2-17: Electrolytic Corrosion Cell Lab Setup (Fricker and Vogel 2007).....	35
Figure 2-18: Electrolytic Corrosion Cell Field Setup (Fricker and Vogel 2007).....	36



Figure 2-19: Galvanic Corrosion Cell Setup (Wood et al. 2013).....	37
Figure 2-20: Fabrication of Voids Using Polystyrene Foam (Tinkey and Olson 2007) .	38
Figure 2-21: Vacuum Pump Setup (Im 2009) .....	39
Figure 3-1: Electrolytic Corrosion Cell Setup for Uniform Corrosion .....	53
Figure 3-2: Laboratory Uniform Corrosion Setup .....	54
Figure 3-3: Fabrication of Corrosion in the Field .....	55
Figure 3-4: Strand Corrosion.....	56
Figure 3-5: Strand Breakage .....	56
Figure 3-6: Strand Section Loss .....	57
Figure 3-7: Foam Void Attachment to Strand.....	58
Figure 3-8: Foam Void in HDPE Duct.....	59
Figure 3-9: Exposed Strand Visible Through Drilled Hole .....	60
Figure 4-1: Stay Cable and External PT Specimen Setup.....	62
Figure 4-2: Breakage, Section Loss, and Corrosion Placement .....	64
Figure 4-3: Foam Void Placement .....	65
Figure 4-4: Anchorage System under Construction .....	67
Figure 4-5: Grout Ports at Anchorage: (a) Non-Stressing End, (b) Stressing End .....	68
Figure 4-6: Grouted Stay Cable and External PT Specimen.....	69
Figure 4-7: Grout Leakage: (a) Anchorage, (b) Drilled Hole, (c) Anchorage .....	70
Figure 4-8: Wick-Induced Bleed Test Setup: (a) Full View, (b) Close-Up .....	71
Figure 5-1: Borescope Used on Specimen .....	74
Figure 5-2: Void Mapping Sheet (Im 2009).....	75
Figure 5-3: Borescope Map of Voids .....	75
Figure 5-4: Borescope View of Foam Void .....	76

Figure 5-5: Borescope View of Several Exposed Strands .....	77
Figure 5-6: Borescope View of Air Void.....	77
Figure 5-7: Borescope View of Anchorage Region .....	78
Figure 5-8: Borescope View Inside Grout Cap.....	79
Figure 5-9: Borescope View of Section Loss.....	80
Figure 5-10: Sounding Tools.....	81
Figure 5-11: Sounding Map of Voids .....	82
Figure 5-12: Ultrasonic Tomograph.....	83
Figure 5-13: Specimen Spans for UST Testing .....	85
Figure 5-14: Infrared Thermography Device .....	86
Figure 5-15: (a-d) IRT QC of Duct Free Span during Cool Down .....	88
Figure 5-16: (a-b) IRT QC of Top Void Variation during Cool Down .....	89
Figure 5-17: (a-b) IRT QC of Anchorage Ends during Cool Down .....	90
Figure 5-18: (a-b) IRT QC of Anchorage Ends during Warm Up .....	90
Figure 5-19: (a-b) IRT QC of Foam Void Locations during Warm Up.....	91
Figure 5-20: (a-d) IRT Inspection of Duct Free Span during Cool Down .....	92
Figure 5-21: (a-b) IRT Inspection of Anchorage Ends during Cool Down .....	93
Figure 5-22: (a-b) IRT Inspection of Anchorage Ends during Warm Up .....	93
Figure 5-23: (a-d) IRT Inspection of Foam Void Locations during Warm Up.....	95
Figure 5-24: (a-b) IRT Inspection of Foam Void Locations during Cool Down .....	95
Figure 5-25: Ground Penetrating Radar Unit .....	96
Figure 5-26: Specimen Sections for GPR Testing .....	97
Figure 5-27: GPR QC Test A1 at Small Air Void .....	99
Figure 5-28: GPR QC Test C1 at Large Air Void.....	99

Figure 5-29: GPR Inspection Test A2 at Small Air Void .....	100
Figure 5-30: GPR Inspection Test C2 at Large Air Void.....	100
Figure A-1: Borescope Map of Voids .....	112
Figure A-2: Sounding Map of Voids.....	112
Figure A-3: GPR Path 1 QC Results (Scan Depth 4 inches) .....	112
Figure A-4: IRT QC Images (a-b) Span 1, and (c) Span 2.....	112
Figure B-1: UST QC of Span 1 Top at 25 kHz .....	113
Figure B-2: UST QC of Span 1 Top at 50 kHz .....	113
Figure B-3: UST QC of Span 1 Top at 85 kHz .....	113
Figure B-4: UST QC of Span 1 Side at 25 kHz .....	113
Figure B-5: UST QC of Span 1 Side at 50 kHz .....	114
Figure B-6: UST QC of Span 1 Side at 85 kHz .....	114
Figure B-7: UST QC of Span 2 Top at 25 kHz .....	114
Figure B-8: UST QC of Span 2 Top at 50 kHz .....	114
Figure B-9: UST QC of Span 2 Top at 85 kHz .....	114
Figure B-10: UST QC of Span 2 Side at 25 kHz .....	115
Figure B-11: UST QC of Span 2 Side at 50 kHz .....	115
Figure B-12: UST QC of Span 2 Side at 85 kHz .....	115
Figure B-13: UST Inspection of Span 1 Top at 25 kHz .....	115
Figure B-14: UST Inspection of Span 1 Top at 50 kHz .....	115
Figure B-15: UST Inspection of Span 1 Top at 85 kHz .....	116
Figure B-16: UST Inspection of Span 1 Side at 25 kHz .....	116
Figure B-17: UST Inspection of Span 1 Side at 50 kHz .....	116
Figure B-18: UST Inspection of Span 1 Side at 85 kHz .....	116

Figure B-19: UST Inspection of Span 2 Top at 25 kHz .....	116
Figure B-20: UST Inspection of Span 2 Top at 50 kHz .....	117
Figure B-21: UST Inspection of Span 2 Top at 85 kHz .....	117
Figure B-22: UST Inspection of Span 2 Side at 25 kHz .....	117
Figure B-23: UST Inspection of Span 2 Side at 50 kHz .....	117
Figure B-24: UST Inspection of Span 2 Side at 85 kHz .....	117
Figure C-1: GPR QC Test A1 .....	118
Figure C-2: GPR QC Test A2 .....	118
Figure C-3: GPR QC Test B1 .....	118
Figure C-4: GPR QC Test B2 .....	119
Figure C-5: GPR QC Test C1 .....	119
Figure C-6: GPR QC Test C2 .....	119
Figure C-7: GPR QC Test D1 .....	120
Figure C-8: GPR QC Test D2 .....	120
Figure C-9: GPR Inspection Test A1 .....	120
Figure C-10: GPR Inspection Test A2 .....	121
Figure C-11: GPR Inspection Test B1 .....	121
Figure C-12: GPR Inspection Test B2 .....	121
Figure C-13: GPR Inspection Test C1 .....	122
Figure C-14: GPR Inspection Test C2 .....	122
Figure C-15: GPR Inspection Test D1 .....	122
Figure C-16: GPR Inspection Test D2 .....	123

## LIST OF TABLES

	Page
Table 3-1: Fabrication of Condition Protocols.....	51
Table 4-1: Tendon Deterioration Conditions .....	64
Table 4-2: Grout Deterioration Conditions .....	65
Table 4-3: Grout Cube Strength .....	72

## 1. INTRODUCTION

Bridge post-tensioning (PT) and stay cable systems have gained popularity in recent decades due to their ability to facilitate longer bridge spans. These systems can increase the durability and load carrying efficiency of bridges if proper inspections and necessary maintenance is carried out. Continuous condition assessment of post-tensioning and stay cable systems is vital to the structural health of these in-service bridges. There are multiple conditions that can become present during both construction and over the life of the bridge. These undesired conditions in the stay cable and external PT systems can escalate in severity quickly if there are not regular and thorough inspections to identify the conditions.

Unlike internal PT embedded in concrete within the bridge girders, external PT is similar to stay cables in that there is most often clearance around the exterior of the duct for inspection. However, access to stay cables and external post-tensioning can be difficult and especially challenging due to the current practice of using nontransparent ducts. Undesired conditions can easily go undetected because visual bridge inspection is typically not adequate for detection of conditions existing within the ducts. These conditions include corrosion, steel strand and wire breakage, tendon section loss, voids in the grout, water infiltration, and other undesired grout conditions. Tendon deterioration in the anchorage region is also problematic and highly likely to occur as a combination of the aforementioned conditions. Non-destructive evaluation (NDE)

technologies can be largely appropriate for the detection of these conditions in post-tensioning and stay cable systems. The use of NDE methods or a combination of NDE methods in bridge inspections allows for the possible identification of detrimental conditions prior to them being at a critical level in terms of the strength and safety of the bridge. In this research, the NDE methods used are ultrasonic tomography, infrared thermography, ground penetrating radar, and sounding. These methods are used in comparison with borescope results and visual inspection.

Since there is often similarity in their materials and cross-sections, the same methods of non-destructive evaluation can prove to be applicable to the free spans of both stay cable and external PT system inspections. In this research, a high-density polyethylene (HDPE) duct of 4 inch diameter with 19 grouted 0.6 inch diameter seven-wire strands is used for evaluation applicable to both stay cable systems and external PT systems.

Also, different conditions can exist at the same locations along the length of the ducts or within the duct cross-sections. This must be acknowledged during the use of non-destructive testing. For example, voids in the grout alongside water infiltration provides an optimal environment for continuous corrosion of the steel strands in the duct. This corrosion can lead to significant steel section loss. From this example alone, it is very evident that all of the undesired conditions must be able to be detected properly during NDE bridge inspections so that there is full understanding of the condition of the bridge and no possible decreasing load capacity mechanisms are missed. The ability of ultrasonic tomography, infrared thermography, ground penetrating radar, sounding, and

borescope methods to identify individual conditions or a combination of conditions at different locations along the duct is evaluated using a representative constructed mock-up specimen.

### *1.1. Research Significance*

The significance of this research is demonstrated in the non-destructive evaluation methods testing results. Through the testing results, the applicability of each method to identify each condition or a set combination of conditions in the mock-up specimen is established. The mock-up specimen replicates both potential stay cable system and external PT system conditions and is representative of field conditions as closely as possible. Therefore, the testing results are applicable to inspections of stay cable systems and external PT systems of in-service bridges. The specimen contains a common material arrangement now used in the field, 19 0.6 inch diameter seven-wire strands grouted in HDPE pipe.

Also significant to the results of this research work are the methods used to fabricate the conditions in the specimen. Fabrication of condition protocols have been established in great detail in order to be easily replicated for future construction of more mock-up specimens. The fabrication of condition methodologies were subject to multiple trials before the best method was standardized for extended use in fabricating the conditions. All of the considered conditions were also extensively compared to field conditions of stay cable and external post-tensioning systems to ensure the best possible replicated conditions were represented in the created protocols.



## *1.2. Research Objectives*

The overall objective of this research is to determine the applicability of ultrasonic tomography, infrared thermography, ground penetrating radar, and sounding in identifying the undesired conditions within stay cable and external post-tensioning systems, along with using the most field representative condition fabrication methodologies. This research is divided in to four main goals. These goals are as follows.

- 1) Develop procedures for the fabrication of conditions that result in the fabricated condition's close alignment to the actual conditions in current bridge structures with stay cable and external PT systems.
- 2) Design a specimen representative of stay cable and external PT systems with specified locations of corrosion, steel strand and wire breakage, tendon section loss, and voids in the grout.
- 3) Construct the specimen with the conditions at their specified locations as accurately as possible according to the established fabrication of condition procedures.
- 4) Conduct ultrasonic tomography, infrared thermography, ground penetrating radar, and sounding testing on the specimen in comparison to known locations and borescope results in order to identify the appropriate NDE method for the detection of each condition or combination of conditions in the mock-up specimen.

### *1.3. Research Outline*

This research is outlined in seven tasks. These tasks extend from a complete review of current relevant literature to presentation of the research results in this thesis.

The included tasks are:

- 1) Literature Review
- 2) Condition Fabrication Procedures
- 3) Specimen Design
- 4) Specimen Construction
- 5) NDE Testing of Specimen
- 6) NDE Testing Results Evaluation
- 7) Presentation of Results

As Task 1, thorough literature review was conducted on both condition fabrication techniques and the current accepted applicability of NDE methods in identifying undesired conditions in bridge stay cables and external PT systems. It compiles pertinent information from many different resources in order to be sure it contains all applicable prior research results and conclusions, along with current practices. The results of this extensive literature review are used as a comparison to the findings of this research.

Procedures were established for the fabrication of conditions possibly present in stay cable and external PT systems as Task 2 of the research. These conditions include corrosion, steel strand and wire breakage, tendon section loss, voids in the grout, water infiltration, other undesired grout conditions, and tendon deterioration in the anchorage

region. However, in this study, water infiltration, other undesired grout conditions, and tendon deterioration in the anchorage region are not included in the specimen for evaluation. A detailed protocol for each condition fabrication method has been written to include introduction, procedure, and reporting sections. The introduction section contains the scope of the condition, any relevant terminology, the significance of the condition, and referenced documents. The procedure section of the fabrication protocol includes apparatus, a process description, photos, and detailed fabrication of condition methodology. The reporting section includes a detailed description of the condition locations in the specimen and a table to organize all of the necessary information to be collected during the fabrication of the condition. As stated, there is a protocol in the described format for each condition fabrication procedure. Some conditions, such as voids, were fabricated using more than one method. In this case, there is more than one protocol for a condition. Data logs were also created and used as necessary. For example, the time and current required for inducing corrosion on steel wires and strands via an electrolytic corrosion cell was kept in a data log.

The processes used to construct the conditions in the specimen were decided upon using the literature review and best judgment, along with multiple trials. The conditions were fabricated with the highest effort to have strong correlation with current field conditions and to remain in their specified location along the length and within the cross-section of the specimen.

The objective of Task 3 was to optimally design the specimen in the best layout for NDE testing of several conditions. Since there is very limited specimen length,

adequate spacing of the conditions was determined to maximize space yet not hinder the NDE testing results. It was vital to have clear definition between conditions in order to accurately correlate the testing results with the planted conditions.

In this same task, detailed drawings of planted condition locations in the specimen were produced. Information on the idealized size and location of the condition along the length of the specimen is included in detail. Along with this information, all construction procedures were meticulously planned out and documented for use in the next task. Decisions on all materials to be used were also made.

As Task 4, the stay cable and external PT specimen was constructed according to the condition fabrication procedures of Task 2 and the specimen design outlined in Task 3. Great care was taken in ensuring that the fabricated corrosion, steel strand and wire breakage, tendon section loss, and voids in the grout are constructed in the exact locations designated in the detailed design drawings. The location of the fabricated conditions warranted much attention during the construction task because the validity of the NDE testing results depended on it.

Conditions of the steel tendon such as corrosion, breakage, and section loss were first fabricated before the steel was pushed/pulled through the duct. The voids were then fabricated using two different methods at their designated point in the timeline of the construction of the specimen, either before or while grouting of the duct. Figure 1-1 shows the overall specimen configuration. All three of the duct support pieces are bolted to 8 in. of concrete below. A 4 in. diameter HDPE duct was used and has two spans of approximately 18 feet for the condition placement.



**Figure 1-1: Stay Cable and External PT Specimen**

Task 5 was non-destructive testing of the specimen. Upon completion of Task 4, NDE was conducted on the specimen, including the use of ultrasonic tomography, infrared thermography, ground penetrating radar, and sounding, along with borescope use for visual inspection. All of the NDE equipment was implemented to test along the free span lengths of the specimen. The non-destructive testing was performed twice. Testing was first performed within the same week as grouting in order to test the methods for use in construction quality control. Then, NDE was performed again after the grout had fully cured over a month after construction, this time to represent a situation similar to inspection.

As Task 6, the results of the NDE conducted in Task 5 were processed and analyzed in order to determine the applicability of the NDE methods in detecting each condition. Conclusions were then drawn based on the correlation between the NDE results and the known locations of conditions within the specimen length and cross-section. It is important to note that the focus is on which NDE method can accurately identify each of the planted conditions in the specimen even when the conditions overlap with one another. It was also determined whether ultrasonic tomography, infrared thermography, ground penetrating radar, sounding, and borescope use are each capable of accurately sizing the extent of the conditions during both quality control and inspection.

In the final task, Task 7, the complete results of the research are included in this thesis and recommendations for further research is made. Also, recommendations for future fabrication of conditions within stay cable and external PT specimens are discussed.

#### *1.4. Thesis Organization*

This thesis is organized with Chapter 2 covering a review of relevant literature. This literature review contains an overview of both stay cable and external post-tensioning systems, deterioration conditions in these systems, and noteworthy case studies of bridges with significant early deterioration. Also, this section includes an overview of prior research findings in literature on the applicability of ultrasonic tomography, infrared thermography, ground penetrating radar, sounding, and visual inspection by borescope use in identifying these conditions in stay cable and external PT systems.

In Chapter 3, the methods in which the conditions were fabricated are described in detail. The fabrication of condition protocols that correspond to Chapter 3 of this thesis are included in full in Appendix D.

Chapter 4 contains in detail the design and construction of the mock-up specimen. The condition placements within the specimen are thoroughly laid out and documented along with all of the aspects of constructing the specimen.

In Chapter 5, the individual use of a borescope, sounding, ultrasonic tomography, infrared thermography, and ground penetrating radar on the specimen is explained and the results of the testing are presented.

In Chapter 6 of this thesis, the overall conclusions from the research are presented. Recommendations for future research and fabrication of the conditions are also included.

## 2. LITERATURE REVIEW

This literature review contains information on stay cable and external post-tensioning systems followed by case studies of bridges that have experienced significant deterioration of their stay cable and external post-tensioning systems. Possible deterioration conditions are explained in detail and an overview of prior use of the non-destructive evaluation methods contained in this research is also included.

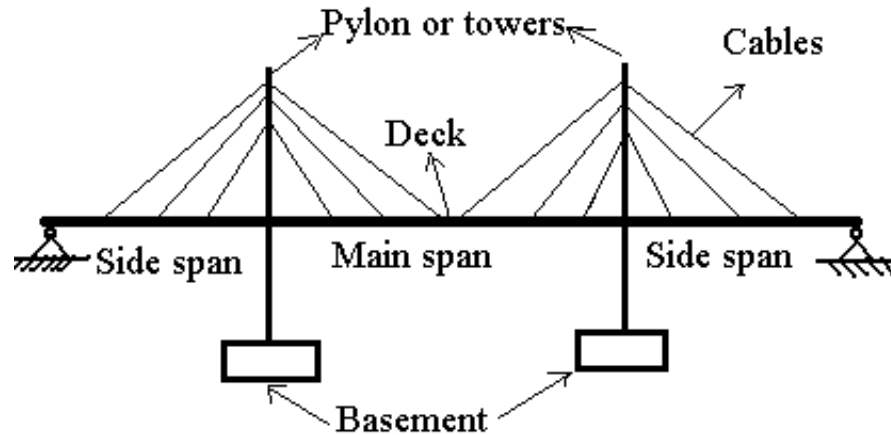
### *2.1. Stay Cable Systems*

Modern cable-stayed bridges, first introduced in Germany in 1955, were also built in Great Britain, Canada, and South America before appearing in the United States in the early 1970s (Grant 1991). In 1997, there were barely over 20 major stay cable bridges in the U. S. and around 600 across the world (Angelo 1997). Since then, the number of stay cable bridges in the United States has doubled to over 40 with typical main span lengths between 600 and 1400 feet. With this increasing number of cable-stayed bridges comes the requirement of a feasible method of inspecting the stay cables for deterioration conditions.

A typical stay cable bridge is shown in Figure 2-1. The stay cables directly carry the loads on the bridge deck to the towers of the bridge, enabling longer span lengths dependent on the stay cable configuration. Both internal and external PT systems are often used in conjunction with stay cable systems to carry the loads of this long span bridge type. Over the years, four cable configurations have been implemented into cable-



stayed bridge structures. These cable designs include parallel bar, parallel wire, stranded cable, and locked-coil cable (Elliott and Heymsfield 2003).



**Figure 2-1: Stay Cable Bridge (Vannemreddi 2010)**

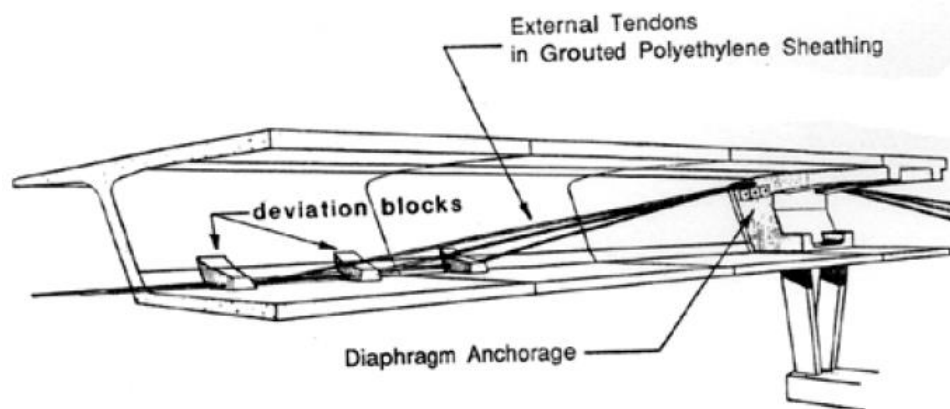
Stay cable configurations require inspection methods able to overcome the difficult accessibility of stay cables. In the design of cable-stayed bridges, engineers often neglect to consider the long-term maintenance of the cables, as they are focused on the design of the bridge (Mehrabi 2006).

New developments in stay cable systems are continually being made. In 1990, recommendations from the Post-Tensioning Institute (PTI) required stay cables to be designed to be able to be replaced without any damage to the superstructure of the bridge (Freyermuth 1991). Periodic surveillance of the stay cables also became a requirement. Stay cable systems are now even being designed to allow for the removal and replacement of any cable without disrupting the functionality of the bridge (Grant 1991).

Another stay cable advancement includes an innovative cradle system that has been designed, tested, and then first constructed in the New Maumee Bridge River Crossing in Ohio (Pate 2002). This cradle system allows for a continuous stay cable through the pylon from bridge deck to bridge deck and contains individual sleeves for each strand through the pylon. Therefore, both tensile forces in the pylon from discontinuous cables and contact forces between strands are not areas for concern. Although new advancements in stay cable designs are exceedingly beneficial, these advancements can sometimes add to the difficulty of inspections and require the development of new inspection methods for thorough condition assessment.

## *2.2. External Post-Tensioning Systems*

Figure 2-2 shows an example of the setup of an external post-tensioning system within a bridge girder. The external tendons are in grouted polyethylene sheathing and their geometry is controlled by the deviation blocks and diaphragm anchorage within the girder.



**Figure 2-2: Example of External Post-Tensioning System Setup (Lee 2007)**

External tendons, in comparison to bonded internal tendons, yield the advantage of easier replacement, if necessary (VSL 2002). Although tendon replacement is only advised if there is significant risk of tendon failure, it is an option available to most external tendons. Also, if during the service life of the bridge, greater PT forces are needed, additional external tendons can be connected to the bridge girders as a means of rehabilitation and increasing the load carrying capacity (Tilly 2002). Despite these advantages over internal tendons, external tendons are also subject to durability problems. External tendons hold greater vulnerability to corrosion environments than internal tendons since the ducts are not embedded in the concrete. External tendons are also susceptible to damage from traffic during construction and temperature cycles. The restraint areas for external tendons are often at expansion joints or closure points in the bridge where the collection of deicing salts or a saltwater environment pose a threat (Goodwin 2002).

In Japan, the Japan Highway Public Corporation has even actively adopted solely using external post-tensioned tendons for box girder bridges, over using both internal and external tendons, because of the proven durability of external tendons in the country (Mutsuyoshi and Witchukreangkrai 2004). The external tendons are placed within the concrete box girder and yield the advantages of a reduced web thickness, the potential to change forces in the tendons, and an easier inspection of the tendons during construction (Mutsuyoshi and Witchukreangkrai 2004). As external PT systems become more

prevalent, the importance to have applicable and cost effective inspection practices also rises.

### *2.3. Deterioration Conditions*

When PT concrete bridges are properly designed and constructed, they may prove to be the most durable bridge type, also requiring the least amount of maintenance (Clark 2010). When bridge PT systems are not designed, detailed, and constructed properly however, there are several deterioration conditions that can take away from the strength and longevity of the bridge. Environmental conditions also share a critical role in the development of bridge system deterioration. If inspection and repair of these systems is not done properly, early failure and public endangerment can occur (Trejo et al. 2009). Deterioration conditions such as corrosion, breakage, section loss, voids, water infiltration, and undesired grout conditions can pose a serious threat to the safety of in-service bridges. For example, significant corrosion rates can cause early failure of stay cable and external PT systems if necessary repairs are not carried out (Trejo et al. 2009).

#### **2.3.1. Corrosion**

The most critical and prevalent condition causing cable deterioration is corrosion of the steel tendons in both stay cables and external post-tensioning (Grant 1991). The cost of corrosion has been estimated as annually over 3% of the United States' gross national product (Griffin 2006) and a portion of that is attributed to the nation's bridges.

The occurrence of corrosion is dependent on the environment around the steel strand surface. This environment dictates both the type and the rate of the tendon corrosion. Corrosion occurs in the presence of electrochemical potential from different metals or chemical constituents, a sufficient oxygen supply, and an electrolyte (Grant 1991). With these three components present, corrosion occurs as electrons are exchanged between the steel and the environment. If there is only water and oxygen present in a constant environment surrounding the tendon, then uniform corrosion can occur at a steady rate. However, a corrosion test on several strand specimens concluded that the most severe corrosion occurs at or near the grout-air-strand (GAS) interface (Trejo et al. 2009).

There are multiple mechanisms of corrosion that can be present. Corrosion mechanisms include uniform or atmospheric corrosion, pitting corrosion, crevice corrosion, stress corrosion cracking, hydrogen cracking, corrosion fatigue, and electrolytic corrosion (Elliott and Heymsfield 2003). In atmospheric corrosion, the presence of other chemicals in the tendon's surrounding area can cause corrosion to occur and often serve to accelerate the rate of the corrosion. Substances in the atmosphere, such as carbon dioxide, chlorine, and sulfur compounds can lead to atmospheric corrosion of the strands. This type of corrosion is highly dependent on the degree of these chemicals present in the environment and the length of the exposure time to the steel in the PT and stay cable systems. For example, chlorides from deicing salts can contaminate the tendons at expansion joints and other tendon anchorage areas, causing severe damage.

Pitting corrosion is a form of localized corrosion. When the passivating layer of the steel is deteriorated by means such as high chloride concentrations or acidic solutions, crevices are created. These small areas become anodic, while the surrounding environment becomes cathodic, leading to extremely localized corrosion and often galvanic corrosion. Galvanic corrosion occurs due to the close presence of different metals, which contain differing electrode potentials. This difference can result in galvanic coupling and therefore accelerate the rate of corrosion.

Creep of the stay cables is a significant problem in maintaining the corrosion protection system (Watson and Stafford 1988). Elongation of the cables sanctions the steel, grout, and pipe to move independently and can form a gap between the interior surface of the duct and the grout layer, creating cracking (Watson and Stafford 1988). Chlorides and moisture seep into the duct and reach the steel tendon to facilitate corrosion. Corrosion can occur even if the tendon is completely covered by grout. The rate of the tendon corrosion largely depends on the amount of chloride contamination and the surrounding grout quality. Although regardless of chloride levels, corrosion can occur at the location of voids and low grout pH levels (Venugopalan 2008).

The exposure of PT and stay cable tendons to environments ideal for corrosion is a critical concern in maintaining bridge structures. Although the tendons are designed to be encased in grout and duct, undesired conditions such as voids and moisture exposure are often present to facilitate corrosion. In PT and stay cable systems, corrosion of the tendons results in loss of steel cross-sectional area which directly corresponds with their loss of tensile strength. This strength loss negatively impacts the load carrying capacity of

the bridge, making corrosion a significant condition to take note of during bridge inspection.

### **2.3.2. Breakage and Section Loss**

Strand or wire breakage can occur as a result of corrosion, fatigue loading, or overloading in the PT and stay cable systems of bridge structures. Corrosion induced breakage is highly dependent on the environment surrounding the steel. In the presence of oxygen and moisture, often with other substances, the wires or strands can corrode resulting in breakage.

Breakage due to fatigue loading can occur as fatigue of the individual wires or by fretting fatigue. Cyclic loading on bridges can initiate and propagate fretting fatigue of the post-tensioned steel tendons (Wollman et al. 1988). This fretting fatigue is experienced as wire breakage and gradually can escalate in severity. The majority of this type of tendon fracture occurs as a result of the steel tendon severely rubbing on the interior duct surface at locations of tendon curvature. This tendon curvature causes lateral pressure on the steel. Fretting fatigue breakage locations have been found to be prevalent at locations of steel slipping along the duct at flexural cracks and where surface micro cracks in the steel are present. Duct material and the stress range of the steel also play a role in the occurrence of fretting fatigue and later breakage (Wollman et al. 1988).

Section loss occurs as a result of excessive corrosion or breakage in tendons of post-tensioned and cable stayed bridge structures. Once the damage to tendons reaches the level of significant steel section loss, the tensile strength of the load-bearing systems are

significantly decreased. In the case of extreme section loss, repair or rehabilitation methods are often necessary to correct the undesired condition of the steel and maintain the safety of the bridge.

Wire and strand breakage in the tendons of PT and stay cable systems is significant in that it can be a precursor to section loss of the entire tendon. Locating breakage during bridge inspections can enable preemptive repair or rehabilitation to prevent noteworthy loss in tensile strength before rehabilitation is not viable.

### **2.3.3. Voids, Water Infiltration, and Grout Conditions**

Optimally, grouting serves as a corrosion resistant layer, protecting the steel tendons (VSL 2002). However, if high quality grouting is not achieved during construction, grout cannot act in increasing the durability of the tendons. Voids can occur during the grouting process of PT and stay cable systems due to improper grout mixing and placement procedures. Improper grouting procedures may include not injecting grout at the low point of the tendon profile, injecting grout in the wrong direction, and using improper grouting pressure. Voids in PT and stay cable systems at locations within the ducts can be detrimental to the bridge structure because it prevents proper bonding of the materials. Voids can also facilitate an environment prone to corrosion by the presence of oxygen and potentially other gaseous substances.

Water presence due to grout bleeding nearly always occurs during grouting of the ducts unless special precautions or grout mixtures are used (Goodwin 2002). Bleeding occurs as the water separates from the cement due to the materials' different densities.



Bleeding happens as a function of the changing duct elevation, grout mixture and mixing efficiency, temperature, and interstices in the strands (Goodwin 2002). The gaps in the strands serve as wicks for the bleed water to reach the highest points in the duct. Bleed water can evaporate to form air voids in the duct or even freeze in the appropriate climate, possibly causing damage to the ducts. This water infiltration in stay cable and external PT systems is highly undesirable.

Water infiltration after construction is usually focused near the anchorage regions of PT and stay cable systems due to access points in the duct. This infiltration can cause problems due to the water's interaction with the grout and steel. Moisture is needed for corrosion to initiate and propagate and therefore water infiltration can be an early warning sign for the onset of corrosion. Depending on the state of the grout at the time of water infiltration, compromised grout can be formed from the excess water in the duct.

Poor grout conditions such as segregated grout, white paste, soft grout, un-hydrated grout, and gassed grout can occur during the grouting process of PT and stay cable systems. Segregated grout, white paste, and soft grout are the result of excess water in the grout. Un-hydrated grout results from insufficient water in the grout mix, and gassed grout can be the result of gas being introduced into the grout mix during grout placement. These types of compromised grout are all detrimental to the bridge structure. Without the presence of good grout between the steel tendons and the duct walls, proper bonding does not occur and the grout does not create the protective environment necessary.

#### **2.3.4. Tendon Deterioration in the Anchorage Region**

Strand breakage, corrosion, steel section loss, water infiltration, voids and grout conditions occur in a large degree in the anchorage region of PT and stay cable systems. These anchorage regions are especially vulnerable to the atmosphere and must be subject to thorough bridge inspections to ensure they are properly connected and sealed from the elements. The secure anchorage of the PT and stay cable tendons is critical to carrying the load of the bridge and sealed ducts are vital to protect the steel tendons.

### *2.4. Case Studies*

Significant deterioration conditions of both stay cable and PT systems have been found during bridge inspections and often warrant complete tendon replacement. Some of the most documented undesired stay cable conditions have been identified in the Luling Bridge in Louisiana and the General Rafael Urdaneta Bridge in Venezuela, both of which required stay cable replacements. The Mid-Bay Bridge, Varina-Enon Bridge, Niles Channel Bridge, Bradley Road Bridge, and Ringling Causeway Bridge have all experienced external tendon deterioration largely due to corrosion and poor grout conditions.

#### **2.4.1. Luling Bridge, Louisiana**

The Luling Bridge in Figure 2-3, also known as the Hale Boggs Bridge, over the Mississippi River is a two-pylon cable-stayed bridge with steel box girders completed in 1984 (Mehrabi et al. 2008). During construction, 42 repairs were made to the stay

cables, mostly as a result of poor handling by the contractor (Watson and Stafford 1988). Circa 1998, the Louisiana Department of Transportation and Development (LADOTD) devised a new method using two trolleys, shown in Figure 2-4, to inspect the unique Luling Bridge for damage and corrosion. One trolley, connected to four stay cables, is used to inspect the cables of the side bridge spans, while the other trolley is connected to only two cables in the main span and serves as a means to inspect two stay cables of the main span in close proximity (Elliott and Heymsfield 2003).



**Figure 2-3: Luling Bridge (Mehrabi et al. 2010)**



**Figure 2-4: Luling Bridge Stay Cable Inspection Basket (Mehrabi et al. 2010)**

After cumulative problems with the stay cables of the Luling Bridge, a detailed evaluation program was carried out to identify the overall integrity of the stay cable system (Mehrabi et al. 2004). The bridge was found to have significant damage to the stay cable protective sheathing with complete exposure of some of the stay cables and corrosion playing a major role in their deterioration, shown in Figure 2-5 (Mehrabi et al. 2010).



**Figure 2-5: Luling Bridge Corrosion and Sheathing Split (Mehrabi 2009)**

In 2006, a life cycle cost analysis by LADOTD determined that complete replacement of the bridge's 72 stay cables was necessary or recurrent and costly rehabilitation would continue. The new stay cables included recent improvements in corrosion resistance and vibration control, along with a parallel-strand system that allows for the replacement of single strands (Mehrabi et al. 2010).

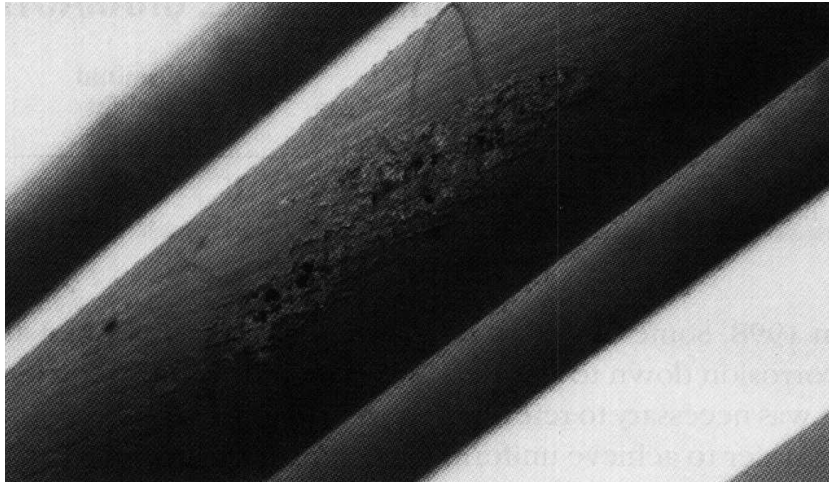
#### **2.4.2. General Rafael Urdaneta Bridge, Venezuela**

The General Rafael Urdaneta Bridge in Figure 2-6 across Lake Maracaibo in Venezuela was built in 1962 with 384 stay cables (Sarcos-Portillo et al. 2003). By 1978, severe corrosion was found in the cables due to a saline environment of high humidity. Within the next year, one of the stay cables had already broke and was swiftly followed by others (De Rincon et al. 2001). Quickly after, in 1980, all of the stay cables were replaced since access to replace only the broken strands was impossible.



**Figure 2-6: General Rafael Urdaneta Bridge (Sarcos-Portillo et al. 2003)**

Again, during inspection of the bridge in 1997-1998, significant cable corrosion and cable socket settling was discovered (Sarcos-Portillo et al. 2003). Typical localized corrosion is shown in Figure 2-7 and was especially prevalent in the stay cables on the north side of the bridge due to the wind patterns in the area.



**Figure 2-7: Cable Corrosion in the General Rafael Urdaneta Bridge (De Rincon et al. 2001)**

During the bridge inspection, it was also discovered that the tension in the cables varied enough to warrant retensioning. The bridge was horizontally leveled before retensioning began and remained under careful consideration during the retensioning process. The cables were retensioned through use of a hydraulic jack and corrosion protection quickly followed (Sarcos-Portillo et al. 2003).

#### **2.4.3. Mid-Bay Bridge, Florida**

The Mid-Bay Bridge, shown in Figure 2-8 and constructed in 1992 in the western panhandle of Florida, required repairs costing over one million after several locations of tendon deterioration were found during a routine inspection (Clark 2010). The bridge had only been in service for nine years.



**Figure 2-8: Mid-Bay Bridge (Hartt and Venugopalan 2002)**

Tendon deterioration conditions found included over 700 voids, corroded and broken tendons, and powdery, cementitious grout as shown in Figure 2-9 (Clark 2010, Corven 2001). These significant conditions were largely caused by poor grouting of the PT ducts. Notably at high points in the tendon profile, several of the external tendon anchorage regions were found only partially filled with grout (VSL 2002). It was clear during inspection that the external PT tendons had not been grouted to specifications (Hartt and Venugopalan 2002). Eleven out of a total of 846 tendons were replaced, with ten of these tendons located at expansion joints (Pereira 2003).





**Figure 2-9: Corrosion of the Mid-Bay Bridge (Corven 2001)**

#### **2.4.4. Varina-Enon Bridge, Virginia**

During an inspection of the PT tendons of the Varina-Enon Bridge, shown in Figure 2-10, 11 years after its construction completed in 1990, voids were found in the ducts (Hansen 2007). The voids are assumed to be caused by the use of a Portland cement grout often used in similar bridges until 2000. The grout was found to be inadequate in several bridges, causing first bleed water and then air-filled voids in the grout.



**Figure 2-10: Varina-Enon Bridge (from [http://www.figgbridge.com/varina\\_enon\\_bridge.html](http://www.figgbridge.com/varina_enon_bridge.html))**

In response, these voids were filled with a new high performance grout to mitigate the problem. However, in 2007, inspection of the Varina-Enon Bridge brought to light the failure of a severely corroded external tendon at a location where the cement grout met the high-performance grout. The tendon failure shown in Figure 2-11 and Figure 2-12 could have been caused by a corrosive interaction between the two grout types (Hansen 2007).



**Figure 2-11: Varina-Enon Bridge External Tendon Failure (Hansen 2007)**

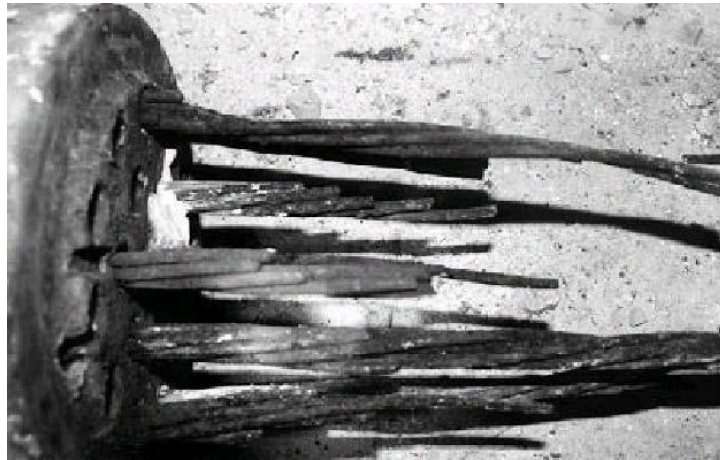


**Figure 2-12: Close-Up View of External Tendon Failure (Hansen 2007)**

#### **2.4.5. Niles Channel Bridge, Florida**

The Niles Channel Bridge had only been in service for 16 years when, in 1999, all 19 strands of an external tendon failed due to exposure and corrosion at an expansion joint (Tilly 2002). The failure was identified first by the significant displacement of a

tendon through one of the deviation saddles (Pereira 2003). This significant corrosion in the anchorage region of the tendon is shown in Figure 2-13.



**Figure 2-13: Strand Corrosion of the Niles Channel Bridge (Powers et al. 2002)**

#### **2.4.6. Bradley Road Bridge, UK**

The Bradley Road Bridge, pictured in Figure 2-14, in the United Kingdom was built in 1970 using external post-tensioning of 19-wire strands with paint and PVC coating (Tilly 2002). During construction and in the years following, fractured wires were repeatedly an area of concern until nine years after construction, the decision was made to replace all of the tendons. Although many investigations were made into the cause of the wire fractures, multiple theories were prevalent due to the range of corrosion levels at the different fracture locations. Most likely, there was a combination of unbalanced stresses between the wires and stress-corrosion was occurring (Tilly 2002). The replacement of all the external tendons of the Bradley Road Bridge in part

led to better protection systems for external PT systems, including the use of grout and HDPE duct.



**Figure 2-14: Braidley Road Bridge (from [http://commons.wikimedia.org/wiki/File:Bournemouth,\\_temporary\\_traffic\\_lights\\_in\\_Braidley\\_Road\\_-\\_geograph.org.uk\\_-\\_1772594.jpg](http://commons.wikimedia.org/wiki/File:Bournemouth,_temporary_traffic_lights_in_Braidley_Road_-_geograph.org.uk_-_1772594.jpg))**

#### **2.4.7. Ringling Causeway Bridge, Florida**

Two failed external tendons of the post-tensioned Ringling Causeway Bridge, seen in Figure 2-15, completed in 2003 in Florida required complete replacement after a bridge service life of only eight years (Paredes 2013). The first failed tendon, shown in Figure 2-16, was found on the floor during an electrical inspection and the second tendon failure was found during inspection a few months later. Both external tendon failures were attributed to corrosion in response to segregation of the grout and



unreacted grout paste. High sulfate and moisture contents were present at the failure locations.



**Figure 2-15: Ringling Causeway Bridge (Paredes 2013)**



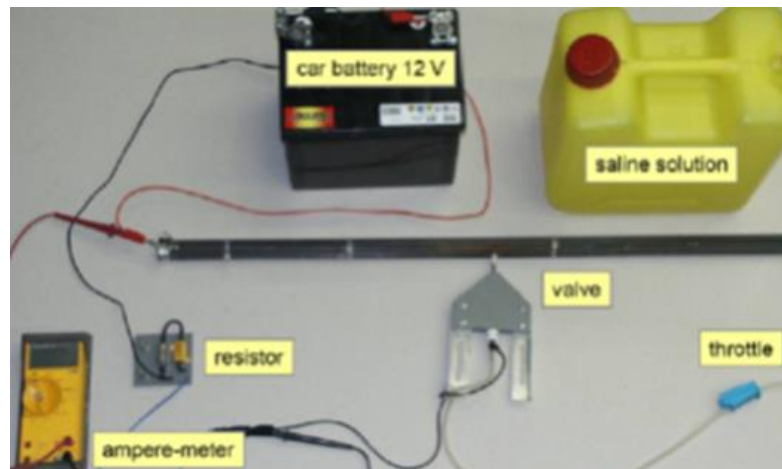
**Figure 2-16: External Tendon Failure of the Ringling Causeway Bridge (Paredes 2013)**

### *2.5. Prior Fabrication of Conditions*

Research teams have documented methods to fabricate both corrosion and voids in prior experiments on condition assessment and non-destructive testing. Corrosion has been fabricated successfully by two different research teams in similar electrolytic corrosion cell configurations and has also been observed closely in a corrosion test program. Voids have been created in PT ducts using two very different methods. Voids were effectively formed in internal PT ducts of a concrete girder using polystyrene foam placement before grouting and conversely have been fabricated in external PT ducts using a vacuum pump to extract a specified volume of grout at a set time after specimen grouting.

### 2.5.1. Prior Fabrication of Corrosion

Previously, an electrolytic corrosion cell was used to fabricate localized corrosion of wires in the PT of an existing bridge structure for testing (Fricker and Vogel 2007). Continuous acoustic monitoring was performed on the strands during corrosion to test the applicability of the monitoring system to detect the eventual wire breakage. The laboratory corrosion cell setup is seen in Figure 2-17 and the blind testing setup used in the field is shown in Figure 2-18.



**Figure 2-17: Electrolytic Corrosion Cell Lab Setup (Fricker and Vogel 2007)**

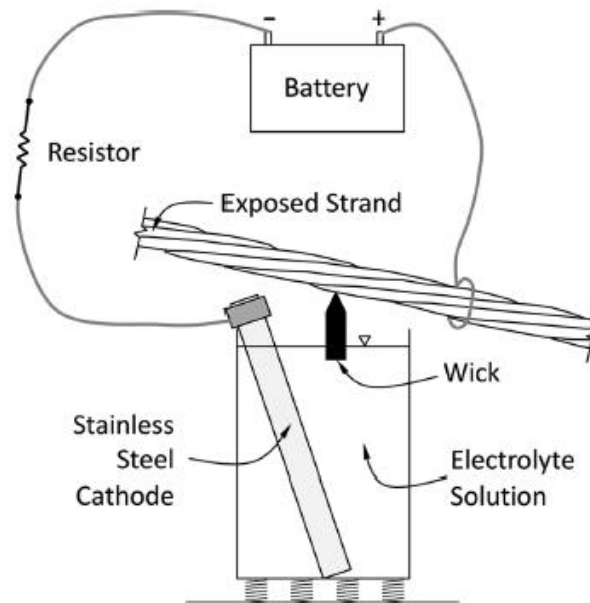
A 12 V battery was used as the power supply to create a current through the strand to be corroded. This current was controlled by a resistor in the corrosion cell setup. A saline solution was gravity fed down a hose to create a corrosive environment at the desired corrosion location. The solution contained 50 g of sodium chloride and 1 mL of hydrochloric acid (2%) per liter of solution (Fricker and Vogel 2007).





**Figure 2-18: Electrolytic Corrosion Cell Field Setup (Fricker and Vogel 2007)**

A similar corrosion cell setup was also used for fabricating localized corrosion on steel strands to be tested for residual tensile capacity (Wood et al. 2013). The galvanic corrosion cell used a solution of 20% hydrochloric acid and 10% sodium chloride by weight in which the exposed strand was immersed. A 12 V battery was also used in this localized corrosion setup seen in Figure 2-19.



**Figure 2-19: Galvanic Corrosion Cell Setup (Wood et al. 2013)**

A strand corrosion test program was conducted using 298 strand specimens to determine parameters that have a noteworthy effect on both corrosion and tensile capacity (Trejo et al. 2009). Several different corrosion environments were fabricated for comparison of void sizes, stress conditions, grout class, and moisture and chloride levels. The highest levels of corrosion were found at the grout-air-strand (GAS) boundaries (Trejo et al. 2009). This is a significant conclusion to take into account in order to fabricate artificial conditions with close association to realistic field conditions of cable-stayed and externally post-tensioned bridges.

### 2.5.2. Prior Fabrication of Voids

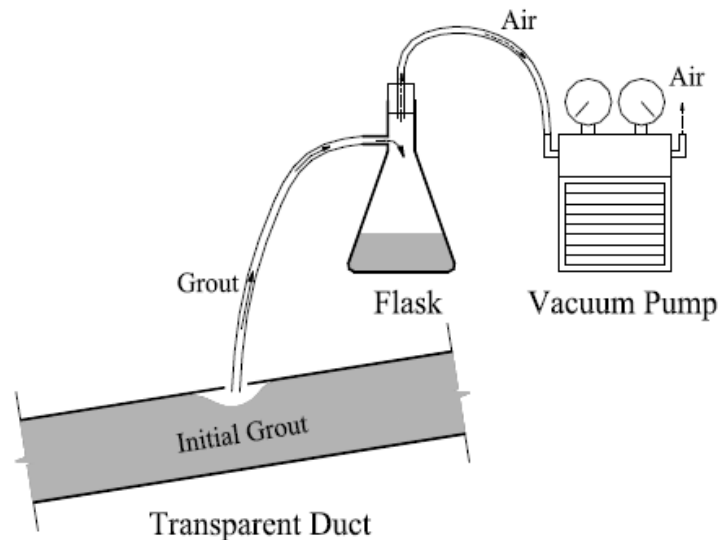
Previously, voids have been fabricated in the grout of a girder PT system using stepped and tapered polystyrene foam rods (Tinkey and Olson 2007). The foam was inserted in the ducts prior to grouting as shown in Figure 2-20 in order to have predetermined locations where grout would not be placed in the ducts. The polystyrene foam was placed using wire rods to support the foam to be on the roof of the duct, representative of voids in the field. Smaller polystyrene foam pieces were also glued directly on to the duct (Tinkey and Olson 2007).



**Figure 2-20: Fabrication of Voids Using Polystyrene Foam (Tinkey and Olson 2007)**

To fabricate voids in several transparent external PT specimens, a vacuum pump configuration has been successfully used in the past (Im 2009). Trials concluded that the best time to extract grout from the specimens was two hours after grouting. As shown in Figure 2-21, the vacuum pump draws air out of a sealed flask, which in turn extracts grout from the specimen. The volume of grout extracted can be read on the flask, but the

drawback to this void fabrication methodology is that the shape of extracted grout left in the specimen is unknown without transparent ducts. To allow for the grout removal after grouting of the specimens, holes of one inch diameter were drilled into the duct at locations for later vacuum pumping and then temporarily sealed during the grouting process (Im 2009). This method has been proven to work for void fabrication, yet more research is needed on its usefulness with non-transparent ducts that hinder the view of the created air void shape.



**Figure 2-21: Vacuum Pump Setup (Im 2009)**

### *2.6. Non-Destructive Evaluation Methods*

Non-destructive evaluation methods provide a means of inspecting stay cable and external PT systems without requiring the inspected area to be repaired afterward. These non-destructive techniques keep the environmental protection of the steel tendons intact

and do not facilitate the further damage that could result from a destructive inspection of these systems. NDE methods exempt the inspection from regrouting or resealing the ducts. The limitations of visual inspection are first introduced, including the typical usage of a borescope or videoscope, and then the use of sounding, ultrasonic tomography, infrared thermography, and ground penetrating radar is examined.

### **2.6.1. Visual Inspection**

Visual methods of stay cable and external PT inspection can be useful, although this method is typically only able to identify visible or incredibly advanced damage that would likely require extensive repair (Mehrabi 2006). Most often, damage to structurally critically stay cable and external PT elements goes undetected if solely subject to visual inspection. Access to ducts and stay cables for visual inspection is usually difficult and visual inspection of the anchorage zones is most often impossible (Tabatabai 2005).

Visual methods are often included in bridge evaluation plans as a preliminary global integrity check. Visual inspection can act as a means of local damage detection to be combined with non-destructive testing methods (Mehrabi 2006). Often, the strand ends, sockets, and locking plates are visually inspected after removal of the system's anchorage caps, whereas the deck, tower, and duct or stay cable free length can be visually inspected without any dismantling of the structure. Although more invasive, in situ cable dissection is sometimes used for further visual inspection of the steel strands and condition of the grout.

In most cases, visual inspection is the only means used for cable-stayed bridge inspections (Tabatabai 2005). It is recommended that future research include studies into the effectiveness of stay cable visual inspections and the development of stay cable systems that can be subjected to complete visual inspection. Visual inspection of stay cables should be complemented by other inspection tests, including the measurement of cable strains and bending fatigue cable tests in the laboratory. In one case, an Argentine stay cable's internal deterioration went undetected during visual methods of inspection and reached failure (Tabatabai 2005).

Visual inspections usually consist of a survey of the cable exterior surfaces, anchorage exposed surfaces, cross cables and their connections, dampers, and the neoprene boots and guide pipes conditions (Tabatabai 2005). Neoprene rings within guide pipes are also sometimes included in the survey. The condition of the wedges or button heads can possibly be inspected by removal of the anchorage caps. The sag and inclination angle of cables could also be measured through the use of optical and photogrammetric devices. In the case of external PT, visual inspection has revealed corrosion, broken wires, grout voids, poor grout quality, and polyethylene duct cracking in bridges where these conditions were severe (Hartt and Venugopalan 2002). When the conditions in both stay cables and external PT are still at mild stages, detection is much more difficult.

Overall, visual inspection is a fast and simple inspection method often used to zone in on problem areas in both stay cable and external PT systems. However, it should

not be warranted as a complete and thorough inspection method without the aid of other inspection methods.

### **2.6.2. Borescope**

Borescopes can be used in visual inspection to non-destructively determine the condition of the exterior surface of stay cables and external PT (Tabatabai 2005).

Although time consuming, visual inspection of stay cables has been advanced by the use of technology such as borescopes and videoscopes, essentially borescopes capable of recording video (Azizinamini and Gull 2012). In locations where voids are identified within the ducts, this visual inspection method is used to determine the extent of the void by gaining access through the anchorage, if possible. The borescope end is inserted in the grout port for access to inspect further into the trumpet area of the anchorage (Shahawy and Cox 2005).

Borescopes and videoscopes are also used to inspect the interior of the free duct or cable span as well. A small hole can be drilled into the duct or cable for access and repaired immediately following the inspection. Although this type of testing is destructive, it is only minimally invasive and can serve to acquire a large amount of information on the condition of the stay cable or external PT system to be paired with non-destructive evaluation. Along with the necessary void presence for borescope use, this type of inspection can conclude if there is also corrosion or moisture present in the anchorage system or free span. Borescopes and videoscopes can also identify the

locations where sufficient grouting begins, if there are such locations present (Corven 2001).

### **2.6.3. Sounding**

The acoustic sounding method involves striking a hammer on the external PT duct or stay cable in order to then hear the acoustic response. It is fairly accurate and easy to implement, although it is dependent on the test operator and is mainly applicable to the detection of dry grout voids (Azizinamini and Gull 2012). The operator must be able to determine the tonal difference between acoustic responses of external PT and stay cable ducts with and without voids in the grout. If there is any extent of delamination present between the grout and interior duct surface, sounding can give false results (Corven 2001, Shahawy and Cox 2005). The testing may identify a void at a location of fully grouted duct only with delamination. Although this NDE method is highly subjective, it can usually be used quickly and effectively to identify large voids in the grout along free spans of the systems.

Extensive sounding was performed on several external PT mock-up specimens to determine the accuracy of the sounding method. The external PT specimens were constructed with transparent ducts in order to directly compare the visible void locations and sizes to blind sounding results (Im and Hurlebaus 2012, Im et al. 2010). In comparison to other non-destructive methods used on the external PT specimens, sounding was the most successful in identifying large voids.



#### **2.6.4. Ultrasonic Tomography**

Ultrasonic tomography is a non-destructive evaluation method that employs acoustic waves. The waves are propagated through material and as waves are reflected by structure anomalies, the reflections are detected by sensors. Ultrasonic tomography has been widely used in NDE applications and exhibits promising results for identifying defects in stay cable and external post-tensioning structures (Baltazar et al. 2010, Branham et al. 2006, Chaki and Bourse 2009, Rizzo et al. 2007). Following are some examples in which the success of ultrasonic tomography has been documented in research efforts.

The ultrasonic method successfully detected and localized defects in stay cable specimens in laboratory tests (Baltazar et al. 2010, Branham et al. 2006). In another study, the ultrasonic method, using piezoelectric transducers, was directly applied to strands and acoustoelasticity theory was used to measure the stay cable's stress levels (Chaki and Bourse 2009). It has also been documented that the ultrasonic method has also been used with magnetostrictive transducers to assess strand defects inside grouted PT tendons (Liu et al. 2010, Rizzo et al. 2007).

Ultrasonic tomography has been used to effectively identify grout voids and wire breaks in stay cable anchorage areas on both the Talmadge Bridge in Georgia and the Cochrane Bridge in Alabama (Mehrabi 2006, Mehrabi et al. 2004). Ultrasonic stay cable testing can accurately detect voids in stay cable grout and wire breaks up to 5 feet from the cable strand ends, depending on the filler type in the anchorage socket. Ultrasonic testing was also performed on anchorages of the Zarate-Brazo Largo Bridges in

Argentina after a bridge cable failure (Tabatabai 2005). The ultrasonic test methods detected multiple wire breaks in various stay cables following the cable failure.

During inspection of the Cochrane Bridge in Alabama, ultrasonic flaw detection was implemented on the cable anchorage areas for the identification of wire breakage (Ciolko and Yen 1999). It was the first ultrasonic technique used on seven-wire strands. The wave passage is more difficult for this cable configuration due to the wrapping of the six wires around the middle wire (Tabatabai 2005). The anchorage covers were removed for the testing and the ends of the wire strands were smoothed out. The ultrasonic test verified that broken cable wires at the stay cable anchorages were not an issue for the bridge at this point in time due to the sufficient signal penetration through the stay cables. This use of the ultrasonic NDE method was able to confirm that the current strength of the stay cables was adequate and prevented the unnecessary use of bridge repair or rehabilitation funds on a bridge system with acceptable sufficiency.

In a study on ultrasonic frequencies that conducted testing of 2-in. grout cubes, the optimal ultrasonic frequency for stay cable testing was found to be 0.5 MHz (Bligh et al. 1994). It was also determined that the passing of energy through the common stay cable polyethylene pipe and grout layer is not an area of concern for the effectiveness of the ultrasonic method as approximately 72% of the incident energy can be transmitted through the polyethylene and therefore through the grout layer. However, ultrasonic testing can be ineffective if there is not a sufficient bond between the polyethylene pipe and stay cable grout. It was concluded that ultrasonic defect detection techniques can be effective in locating grout layer anomalies, yet more research is necessary for the

conclusion of flaw types and sizes along with bleed water effects on void detection (Bligh et al. 1994). Also, the use of ultrasonic tomography is limited for inspecting stay cable condition in fire and crash protection zones of the bridge because access to the cables is more difficult.

Through the available literature and past research on ultrasonic tomography of stay cable and external PT systems, there are evident instances in which ultrasonic tomography has been successful in detecting conditions and other cases in which more research is required. The importance of implementing ultrasonic tests on a mock-up structure before performing field testing is stressed in order to interpret the defect detection and location results accurately (Tabatabai 2005).

#### **2.6.5. Infrared Thermography**

Infrared thermography is a non-destructive infrared imaging technique that uses the thermal energy present to produce an image. Current literature review of the use of infrared thermography on stay cable or external PT systems focuses on the ability to detect conditions of an HDPE duct and UV tape. It is stated that although infrared thermography is primarily applicable to stay cable and external PT ducts, it is best used to detect the tape condition of the ducts (Azizinamini and Gull 2012), whereas the ability to detect moisture in stay cable ducts is so far unsubstantiated (Minchin et al. 2006). HDPE stay cable sheathing splits hidden under the protective tape can also be identified using infrared thermography (Tabatabai 2005). It is agreed that infrared thermography is effective for detecting these splits along with UV tape damage, stating infrared

thermography is one of the top two non-destructive methods to determine these hidden HDPE unfilled split locations (Telang et al. 2004). It is also recommended for the infrared thermography to be combined with a source of heat generation in order to maintain the success of the thermography method. With the added heat generation, it may even be possible for infrared thermography to also detect filled splits in the stay cable HDPE.

These types of duct conditions will not be evaluated as part of this research, although a split duct likely leads to undesired conditions within the duct. There are major gaps in current literature on the applicability of infrared thermography to detect conditions within the duct, although one source asserts that the use of infrared thermography for the detection of stay cable grout and cover anomalies has been validated in laboratory tests and can be implemented economically in the field (Mehrabi 2006). This thesis will serve to fill in these gaps on the ability of infrared thermography to identify such conditions as corrosion, voids, water infiltration, compromised grout, section loss, and steel strand/wire breakage within the duct.

#### **2.6.6. Ground Penetrating Radar**

Ground penetrating radar (GPR) equipment sends radar pulses using electromagnetic radiation. These radar pulses are then detected as they reflect from anomalies in the structure. This non-destructive technique has been found to work for detecting defects in the grout of stay cable and external PT systems. It is expected to become a more common method of inspection in the future. Hand-held GPR equipment

can be moved longitudinally over the cables to detect grout voids inside the HDPE pipe sheathing (Tabatabai 2005). Even though ground penetrating radar can detect voids inside the sheathing, it is not effective in assessing corrosion or cable breaks. This is because GPR is highly sensitive to metal. Another source agrees GPR is effective for identifying grout defects and reports GPR successfully detected grout voids and damage in two mockup stay cable specimens (Telang et al. 2004). It is added that GPR is ineffective in the detection of UV tape damage and both unfilled and epoxy-filled splits in stay cable sheathing. However, it is highly adaptable to conditions of the environment and can be performed at a relatively low cost in comparison to other NDE methods.

Ground penetrating radar's sensitivity to metal deems it ineffective in the detection of tendon breaks and grout voids inside of steel ducts, therefore GPR is only capable of detecting grout anomalies within plastic ducts (Azizinamini and Gull 2012). Minchin also lists GPR's poor performance with metal containers as a limitation of this non-destructive evaluation method (Minchin et al. 2006).

In the early 1990s, radar systems such as GPR were not as readily adaptable for the monitoring of stay cables and external post-tensioning in comparison to their use for the inspection of internal post-tensioning (Bligh et al. 1993). Equipment for ground penetrating radar testing is now commercially available, including 3D tomographic imaging capability of GPR data in many instances. However, GPR's potential applicability to stay cables has been widely overlooked and therefore this NDE method is still more common for the inspection of internal PT than for stay cable systems. (Azizinamini and Gull 2012).

Overall, ground penetrating radar has been applied to stay cables to successfully identify grout defects inside the HDPE sheath (Mehrabi 2006). Recently, water contents in concrete structures were assessed using GPR (Lai et al. 2011). It is still necessary to evaluate the effectiveness of GPR in identifying water infiltration in stay cable and external post-tensioning systems. This NDE method's use for the detection of steel damage within the cables is limited, if not nonexistent.

### 3. FABRICATION OF CONDITIONS

In order to construct a specimen that represents typical deterioration conditions in stay cable and external PT systems, the best method to fabricate each condition was determined through multiple trials. A direct correspondence between fabricated conditions and field conditions allows for the fabricated conditions to be detected with the same accuracy as conditions in the field using each non-destructive evaluation method. The best fabrication method for corrosion, an electrolytic corrosion cell setup, went through many renditions before reaching a high rate of steady steel strand corrosion. Breakage and section loss conditions were both fabricated through the use of a rotary grinder on the steel strands. These three tendon conditions were fabricated before the 19 steel strands were pushed through the HDPE duct. In addition, the presence of voids in the specimen occurred by two means, through the placement of expanding polyurethane foam prior to grouting and through the creation of an air void during grouting.

Fabrication of condition protocols were formed for the conditions included in the specimen: corrosion, section loss, breakage, and voids. In addition, protocols for the fabrication of water infiltration, grout conditions, and tendon deterioration in the anchorage region were also determined. These protocols are designed to be used in future deterioration conditions research so that the best practice for fabrication of each condition can be used. The developed fabrication of condition protocols are assigned a numerical designation for the type of condition and an alphabetical designation for the

fabrication method for that condition as shown in Table 3-1. Tendon deterioration in the anchorage region is typically a combination of deterioration conditions and therefore can include a combination of fabrication methods. The protocols can be seen in full in Appendix D. In this research, FC001A was used for corrosion fabrication, FC002B for section loss, FC003A for breakage, and FC005A for voids, along with the air void fabricated during grouting. These fabrication methods will be explained in detail in this chapter.

**Table 3-1: Fabrication of Condition Protocols**

<b>Deterioration Condition</b>	<b>Fabrication Method</b>	<b>Protocol</b>
Corrosion	Electrolytic Corrosion Cell	FC001A
Section Loss	Electrolytic Corrosion Cell	FC002A
	Strand Grinding	FC002B
Breakage	Strand Cutting	FC003A
Grout Conditions	Vacuum Pump and Grout Replacement	FC004A
Voids	Polyurethane Foam Placement	FC005A
	Vacuum Pump	FC005B
Water Infiltration	Vacuum Pump and Water Placement	FC006A
Tendon Deterioration in the Anchorage Region	Applicable Method(s) from Other Deterioration Conditions	FC007A

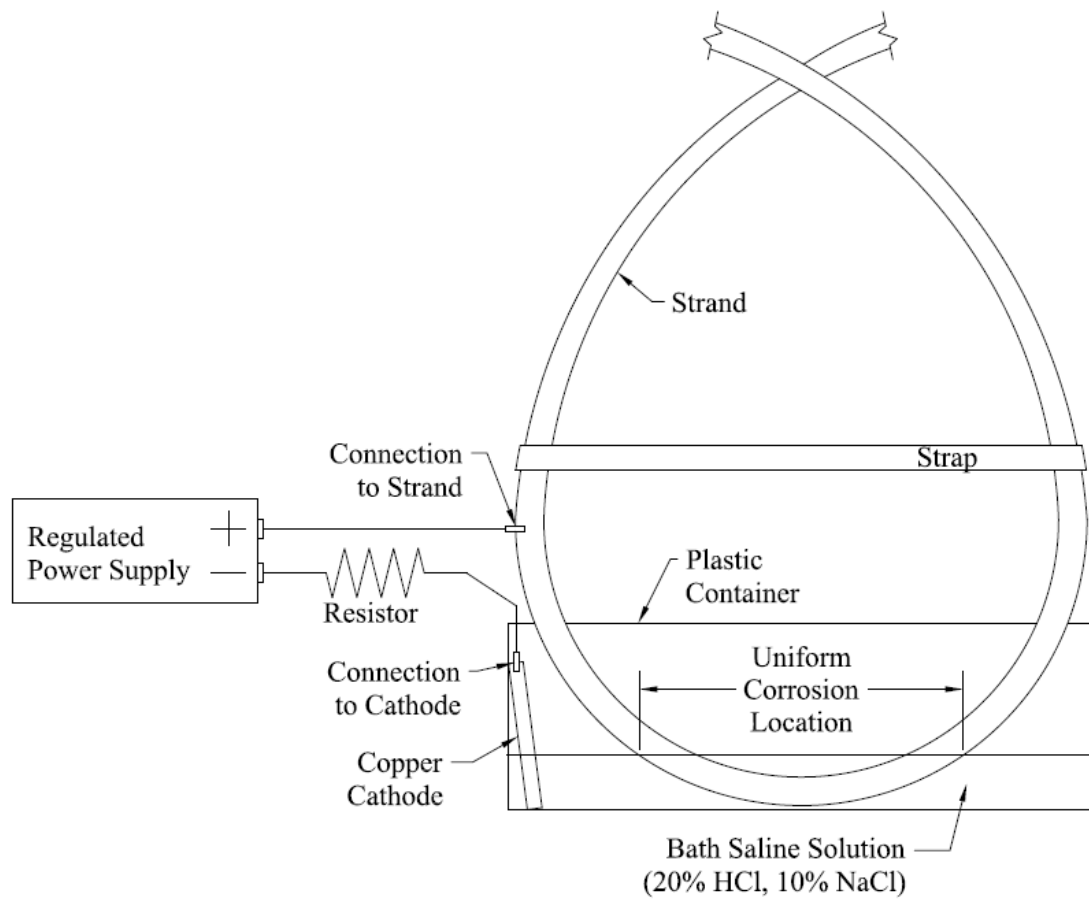
### *3.1. Corrosion*

An electrolytic corrosion cell was set up to fabricate uniform corrosion of a designated length of steel strand. The setup devised is similar to those previously used for localized corrosion by Fricker and Vogel (2007) and Wood et al. (2013), although it was altered to facilitate uniform corrosion. In the electrolytic corrosion cell setup, a saline solution of hydrochloric acid and sodium chloride covered the desired corrosion



area and a circuit was formed to induce current through the strand. The current serves to accelerate the corrosion rate of the steel strand in the saline environment, with a faster corrosion rate at a higher current. In this setup, the current was altered by both changing the resistor used in the circuit and varying the input voltage to ultimately reach 1 Ampere in the final design. At a faster rate of corrosion, fabricating the condition on several strand locations became more feasible. This uniform corrosion setup underwent continuous modifications to increase corrosion speed and setup functionality before a standard corrosion fabrication protocol was reached.

In Figure 3-1 and Figure 3-2, the electrolytic corrosion cell setup used in the laboratory for uniform corrosion is shown. A saline solution of 20% hydrochloric acid and 10% sodium chloride by weight was created and put into a plastic container. The total amount of saline solution was determined by the size of the container and the length of strand that needed to be immersed in the solution. The seven-wire strand was curved into a loop and held in place with a strap before being placed in the container. A copper rod was used as a cathode and partially submerged in the solution. A regulated power supply was used to conduct 1 Ampere of current through the circuit once it was connected and turned on. The power supply anode was directly connected to a location on the exposed steel strand and the power supply cathode went to a resistor and then extended to the end of the copper cathode outside of the solution to complete the current flow through the saline solution. The second rod shown in the plastic container is made up of non-conductive material and was simply used to stir the solution.



**Figure 3-1: Electrolytic Corrosion Cell Setup for Uniform Corrosion**



**Figure 3-2: Laboratory Uniform Corrosion Setup**

Once the power supply was turned on, the electrolytic corrosion cell was continuously monitored by checking the current display on the power supply screen to ensure that the circuit had not been interrupted and the current was remaining constant throughout the fabrication of corrosion. After the section of strand reached the desired level of corrosion, the power supply was turned off and disconnected before removing the strand from the solution and moderately cleaning the corrosion surface as to not spread the saline solution. The finalized version of the electrolytic corrosion cell reduces strand cross-sectional area by approximately 1% every 2 hours when 1 Ampere of current is used. This high corrosion rate was very beneficial to creating the corroded sections of strands in a timely manner.

After completing multiple trials, the same overall electrolytic corrosion cell setup was used in the field except with a different strand configuration to keep the strand immersed in the solution. In the field, the actual strands to be used in the specimen were not held in a loop with a strap, instead a wooden support structure was built to hold the strand down as shown in Figure 3-3.



**Figure 3-3: Fabrication of Corrosion in the Field**

A section of strand corroded by the electrolytic corrosion cell setup in the field is seen in Figure 3-4. In this case, the strand cross-section was reduced by 30% after fabrication of corrosion. The corroded strands were monitored for potential continuous corrosion before placement in the specimen in order to confirm the cross-sectional area loss had not changed. Also, multiple strand diameters were taken, including at every inch of immersed steel to verify that the length of immersed strand was uniformly corroded.



**Figure 3-4: Strand Corrosion**

### *3.2. Breakage and Section Loss*

Breakage and section loss of the steel was implemented using a rotary grinder in two different ways. The breakage condition was replicated by using the grinder to cut a specified number of wires, whereas the section loss condition was fabricated by grinding the steel strands to remove material. The breakage condition on the strand in Figure 3-5 reduced the cross section by 50% by cutting a localized notch in the strand. In this case, three wires are completely severed, along with the center wire partially cut.



**Figure 3-5: Strand Breakage**

In Figure 3-6, material was removed from the strand using a grinder to create a gradual loss of cross-section. In this case, with 86% strand cross-sectional area loss, six of the seven wires are completely severed, although varying levels of section loss are included in the specimen. As a means of quality assurance for both breakage and section loss, multiple strand diameters were taken to compute the most accurate cross-sectional area loss, as was done at the locations of corrosion. Also, the strands were cleaned after condition fabrication and before placement in the HDPE duct prior to grouting.



**Figure 3-6: Strand Section Loss**

### *3.3. Voids*

Two void types were fabricated in the specimen, one consisting of expanding spray foam (a polyurethane plastic foam) and the other of air. The foam voids were placed in the duct prior to grouting by attaching them to one of the 19 strands. Whereas, the air void was formed along the top of the interior duct due to unforeseen grouting inadequacies.

### 3.3.1. Foam Voids

The artificial voids were appropriately sized by using an extra piece of HDPE duct as formwork. A two foot section of duct was cut in half lengthwise and then both pieces were individually lined with a plastic sheet. The polyurethane foam could then be sprayed into the form and easily separated after it had cured for 24 hours. The foam was then cut into the desired void shapes for the specimen.

After cutting each piece of polyurethane foam to the correct size for artificial void placement, the foam pieces could then be glued to the top strand at the desired location along its length before the strand was pushed through the duct. In Figure 3-7, the foam attached to the top strand is shown. In Figure 3-8, the fabricated foam void is seen sliding into the HDPE duct at the top of the duct interior. The strand was pushed farther into the duct until the foam voids were lined up in their correct locations prior to grouting.



**Figure 3-7: Foam Void Attachment to Strand**



**Figure 3-8: Foam Void in HDPE Duct**

### **3.3.2. Air Voids**

The fabrication method for air voids within the specimen was ultimately changed due to complications in the grouting process. The air voids were originally planned to be fabricated using a vacuum pump to extract a designated amount of grout at 2 hours after grouting. This protocol is still included for future reference, however at this point during the specimen construction, air voids were already found in the HDPE duct by visual inspection through the drilled holes as shown in Figure 3-9. Holes of 1.0 in. diameter had been drilled into the ducts for vacuum pump access and subsequently covered prior to grouting. With a large top void already present, the vacuum pump method was no longer executed. The top void was mapped out and included as a condition in the specimen for testing.





**Figure 3-9: Exposed Strand Visible Through Drilled Hole**

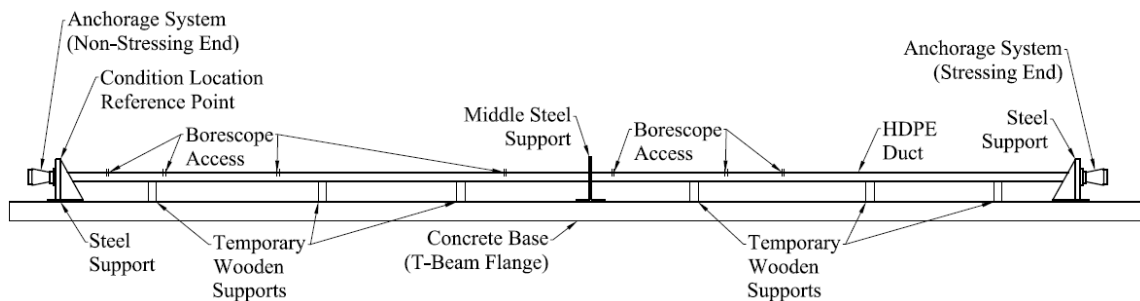
#### 4. SPECIMEN DESIGN AND CONSTRUCTION

The specimen representative of stay cable and external PT systems was initially designed with the objective to include as many conditions as possible, but throughout the construction process this objective became difficult. The steel strand conditions were all included in the specimen at a minimum of two locations and in varying degrees of severity, along with both foam and air voids in the grout. However, compromised grout conditions, water infiltration, and tendon deterioration in the anchorage region were not included due to the long air void that formed across the top of the duct interior.

During construction, the strand deterioration condition locations were closely adhered to in order to evaluate their correspondence with the NDE results. The construction of the specimen with the planted defects at their specified locations was an important objective of this research work and was emphasized in order to provide meaningful information for NDE of stay cable and external PT systems. Despite best efforts for construction to go smoothly, unforeseen issues occurred that caused the course of the research work to change. Equipment did not function as planned and unanticipated problems arose, but the construction process resulted in a realistic specimen to represent stay cable and external post-tensioning deterioration and poor construction practices. The specimen as constructed could effectively be used to assess the applicability of non-destructive evaluation methods in detecting corrosion, section loss, breakage, and voids.

#### 4.1. Specimen Design

The specimen was designed to consist of an opaque, 4.0 in. diameter HDPE duct over 36 feet in length between two anchorage systems as shown in Figure 4-1. There are three steel duct support pieces bolted to eight inches of concrete below, one at each end and one at approximately mid-span of the duct length. The concrete used was a recycled 40 ft long T-beam flipped upside down on wooden supports. Wooden supports were also used temporarily throughout the specimen between the concrete base and the duct for support during grouting. Within the duct, the specimen design includes 19 grouted seven-wire strands of 0.6 in. diameter. Seven holes were drilled into the duct and covered prior to grouting. These drilled holes, originally planned for use in fabricating conditions with a vacuum pump, were used in reality as access points for the borescope inspection.



**Figure 4-1: Stay Cable and External PT Specimen Setup**

#### 4.2. Condition Locations

The specimen design also includes planning the locations of the steel and grout conditions prior to their fabrication. A minimum of two feet was accounted for between

each strand condition location and their placement was recorded in detail before the strands were pushed into the duct. The placement of foam voids was documented in relation to their positioning along the top strand before also being placed in the HDPE duct.

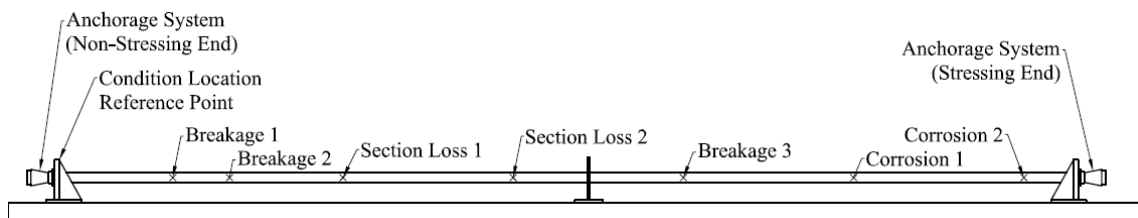
#### **4.2.1. Breakage, Section Loss, and Corrosion Locations**

Each of the steel conditions were fabricated at a designated length along the strands that were measured and cut from the strand spool. The condition locations were recorded as the distance from the inside face of the steel support at the non-stressing anchorage end, the condition location reference point in Figure 4-1. This distance was added to the length of strand needed to extend through the anchorage system in order to determine the total distance from the condition to the strand end before placement in the duct. These conditions include three breakage locations, two section loss locations, and two corrosion locations. Each condition location features a different loss in cross-sectional area of the tendon. At the breakage locations, the tendon cross-sectional area losses are 9.2%, 28.2%, and 4.1%, in order of closest to farthest from the steel support reference point. There is 18% cross-sectional area loss at the first section loss location and 13.5% cross-sectional area loss at the other section loss location. The breakage locations are considerably more localized than the section loss locations because wires were cut to fabricate breakage, whereas material was removed to form a gradual transition at section loss locations.

Each of the two corroded segments were subject to the electrolytic corrosion cell with an immersed strand length of 6 inches. At the first corrosion location, two strands were corroded until 30% loss of cross-sectional area had occurred for each strand. At the other location of corrosion fabrication, only one strand was corroded until 50% cross-sectional area loss was fabricated. The corroded lengths of strand resulted in 3.2% and 2.6% tendon cross-sectional area losses, respectively. These steel deterioration conditions, along with their distance from the reference point at the first steel anchorage support piece are included in Table 4-1. Their locations along the stay cable and external PT specimen are illustrated in Figure 4-2.

**Table 4-1: Tendon Deterioration Conditions**

<b>Deterioration Condition</b>	<b>Distance from Reference Point (ft)</b>	<b>Average Strand Cross-Sectional Area Loss (%)</b>	<b>Number of Strands</b>	<b>Tendon Cross-Sectional Area Loss (%)</b>
Breakage 1	4	43.8	4	9.2
Breakage 2	6	53.6	10	28.2
Breakage 3	22	28.6	3	4.5
Section Loss 1	10	85.7	4	18.0
Section Loss 2	16	42.9	6	13.5
Corrosion 1	28	30.0	2	3.2
Corrosion 2	34	50.0	1	2.6



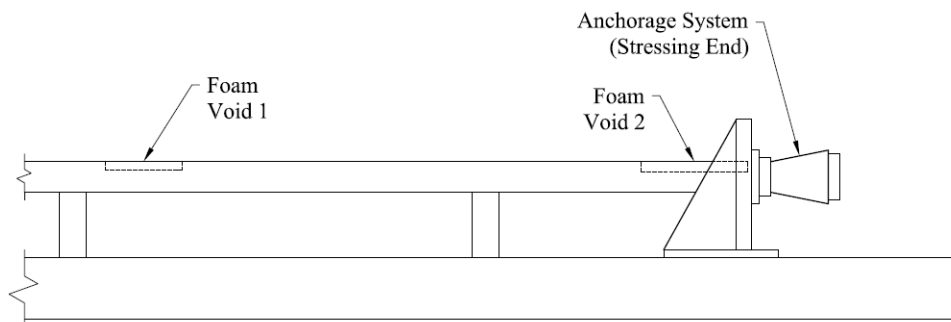
**Figure 4-2: Breakage, Section Loss, and Corrosion Placement**

#### 4.2.2. Void Locations

Two voids, both formed by the expanding polyurethane foam, were planned for placement in the specimen. These artificial voids were designed to press up against the top of the duct interior by attachment to the top strand. When strand stressing occurred to lift the steel off of the bottom of the duct interior, the foam voids were secured in place. One foam void, although only 4 inches longer than the other foam void, was shaped to take up twice the volume in the duct. The void sizes and locations are noted in Table 4-2. The distance from the reference point seen in Figure 4-1 is measured to the center of the foam void length. The placement of these artificial voids is also illustrated in Figure 4-3 with the strands not shown for clarity.

**Table 4-2: Grout Deterioration Conditions**

<b>Deterioration Condition</b>	<b>Distance from Reference Point (ft)</b>	<b>Void Size (in.<sup>3</sup>)</b>	<b>Void Length (in.)</b>
Foam Void 1	29	20	10
Foam Void 2	35	40	14



**Figure 4-3: Foam Void Placement**

In addition to these voids, an unplanned air void was created during grouting of the stay cable and external PT specimen. The void location and size was mapped out using both the borescope and sounding methods, along with visual inspection. Although the air void was not part of the initial specimen design, it is a condition that is known to form in long, straight, horizontal ducts during poor grouting practices.

In addition, this top air void is very representative of voids in the field referred to as bleed lines. During grouting, grout can bleed water to the top surface, although this incident is less likely when proper grout is used and correct grouting procedures are followed. The bleed water then evaporates to leave an air void along the top duct interior surface. In the specimen, the fabrication of the air void did not occur due to bleed water evaporation, but it can be used as a representation of a severe bleed line case in the field or of the typical result seen in horizontal ducts grouted with improper procedures. These grouting procedures will be discussed further with the grouting of the specimen. It was ultimately beneficial to have a top air void fabricated in the specimen to be included in the non-destructive evaluation with the corrosion, section loss, breakage, and foam void conditions.

#### *4.3. Specimen Construction*

Specimen construction included fabrication of the conditions, setup prior to grouting, and ultimately grouting of the specimen, including the necessary grout material tests. The steel deterioration conditions were fabricated first, followed by the formation of the intended foam voids and later the accidental air void during grouting.

#### **4.3.1. Prior to Grouting**

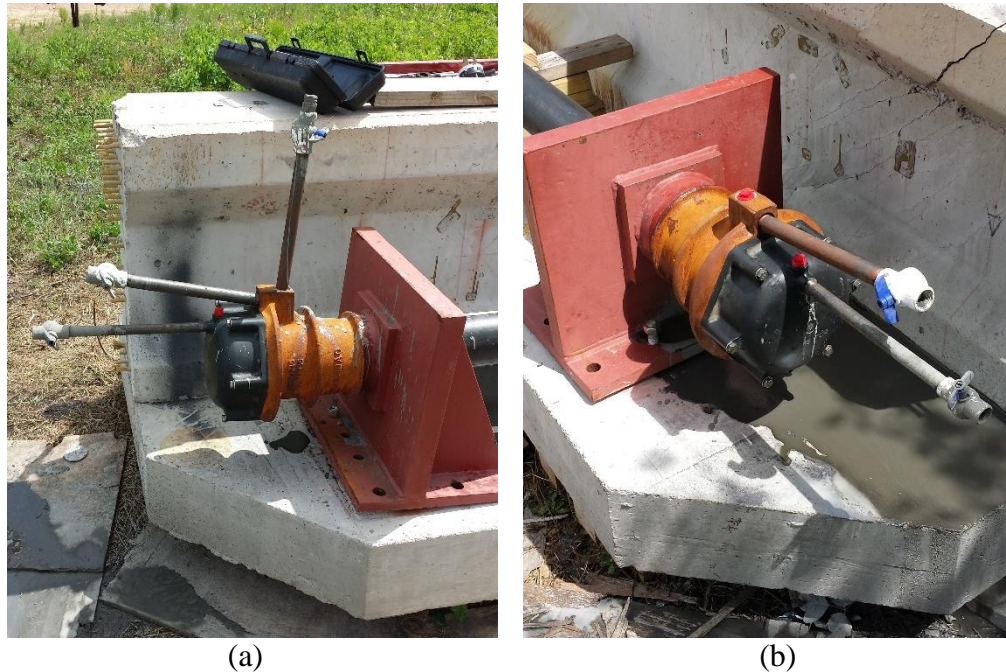
Construction of the specimen began with connecting the three duct supports to the available concrete base at the TAMU Riverside Campus. Then, the wooden supports were set up, the duct was positioned, and the strands were pushed through and organized in the two anchorage systems. Before stressing, all of the strands were secured with wedges in the anchorage system at the non-stressing end. A stressing jack was used at the stressing anchorage end to pull the anchorage systems up into place and tension the strands enough to provide space between the strands and the bottom of the duct. After stressing, wedges were positioned at the stressing end to keep the strands tensioned enough to be straight throughout the duct. Figure 4-4 shows the non-stressing end anchorage system prior to cutting the stressed strand ends.



**Figure 4-4: Anchorage System under Construction**



After the strands were cut, the anchorage caps were screwed on the anchorage system ends and the grout ports were connected prior to grouting. Each grout port included a steel pipe, which was screwed into the anchorage, and an end valve to close the grout port when required. These grout ports are visible in Figure 4-5. A waterproof silicone sealant was then applied between the duct and both faces of the steel support pieces in an effort to create an air tight attachment of the duct to the anchorage systems before grouting.



**Figure 4-5: Grout Ports at Anchorage: (a) Non-Stressing End, (b) Stressing End**

#### **4.3.2. Grouting**

A thixotropic, prepackaged Class C grout was used in the stay cable and external PT specimen. The engineered high strength grout mix was mixed solely with water on

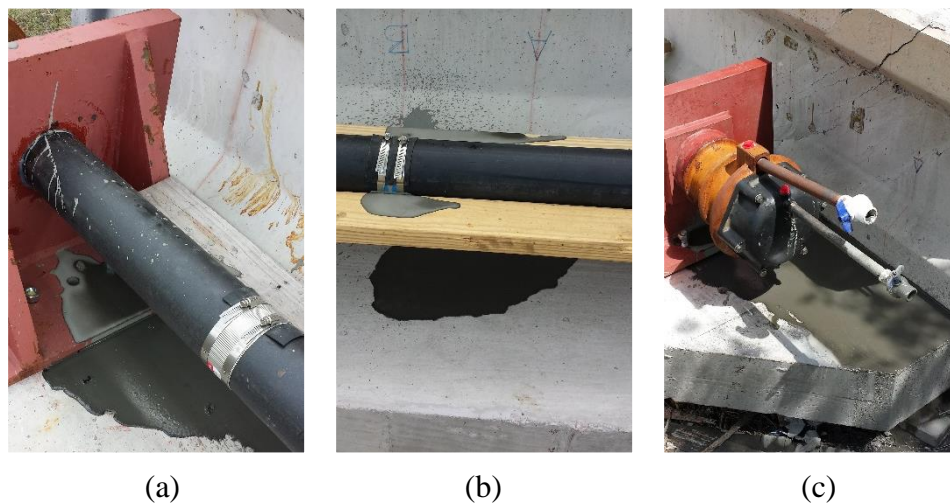
site using a colloidal mixer and pumped into the specimen with a pneumatic pump. A generator was brought on site to power the mixer and an air compressor was likewise transported to the specimen location for connection to the pump. The grouted stay cable and external PT specimen is pictured in Figure 4-6.



**Figure 4-6: Grouted Stay Cable and External PT Specimen**

Although taking every precaution to follow appropriate and necessary grouting procedures, there was ultimately low grouting pressure due to the pneumatic pump. The unplanned top air void extending the length of the specimen was most likely formed due to a combination of this inadequate grouting pressure and three identified grout leakage locations. The grout leakage that occurred after grouting is shown in Figure 4-7. Grout escaped out of each end anchorage setup where the duct was sealed to the steel anchorage support piece and also at one of the drilled hole locations. It is most likely that the sealant around the duct at the end supports was not given ample time to cure since

there was a high temperature and high humidity environment present. At the drilled hole location, the grout leakage likely occurred due to inadequate coverage at a slight low point in the specimen. Although the specimen was designed to be completely horizontal, this was unrealistic due to unlevelled ground and sloping duct between supports after the grout weight was added.

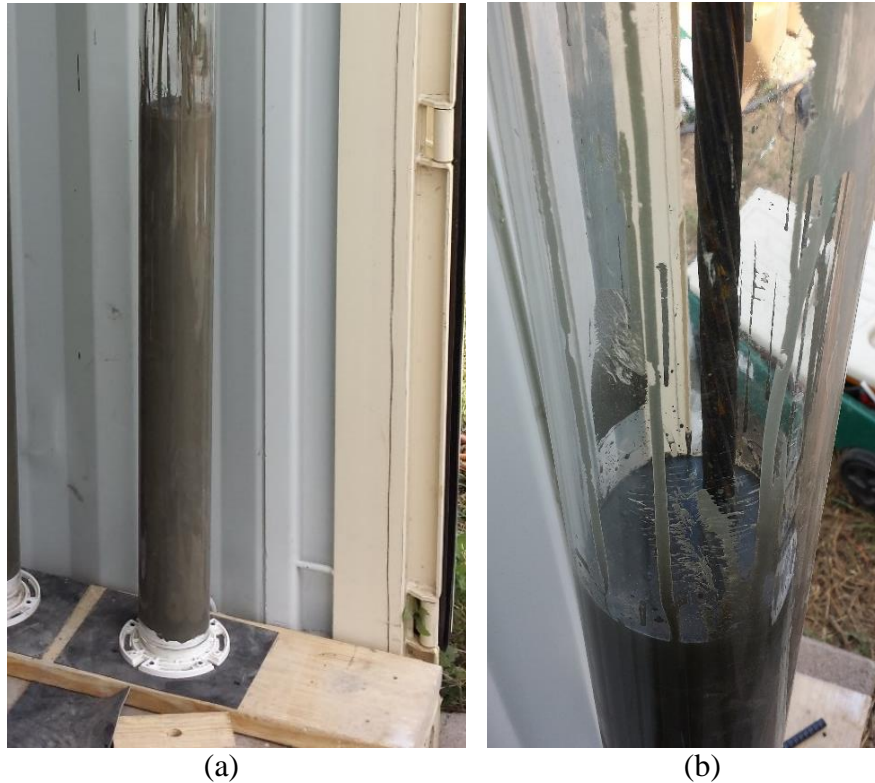


**Figure 4-7: Grout Leakage: (a) Anchorage, (b) Drilled Hole, (c) Anchorage**

#### **4.3.3. Grout Material Tests**

Several material tests were performed on the freshly mixed grout. These tests include a wick-induced bleed test, wet density test, and flow cone test. Grout cubes were also formed for compressive strength testing. The wick-induced bleed test was performed according to ASTM C940-10A (ASTM 2010a). The setup consists of a clean strand inserted into a cylinder container filled with fresh grout to a height of 40 inches.

The grout used for the specimen passed the ASTM C940 standard for 0.0% bleed after 3 hours. One of the two wick-induced bleed test setups is seen in Figure 4-8.



**Figure 4-8: Wick-Induced Bleed Test Setup: (a) Full View, (b) Close-Up**

The grout wet density test was performed using a mud balance prior to using the grout mixed for the specimen. The wet density test procedure followed API Recommended Practice 13B-1 (API 2003). The grout wet density was determined to be 145 pounds per cubic foot, surpassing the minimum required wet density for the grout used, 121.7 pounds per cubic foot. Grout flow was tested using the modified pumpability and fluidity test procedures for thixotropic grout from ASTM C939-10 (ASTM 2010). The time for one liter of freshly mixed grout to flow through the flow cone was clocked



at 8.5 seconds, within the requirement of between 7 seconds and 20 seconds for the grout type used in the stay cable and external PT specimen.

Compressive strength tests were performed for 3 two inch grout cubes at both 7 days and 28 days. The results of the grout compressive strength tests performed by a MTS testing machine in the lab in accordance with ASTM C942-10 (ASTM 2010) are seen in Table 4-3. The grout passed the required strengths of 4000 psi at 7 days and 4600 psi at 28 days. Although the grout met the compressive strength required by the Texas Department of Transportation, the strength results did not reach those provided in the grout test data by the manufacturer. This grout type is expected to exceed 5500 psi at 7 days and 8000 psi at 28 days. The most likely cause for not meeting these expected compressive strength values is that the grout was four months past the end of its six month shelf life. However, the grout still met all of the criteria in the fresh grout tests performed and exceeded the actual required grout compressive strength values in Texas.

**Table 4-3: Grout Cube Strength**

	<b>Grout Compressive Strength (ksi)</b>	
	<b>7 days</b>	<b>28 days</b>
<b>Grout Cube 1</b>	5.02	5.97
<b>Grout Cube 2</b>	5.50	6.84
<b>Grout Cube 3</b>	4.13	6.66
<b>Average of 3 Cubes</b>	4.88	6.49

## 5. NDE RESULTS AND DISCUSSION

The non-destructive evaluation of the stay cable and external post-tensioning specimen occurred during two periods of time. The first evaluation was carried out within days of grouting the specimen as a means to evaluate the applicability of the non-destructive evaluation methods to determine defects during or shortly after construction as a means of quality control (QC). The second evaluation of the specimen occurred at a time greater than 28 days after grouting. This testing was more representative of an inspection since the grout was fully cured by this time. The difference in the specimen during these two times of testing lay in the varying amount of moisture present in the grout during curing and after curing.

During the first testing period, sounding was performed first so that the testing was performed without yet knowing the outline of the voided area. After the blind sounding, the borescope was used on the specimen, followed by use of ultrasonic tomography (UST), infrared thermography (IRT), and ground penetrating radar (GPR). UST, IRT, and GPR were then used again during the inspection testing period. A comparison of NDE results from sounding, borescope use, IRT, and GPR during the quality control testing period is shown in Appendix A.

### *5.1. Borescope*

After discovery of the voided section in the duct that was unintentionally fabricated during construction, a borescope, seen in Figure 5-1, was used to map out the

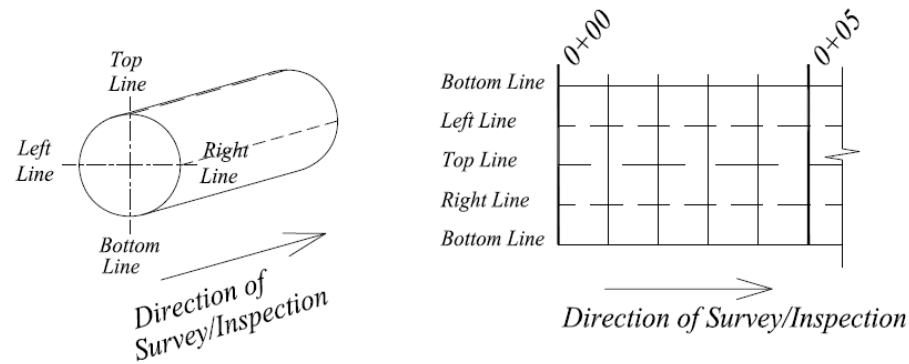
extent of the air void. Access to the voided area was achieved through the seven drilled holes along the top of the duct. Upon uncovering the holes, the borescope could be maneuvered through the void space in either direction along the duct. Photos and videos were recorded with voice over to match the collected images with their location along the duct length. After removal of the grout ports at the system anchorages, the borescope could also be inserted in the grout caps and anchorages to determine the grout level throughout each anchorage region.



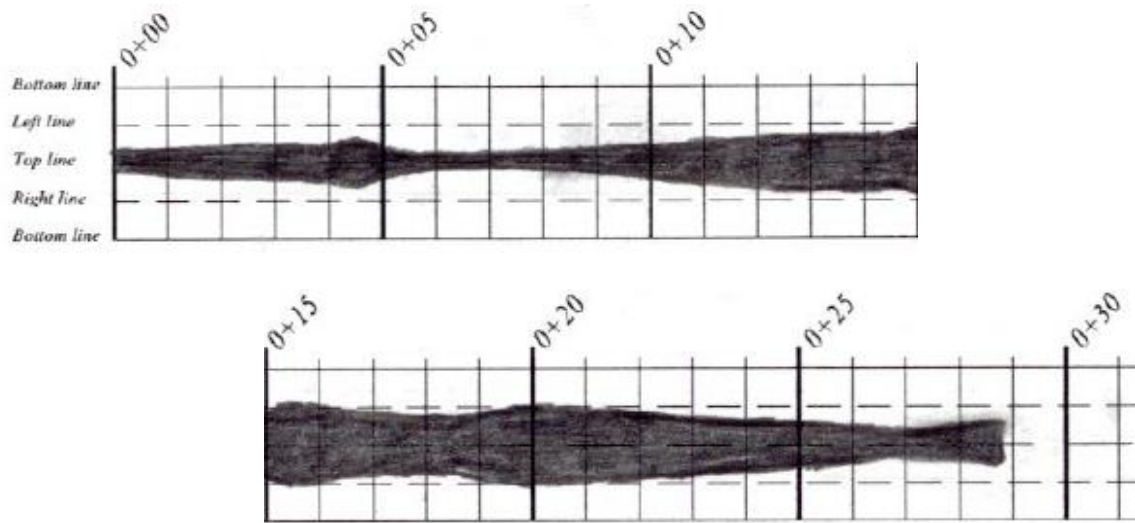
**Figure 5-1: Borescope Used on Specimen**

The collected borescope images inside the HDPE duct were used to map out the void shape created during grouting. The void mapping sheet shown in Figure 5-2, developed by Im (2009), was used to create a map of the borescope results for the full circumference and length of the duct shown in intervals of one foot. This void map was

used as ground truth data to determine the validity of results from the sounding, ultrasonic tomography, infrared thermography, and ground penetrating radar tests.



**Figure 5-2: Void Mapping Sheet (Im 2009)**



**Figure 5-3: Borescope Map of Voids**

As illustrated in Figure 5-3, the void extends across the entire top line of the duct from the void mapping starting point at the non-stressing anchorage end to the first foam



void. The first foam void is planted in the duct starting at 28 feet and 7 inches from the reference location. It is seen compressed in the middle right of Figure 5-4. Although the duct extends to over 35 feet, the range of duct from the first foam void to the second foam void into the stressing anchorage end was inaccessible by the borescope. No drilled holes lay between the artificial voids and at their locations the grout and strands blocked borescope access around them.



**Figure 5-4: Borescope View of Foam Void**

In the duct length that could be mapped out by the borescope, the greatest void extent over the duct cross section occurs between 13 feet and 21 feet, seen in Figure 5-5. Whereas, the smallest void area is seen at 0 feet and between 6 feet to 8 feet, shown in Figure 5-6. The change in air void size along the duct was likely caused by slight variations in the duct height due to unlevelled ground and the weight of the specimen

between supports. These small slopes in the duct caused a varying amount of the cross section to be filled as the grout leveled out in a sloping duct.



**Figure 5-5: Borescope View of Several Exposed Strands**



**Figure 5-6: Borescope View of Air Void**

The borescope was also used in both anchorage regions, in both the anchorage system and grout cap. Exposed strands were visible at both ends of the specimen, although to a lesser extent in the non-stressing anchorage end, shown in Figure 5-7. The stressing anchorage end was less grouted throughout the anchorage region and grout cap at about half full of grout. The non-stressing anchorage end and grout cap, shown in Figure 5-8, ended up at approximately two thirds full of grout.



**Figure 5-7: Borescope View of Anchorage Region**



**Figure 5-8: Borescope View Inside Grout Cap**

Although the borescope was primarily used to map the top air void, a location of section loss at 16 feet from the reference point was also seen during the specimen inspection. If exposed strands within the duct have been subject to corrosion, breakage, or section loss, it is possible that these conditions can be identified during borescope use in a voided section, although they need to be free from grout cover. At locations of breakage and section loss of the strands, the seven wires were held in place as much as possible to eliminate wires fraying from the bundle. However, as the strands were pushed through the anchorage systems and duct, it was difficult to prevent wires from fraying as seen in Figure 5-9.



**Figure 5-9: Borescope View of Section Loss**

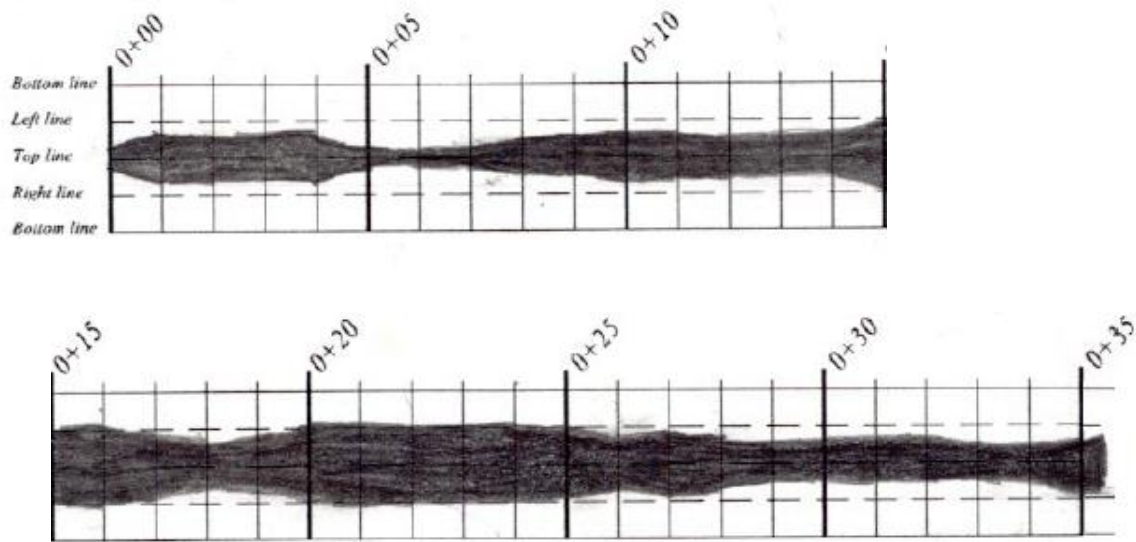
### *5.2. Sounding*

The non-destructive evaluation method of sounding was applied to the duct using the ball peen hammer shown in Figure 5-10. There are numerous impact tools that can be used to perform sounding on stay cables and external PT ducts, including the metal impactor also shown. During inspection, voids are identified by the acoustic response to tapping on the duct. Since these acoustic responses are interpreted by the inspector throughout sounding, it can be a very subjective method of condition evaluation. Tapping on an area of voided duct creates a different sound pitch than tapping on an area of fully grouted duct. Air voids produce a lower pitch response, whereas grouted duct creates a higher pitch response. By recording areas of lower pitch responses, a map of voided areas can be produced and these locations can be marked for further inspection.



**Figure 5-10: Sounding Tools**

The voids detected were recorded using the same void mapping sheet as used for the borescope inspection. The map is shown in Figure 5-11. After both the sounding method and the borescope inspection were carried out, the results were compared. The void map created by sounding is very similar to the void map produced from the borescope inspection. However, in occasional sections of duct length, the sounding method slightly overestimated the void size. This is likely due to the subjectivity involved in the evaluation method.



**Figure 5-11: Sounding Map of Voids**

As seen in the sounding map, the two artificial voids, centered at 29 feet and 35 feet, created acoustic responses similar to that of air voids and were therefore recorded as voided duct. This result helps to validate the use of foam to replicate an air void in specimens subject to non-destructive evaluation, at least for use of the sounding method.

### *5.3. Ultrasonic Tomography*

Ultrasonic tomography was implemented on the specimen during both quality control and inspection time periods. The ultrasonic low-frequency tomograph used, shown in Figure 5-12, was the A1040 MIRA unit with operating frequencies of between 25 kHz and 85 kHz. This ultrasonic testing unit is intended for use on concrete, but was applied to the stay cable and external PT specimen to determine its applicability elsewhere. The underside of the tomograph is made up of an array of 48 total transducers

in a 4 by 12 configuration. The first row of four transducers sends shear waves into the material to be detected by all of the other rows of transducers. Once detected, the second row transmits another set of shear waves to be detected. This phased ultrasonic testing continues until the final row of transducers is reached. In this tomograph, dry point contact transducers are used, meaning no couplant is needed between the transducers and testing surface which makes testing both cleaner and faster. To test, the ultrasonic tomograph is pressed down on the material surface to depress the transducers and then a button is pressed to begin the phased array data collection.



**Figure 5-12: Ultrasonic Tomograph**

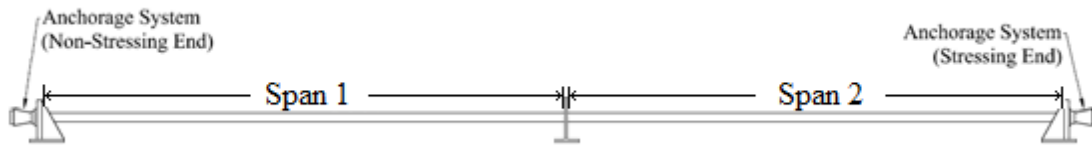
The results from each of the four testing lines in the array are averaged to produce the B-Scan image. The plane of the B-Scan image runs lengthwise with the device and perpendicular to the scanning surface. C-Scans and D-Scans can also be produced. The D-Scan plane runs perpendicular to the tomograph length and perpendicular to the scanning surface, whereas the C-Scan plane lays perpendicular with



both the B-Scan and D-Scan planes. When the tomograph is used on flat surface concrete, typically a rectangular grid is created to test in two directions. The number of steps in each direction is decided by the user and used to create a map of the grid area with all of the collected scans.

In the case of the stay cable and external PT specimen, testing was conducted in only one direction extending along the length of the duct. Scans were taken at a spacing of 100 mm which resulted in scans being overlapped threefold to increase precision. With the curved duct surface, only the center two lines of transducers could be depressed and used to test the specimen. Therefore, only a continuous B-Scan of the duct was able to be collected and analyzed using the available tomograph.

Since there is not an established ideal operating frequency for ultrasonic testing of stay cable and PT grout, data was collected using 25 kHz, 50 kHz, and 85 kHz for comparison. As the frequency used increases, the resolution of the data collected also increases. However, the lower the frequency, the greater the penetration depth through the material, so there are tradeoffs with each frequency used. The specimen was tested along both the top of the duct and the side of the duct. Useful results of the full duct depth were difficult to obtain with ultrasonic testing along the top of the duct due to the air void present along the top of the duct interior. The acoustic waves emitted from the tomograph attenuate when travelling through air, preventing any collection of information on material behind the top air void. For testing, the duct was divided into two sections labelled Span 1 and Span 2, seen in Figure 5-13.



**Figure 5-13: Specimen Spans for UST Testing**

The B-Scan images collected during testing of the specimen are a reflection of the different wave speeds of the acoustic waves transmitted and received by the phased array. The B-Scan image is made up of a range of colors from light blue in regions of low acoustic impedance to dark red in regions of high acoustic impedance.

Ultimately, the results from the ultrasonic low-frequency tomograph A1040 MIRA were difficult to interpret with only B-Scans of the data able to be collected and the results of the MIRA unit being widely inconsistent. Identical ultrasonic tomography tests over the same duct section (top or side), using the same operating frequency (25 kHz, 50 kHz, or 85 kHz), and in the same testing period (QC or Inspection) produced very different results. In order to achieve meaningful results with the ultrasonic tomography non-destructive evaluation method, modifications to the type of unit used for testing on stay cables and external PT are necessary. A sample of UST results from each type of test are given in Appendix B.

#### *5.4. Infrared Thermography*

The infrared thermography method was implemented by viewing the specimen with a FLIR (Forward Looking Infrared) device, shown in Figure 5-14, and capturing

thermal images as desired. The key to this non-destructive evaluation method was to perform testing on the specimen at the right time of day. Higher temperature differentials between the grout, air, and foam inside the duct produced infrared images of greater readability. These higher temperature differentials were found to occur during periods of time in which the specimen was either cooling down or warming up throughout the day. The rate at which different materials change temperature is a function of their specific heat value. With materials of varying specific heat values included in the specimen, the best time to capture thermal images was during temperature changes in the surrounding environment.



**Figure 5-14: Infrared Thermography Device**

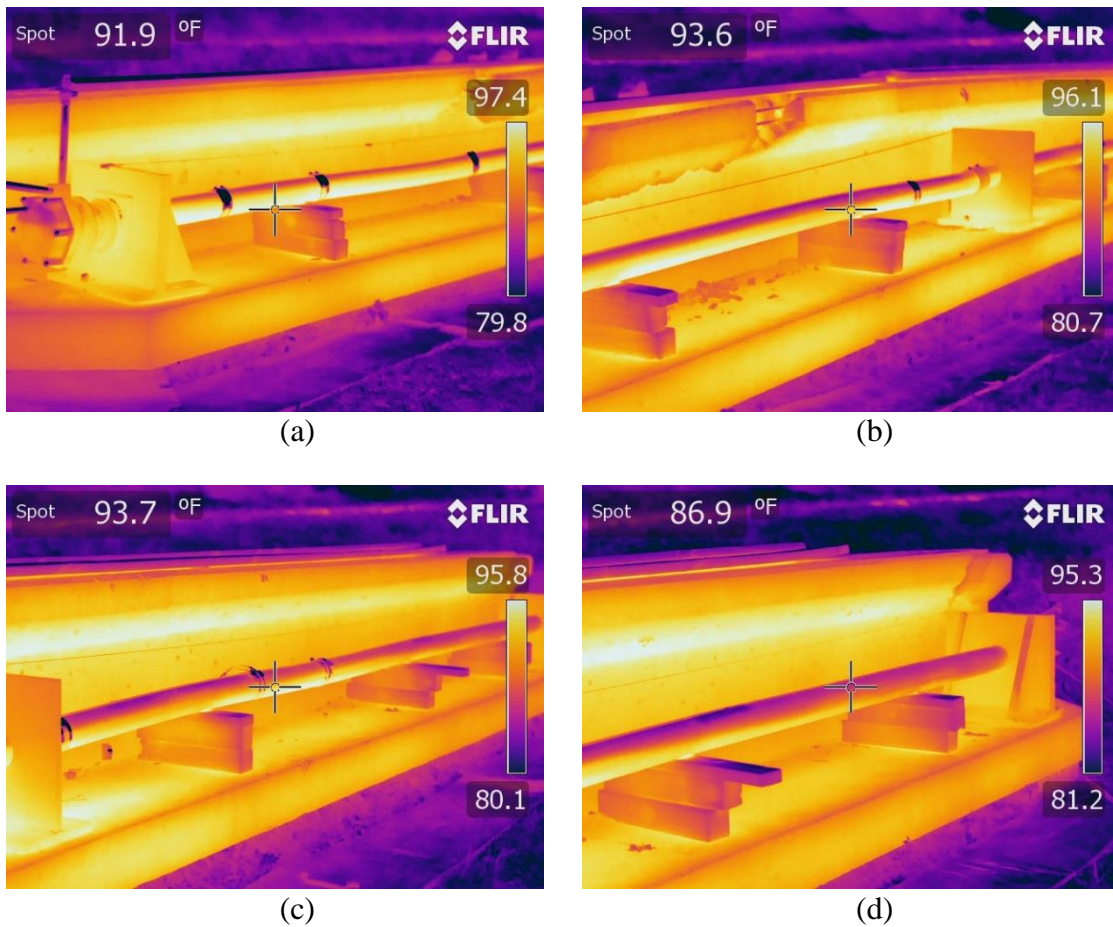
In this research, solely passive infrared thermography was used for the evaluation of conditions within the specimen representative of a stay cable and external post-tensioning. Passive infrared thermography uses the natural temperature changes of the

environment to influence the temperature of the specimen materials for testing. Whereas, active infrared thermography, not used in this research, uses an active heating source to create a greater temperature differential in the materials to be tested.

Infrared thermography was used to evaluate the condition of the stay cable and external PT specimen both soon after grouting and after the grout had cured. Both the quality control and inspection periods produced the same results. The infrared imaging device could detect voided regions filled with both air and foam, but was unable to determine locations of the steel strand conditions. The steel breakage, section loss, and corrosion went undetected by the infrared thermography method.

#### **5.4.1. IRT Quality Control**

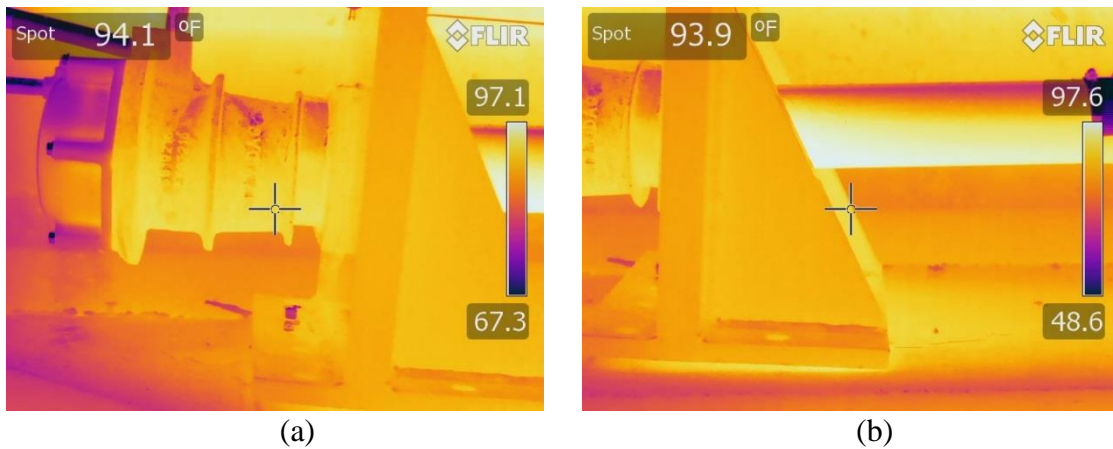
In Figure 5-15 of images taken soon after grouting, the top void can be seen along the duct free span during a period of temperature cool down. During testing, it is important to take into consideration any portions of external PT that had been shaded from the sun for an extended period of time. In the bottom right image, more of the duct appears to be voided than is in reality due to that portion of duct being out of direct sunlight for some time. The other three images show a true representation of the voided duct area, seen by the purple color of cooler temperature in comparison to the orange and yellow colors of hotter temperatures.



**Figure 5-15: (a-d) IRT QC of Duct Free Span during Cool Down**

On occasion, if the specimen was tested at the correct time during temperature change, images could be produced that matched closely with the ground truth borescope results. In Figure 5-16, the thermal views of the non-stressing anchorage region and the beginning of the free duct span align perfectly with the extent of the air void within the specimen during this quality control period of testing. The air void represented by the purple color in the images extends straight through the anchorage and once into the free duct, the void size begins to gradually expand through the first two feet of duct shown in the picture on the right. As the air within the specimen cools down faster than the grout,

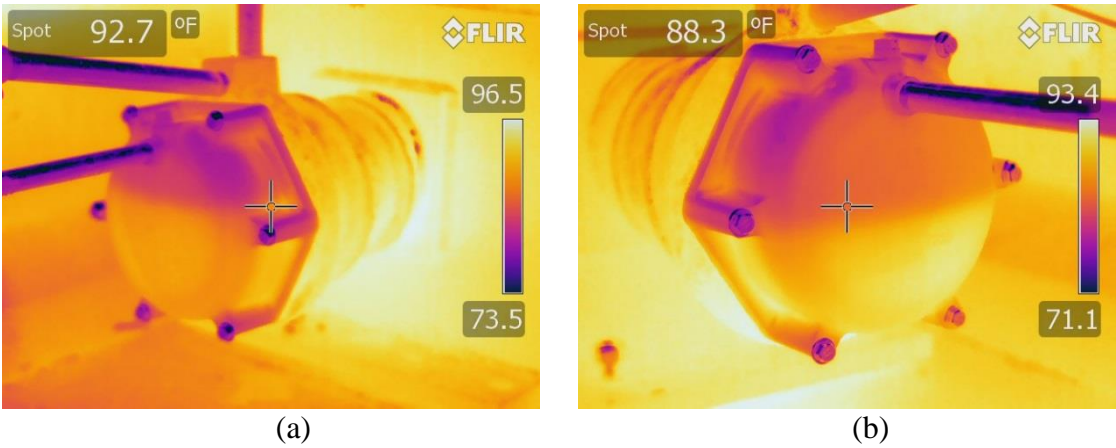
the difference in temperature increases to make capturing these infrared thermal images possible.



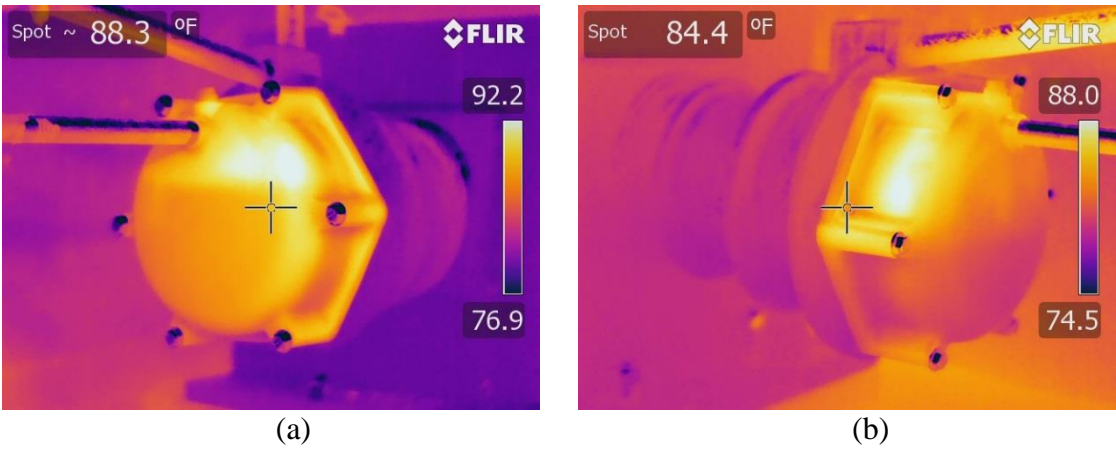
**Figure 5-16: (a-b) IRT QC of Top Void Variation during Cool Down**

A significant finding during this non-destructive evaluation period was the quality of thermal images that could be taken of the grout caps at the specimen ends. The grout level is extremely evident both when the surrounding temperature is decreasing, as in Figure 5-17, and when the surrounding temperature is increasing, as in Figure 5-18. Being able to capture the dividing line between air and grout at the specimen ends soon after grouting makes this method of evaluation a strong candidate to be used as a quality control method specifically for external PT and even internal PT. During construction, a quick image can be taken of the grout caps at the right time of day to ensure that the duct is fully grouted through the anchorage regions. Anchorage regions are typically the most likely area of post-tensioning to include voids due to poor construction practices, especially with the use of harped tendons, either external or within concrete. By using

infrared thermography on the grout caps, the quality of grouting can in most cases be determined quickly and without having to remove the grout caps for inspection. If voids are detected, repair action can be planned and executed before the bridge structure even goes in to service.



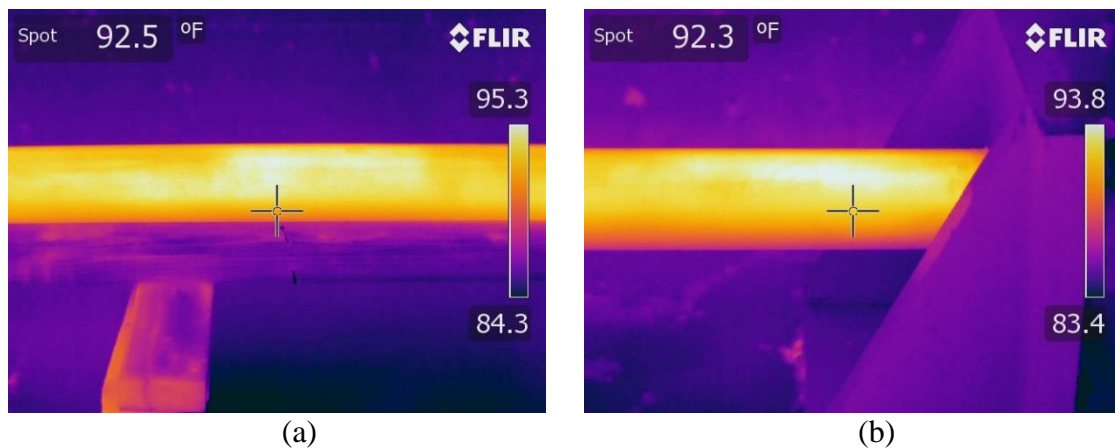
**Figure 5-17: (a-b) IRT QC of Anchorage Ends during Cool Down**



**Figure 5-18: (a-b) IRT QC of Anchorage Ends during Warm Up**



The foam void locations were evident in the thermal images, shown in Figure 5-19, even during quality control testing. Although the foam pieces were meant to be directly representative of air voids, the foam often stood out more than the air in the infrared thermography evaluation of the ducts. The first foam void shown in the left image and the second foam void shown in the right image were here seen to heat up faster than the assumed surrounding air during natural temperature increases. However, there is not ground truth data available from a borescope inspection for this portion of the duct for direct, valid comparison to the actual air void size.



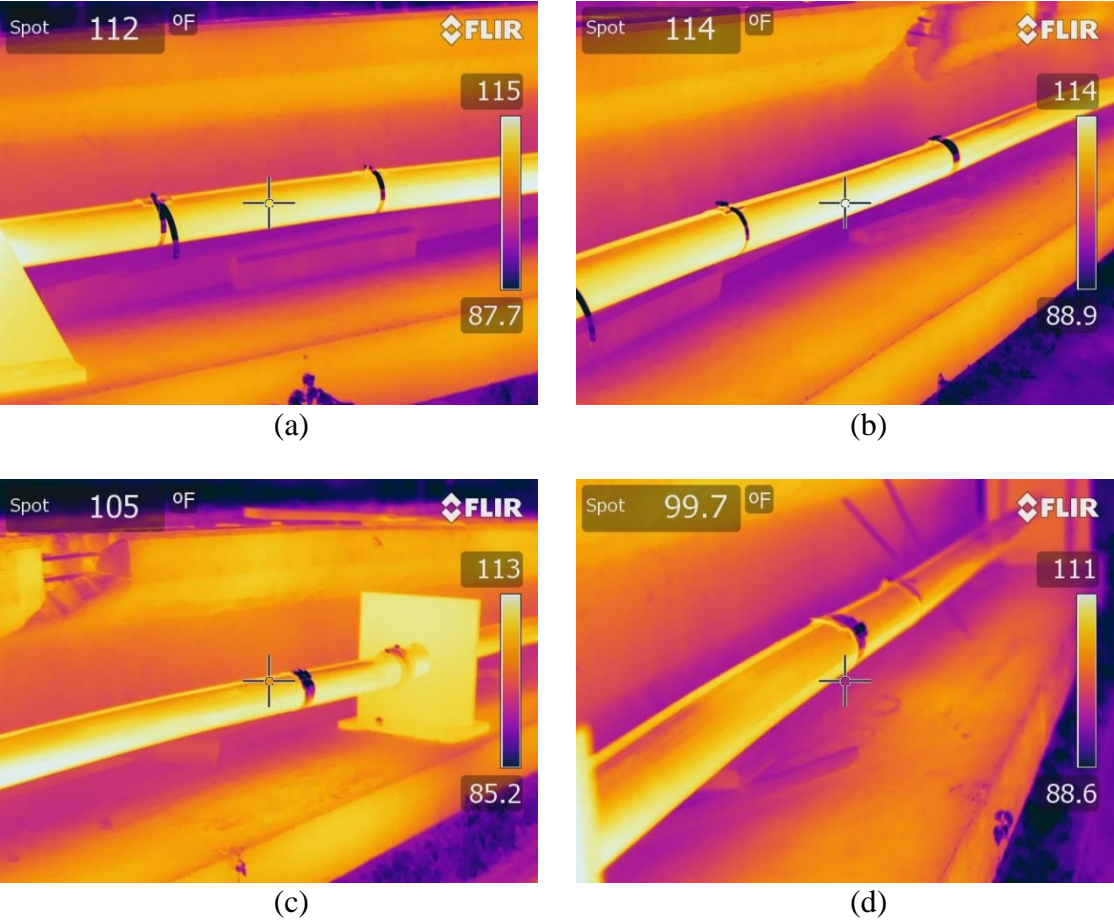
**Figure 5-19: (a-b) IRT QC of Foam Void Locations during Warm Up**

#### **5.4.2. IRT Inspection**

After the grout had fully cured at 28 days, IRT evaluation of the specimen was carried out again to determine if the same results were achieved. Very similar thermal images of the specimen were captured during the inspection testing. In Figure 5-20, four images of the duct free span are shown as the specimen is cooling down. Again, the air

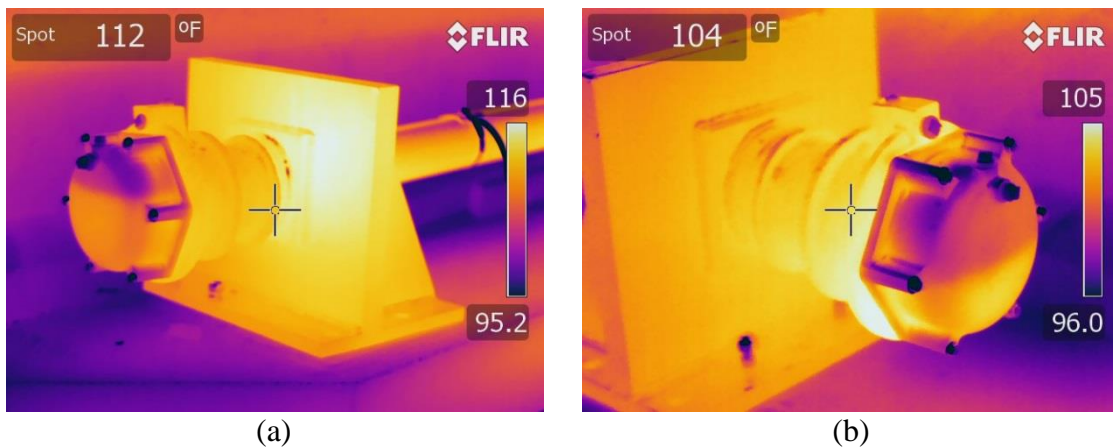


in the duct is decreasing in temperature more quickly than the grout due to the specific heats of air and grout. The void extent can be seen by the deeper orange coloring, while the hotter grout is represented by a light yellow, almost white coloring. In the top left image especially, at the beginning of the free span, it is evident that the amount of air at the top of the duct cross-section is increasing along the first few feet of free span and then decreases again at approximately 5 feet from the steel support, matching the borescope results.

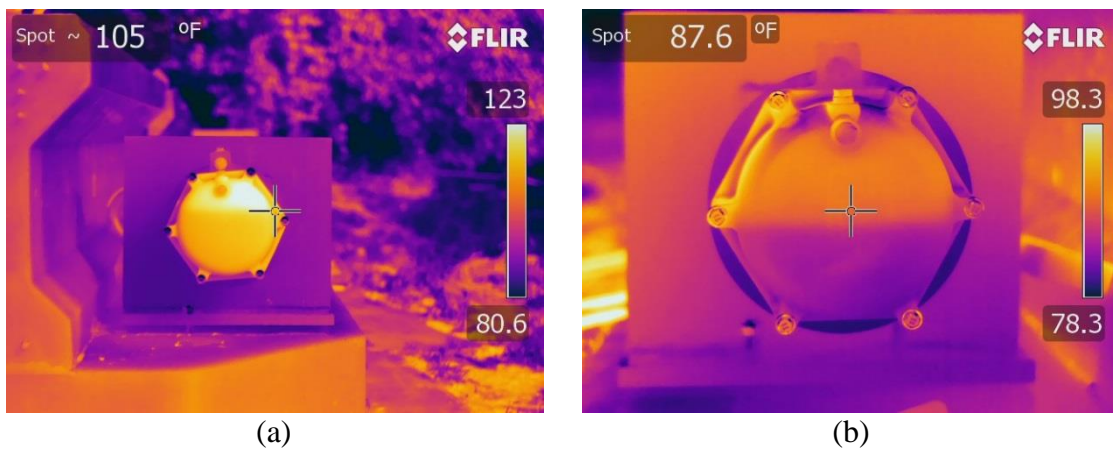


**Figure 5-20: (a-d) IRT Inspection of Duct Free Span during Cool Down**

In Figure 5-21 and Figure 5-22, the grout cap thermal images are shown during cool down and warm up, respectively. Clear changes in temperature are seen at the interface between air and grout within the ends of the specimen, again with more grout filling the non-stressing anchorage end in the left side images. As an inspection method of in-service bridges, infrared thermography would be extremely valuable for quick non-destructive condition assessment of the anchorage systems.

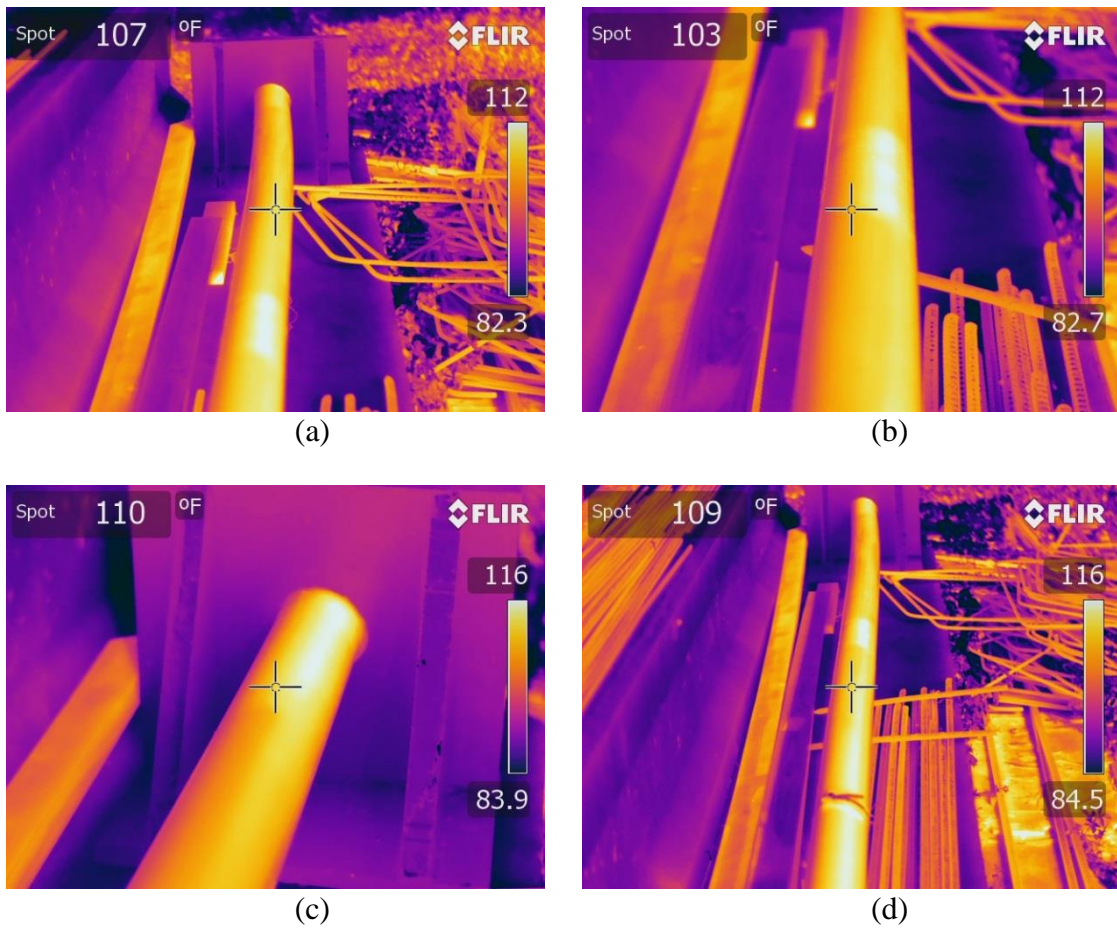


**Figure 5-21: (a-b) IRT Inspection of Anchorage Ends during Cool Down**

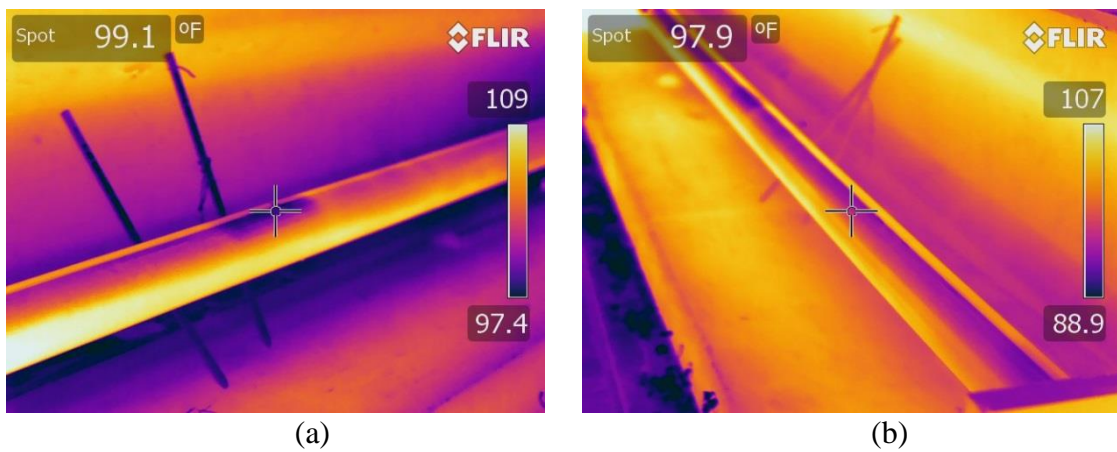


**Figure 5-22: (a-b) IRT Inspection of Anchorage Ends during Warm Up**

During the inspection phase, the foam void locations are once again easily and precisely detected with the use of thermal imaging. Seen both during warm up and cool down of the environment in Figure 5-23 and Figure 5-24 respectively, the foam voids are more apparent than the air voids within the duct. Although this makes locating voids easier during quality control and inspection testing, it creates a problem in that in certain circumstances foam voids may be detected whereas air voids would not be detected by infrared thermography. This means foam voids are not as representative of void conditions in the field as expected due to the different specific heat values of air and foam. Even though the specific heat of foam is closer to that of air than grout, in the future fabrication of conditions, the use of foam may not be desired in order to truly test infrared thermography equipment in the detection of voids representative of field conditions.



**Figure 5-23: (a-d) IRT Inspection of Foam Void Locations during Warm Up**

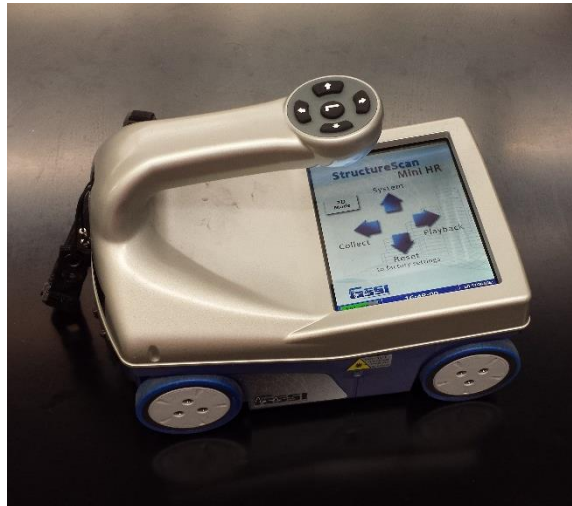


**Figure 5-24: (a-b) IRT Inspection of Foam Void Locations during Cool Down**



### 5.5. Ground Penetrating Radar

Ground penetrating radar testing was conducted on the specimen during both the quality control and inspection time periods using the GSSI StructureScan Mini shown in Figure 5-25. As the GPR unit is wheeled across the material surface, it operates by sending and receiving electromagnetic waves that are altered by encountering materials of different dielectric properties. The detection of structural anomalies can then be concluded. Just as with the ultrasonic tomograph used, this GPR unit's intended use is for concrete, but it is included in this research to determine its applicability to stay cable and external PT systems.

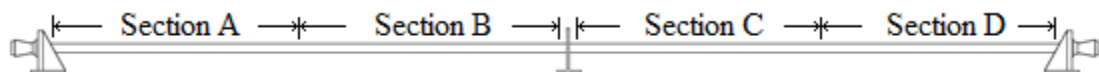


**Figure 5-25: Ground Penetrating Radar Unit**

Data is collected as the wheels turn. To be able to wheel the unit along the free span of the specimen duct, a wooden support structure was temporarily built on each side of the duct. The wheels on one side of the GPR unit could then be in contact with

the wood while the center of the unit was aligned on the duct. The specimen was tested by rolling the GPR unit over two paths, leaning to each side of the duct. If looking down the duct from the non-stressing anchorage end, Path 1 is the GPR unit leaning to the left and Path 2 is the GPR unit leaning to the right at an approximate 45 degree angle from the top of the duct.

During testing, the specimen was divided into four sections (A-D), shown in Figure 5-26. Since the GPR unit tests from the center of the unit, there are a few inches on each end of the duct free spans that were inaccessible by the GPR unit. Section A extends from 5 inches to 110 inches from the reference point at the first steel support (non-stressing end). Section B extends from 110 inches to 216 inches from the same reference point. Section C covers from 5 inches to 100 inches and Section D from 100 inches to 200 inches from the edge of the middle steel support. Each run of the GPR unit was then labelled with the corresponding path number and section letter for organization of the results. For example, Test A1 is over Path 1 in Section A. Each test was performed at least twice and resulted in closely matching data, which helped to validate the results.



**Figure 5-26: Specimen Sections for GPR Testing**

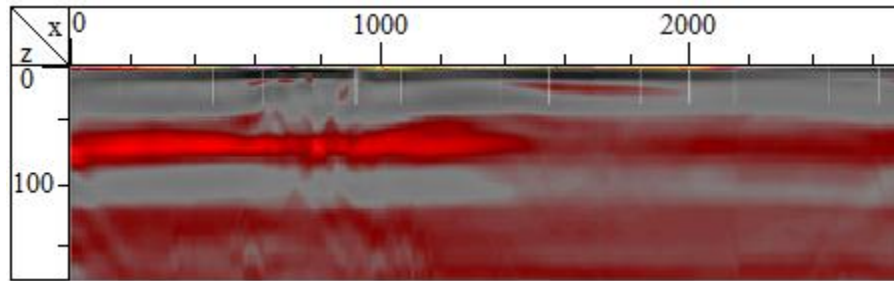
As expected, the ground penetrating radar method was unsuccessful in detecting the presence of breakage, section loss, and corrosion in the specimen due to GPR's high

sensitivity to metal. However, results were obtained that made it very clear where the largest air void sections occurred in the specimen. Although the ground penetrating radar unit detected these areas of large air voids and foam voids, there was no recognizable difference between the two types of voids present. The GPR results also did not present the accurate depth of the voids. Therefore, this method is recommended for the intent to locate any large voids present within stay cable or external PT ducts. Then, at these identified void locations, a more thorough method of inspection can be used to size the voids, such as the use of a borescope.

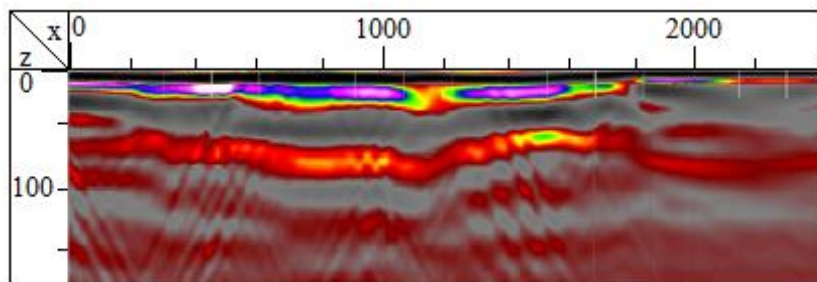
Also, very similar results were obtained both during the quality control time period and the inspection time period despite the changing dielectric properties of the grout as it cured. The results of each different GPR test performed within the same week as grouting the specimen and after the grout had cured are shown in full in Appendix C.

#### **5.5.1. GPR Quality Control**

In Figure 5-27, the GPR scan is taken over Path 1 in Section A along the duct free span and in Figure 5-28, the scan is taken over Path 1 in Section C. The test A1 scan is located at the least voided section of duct, whereas the test C1 scan is within the largest air voided section of duct. The difference is clear in that the ground penetrating radar pulses were significantly affected by the amount of air present in the highly voided regions of duct. The air void size difference across the entire duct length is shown in images included in Appendix C.



**Figure 5-27: GPR QC Test A1 at Small Air Void**

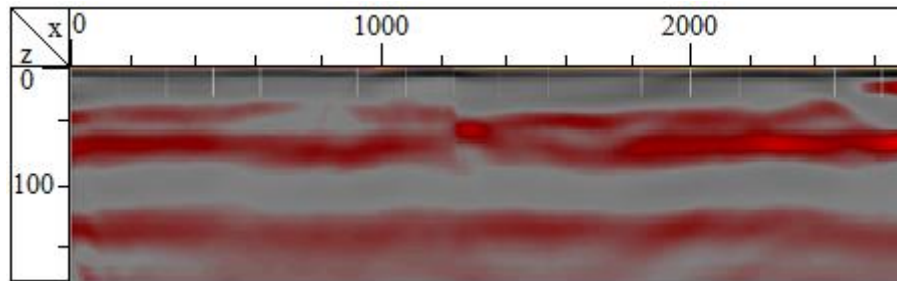


**Figure 5-28: GPR QC Test C1 at Large Air Void**

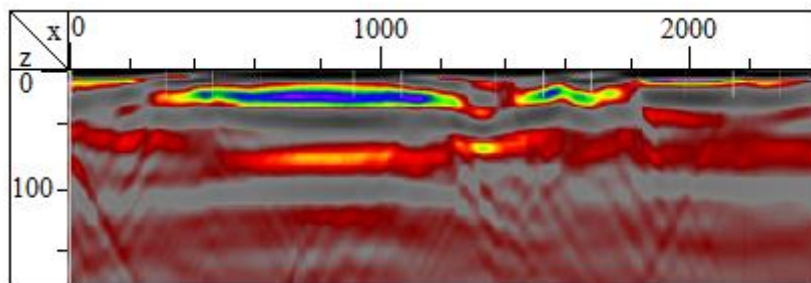
### **5.5.2. GPR Inspection**

In Figure 5-29 and Figure 5-30, GPR results from after the grout had fully cured are shown. In Figure 5-29, the GPR scan is taken in Section A over Path 2 and in Figure 5-30, the scan is taken in Section C also over Path 2. Similar to the QC figures, the test A2 scan is located at the least voided section of duct, whereas the test C2 scan is within the largest air voided section of duct. Again, there is a significant difference in the results of a minimally voided section to a largely voided section.





**Figure 5-29: GPR Inspection Test A2 at Small Air Void**



**Figure 5-30: GPR Inspection Test C2 at Large Air Void**

## 6. CONCLUSIONS AND RECOMMENDATIONS

Research was conducted on the applicability of selected non-destructive evaluation methods to identify and size particular deterioration conditions in the free span of external post-tensioning and stay cable systems. Locations of corrosion, section loss, and breakage were fabricated on the steel strands before placement in the mock-up specimen. Both foam voids and air voids in the grout were also fabricated during construction of the stay cable and external PT specimen. After grouting was performed, non-destructive evaluation began. The NDE method of sounding was carried out across the free spans of the duct, followed by a thorough borescope evaluation of the extent of the air voids in the duct free span, anchorages, and grout caps.

Ultrasonic tomography, infrared thermography, and ground penetrating radar was then performed on the stay cable and external PT specimen during two time periods. These NDE tests were completed both within days of grouting to mimic a quality control situation in the field and later after the grout had finally cured to represent in-service inspection conditions.

### *6.1. Applicability of NDE Methods*

As expected, the sounding method was extremely applicable in accurately detecting air voids in the grout. The sounding results matched closely with the ground truth data of the air void extent collected by the use of a borescope. Although the borescope use was slightly invasive and required access points to the interior duct, it was

an invaluable tool in viewing the true condition of the specimen. Identifying the condition of steel strands within the duct is also possible by borescope use, although with significant limitations. The strands must be exposed at an air void location for corrosion, section loss, or breakage to even have the potential to be seen by borescope.

Infrared thermography and ground penetrating radar did not identify any of the corrosion, section loss, or breakage locations within the specimen, but both of these methods identified air voids and foam voids during both the quality control period and inspection period. In addition, infrared thermography was able to identify air voids within the grout caps at each anchorage end. The ultrasonic tomograph used in this research, designed for use on concrete rather than stay cables and external PT, produced inconsistent results that were difficult to interpret. However, with alterations to the unit used for testing, this method may be applicable to identifying voids in the grout as well.

## *6.2. Recommendations for Future Fabrication of Conditions*

Based on the research performed in fabricating deterioration conditions for a stay cable and external post-tensioning mock-up specimen, there are a few alterations to the fabrication of condition methods that could be made to improve future specimens. The changes believed most beneficial are the following:

- *New electrolytic corrosion cell circuit to incorporate more than one strand.* If there are multiple strands to be corroded by the electrolytic corrosion cell, a new circuit setup is recommended. The current setup enables one strand to be corroded quickly, but if the circuit was redesigned to include more than one

strand at a time, the fabrication of widespread corrosion would be less time consuming.

- *Glued wires at breakage and section loss locations.* After grinding of the steel strands to fabricate breakage or section loss condition locations, it was common for any fully severed wires to snap out of place, fraying out of the strand. This made it difficult for the strands to be pushed or pulled through the wedge plates in the anchorage systems. Unwound wires are also not representative of true field conditions. Therefore, it is recommended the wires be glued in to place at these locations to prevent fraying.
- *Use of both foam voids and air voids.* Due to the infrared thermography results gathered during this research, it is recommended to not solely use foam voids in future mock-up specimens. In certain instances of IRT testing, the foam voids were detected much easier than the air voids within the duct. In order to get a true representation of identifying voids in the field with IRT, air-filled voids should also be considered.
- *Use of proper grouting procedures and adequate equipment.* It is very important to ensure that quality grouting is achieved by eliminating possible areas of concern beforehand. Although the unintentional top void aided research in this case, in the future, it could significantly hamper the designated course of research and NDE testing. It is recommended to check the flow capable from the grout pump to be used, ensure any drilled holes are covered securely, and certify that the sealant around open anchorage regions has fully cured before grouting.

### 6.3. Recommendations for Future NDE Research

The following are recommendations for future research in non-destructive evaluation of stay cable and external post-tensioning systems:

- *Mock-up specimens including water infiltration, grout conditions, and tendon deterioration in the anchorage region.* Since these conditions were ultimately not included in the constructed specimen, it is recommended to fabricate these conditions in future stay cable and external post-tensioning specimens to determine the applicability of ground penetrating radar, infrared thermography, and ultrasonic tomography in detecting these conditions.
- *Use of active infrared thermography.* In this research, passive infrared thermography was used to successfully locate both foam voids and air voids within the HDPE duct. It is recommended for an active heat source to be used with infrared thermography to determine IRT's applicability to detect voids in external PT ducts within bridge box girders.
- *Use of infrared thermography on internal PT grout caps at anchorage ends.* The dividing line between grout and air within the grout caps of the stay cable and external PT specimen of this research was repeatedly located using the infrared thermography device. It is recommended to extend the applicability of IRT to identify voided grout caps of internal PT as well, especially of harped internal PT where voids are most common in the high anchorage regions. This NDE method could be used as a quality control measure during construction to verify that the

grout caps and therefore most likely the entire anchorage regions are filled with grout.

- *Determine the applicability of the ultrasonic tomograph to identify voids in internal ducts.* Since the A1040 MIRA ultrasonic tomography unit is intended for use on flat concrete, it is advantageous to evaluate its ability to identify and size voids in the grout of internal post-tensioning ducts. The ultrasonic tomograph would be able to produce B-Scan, C-Scan, and D-Scan images since all of the transducers could be depressed to collect data. Also, the ideal operating frequency of 50 kHz for the concrete testing surface could be used with the potential for better results.
- *Use of ultrasonic tomography at a higher frequency.* The ultrasonic tomography used in this research was capable of a maximum frequency of 85 kHz. This testing unit was designed for use on concrete where the ideal testing frequency is around 50 kHz. Since the material properties of the stay cable and external PT specimen are different from concrete, the ideal testing frequency for ultrasonic tomography is different as well. A frequency higher than 85 kHz is recommended for use on the grouted HDPE duct in order to gain higher resolution of the data collected. Since the testing depth is only 4 inches deep, the tradeoff for higher resolution with lower penetration depth is beneficial.
- *Develop phased array ultrasonic tomograph suited for curved duct surface.* In addition to the desired higher frequency, research is necessary in the development of a more functional ultrasonic tomography unit for testing the

curved HDPE duct. One recommendation is to use half of the amount of transducers to create an array of 2 by 12 which can all be depressed on the duct surface.

- *Develop ground penetrating radar unit suited for curved duct surface.* In this research, a temporary wood setup was necessary in order to apply the GPR unit designed for use on flat surfaces. It is recommended to design a unit in which the wheels are closer to the radar emission location at the center of the unit. In this proposed setup, the ground penetrating radar testing could occur as the unit is wheeled along the duct surface, without the need for temporary wooden supports of any kind.

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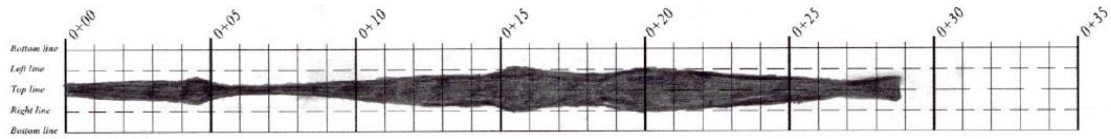
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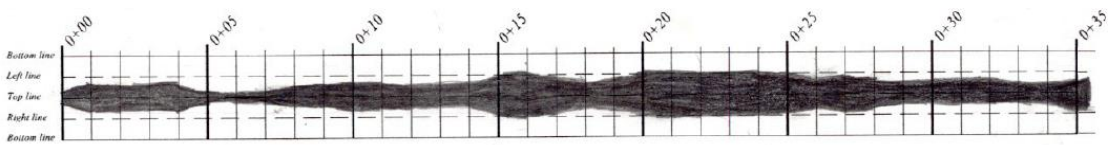
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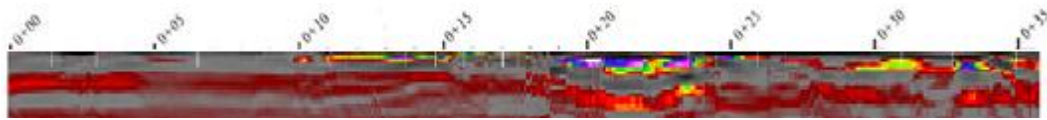
## APPENDIX A: QUALITY CONTROL NDE RESULTS COMPARISON



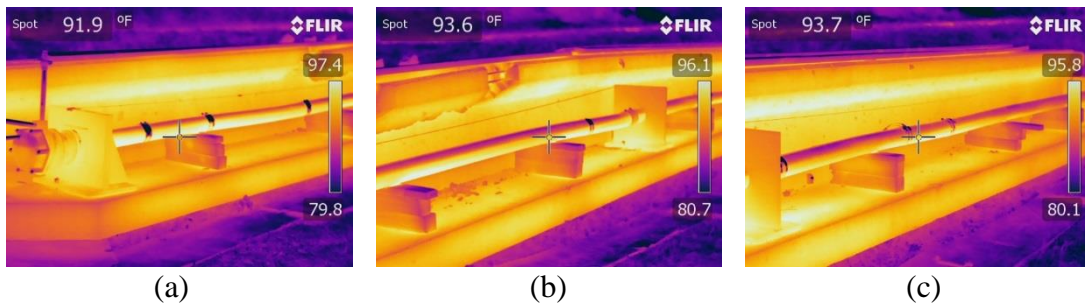
**Figure A-1: Borescope Map of Voids**



**Figure A-2: Sounding Map of Voids**



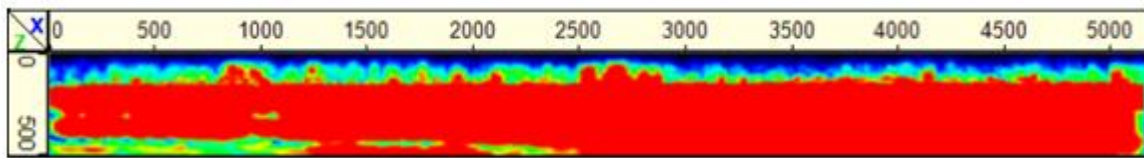
**Figure A-3: GPR Path 1 QC Results (Scan Depth 4 inches)**



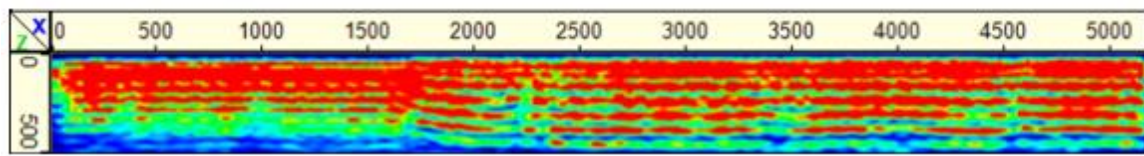
**Figure A-4: IRT QC Images (a-b) Span 1, and (c) Span 2**

## APPENDIX B: ULTRASONIC TOMOGRAPHY RESULTS

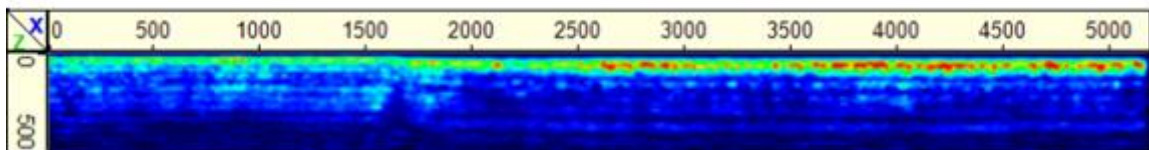
For the B-Scans shown in Figure B-1 through Figure B-24, both the x-axis and z-axis are in millimeters.



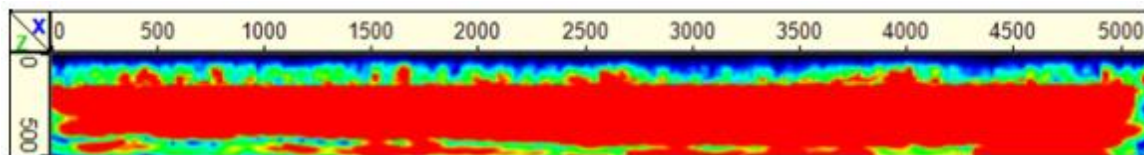
**Figure B-1: UST QC of Span 1 Top at 25 kHz**



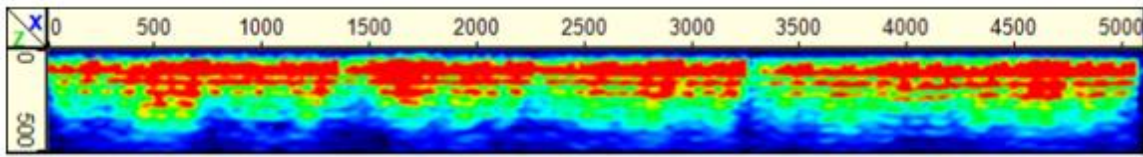
**Figure B-2: UST QC of Span 1 Top at 50 kHz**



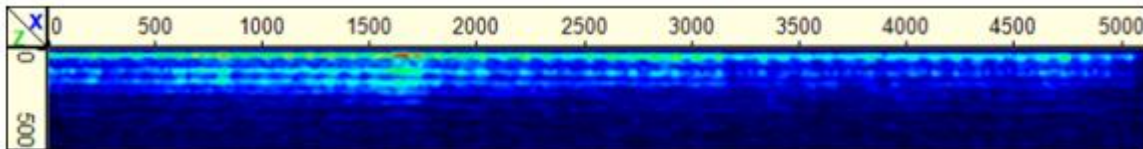
**Figure B-3: UST QC of Span 1 Top at 85 kHz**



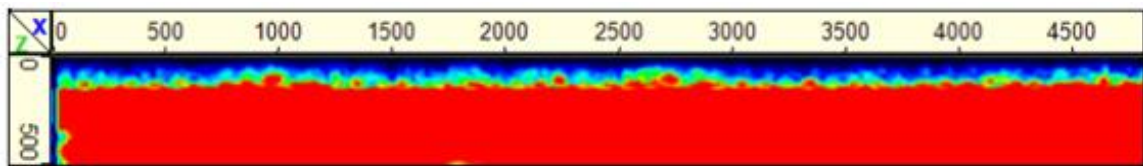
**Figure B-4: UST QC of Span 1 Side at 25 kHz**



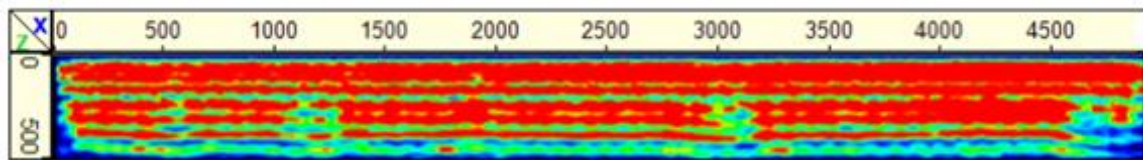
**Figure B-5: UST QC of Span 1 Side at 50 kHz**



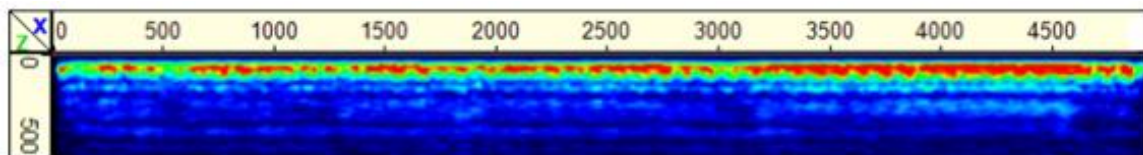
**Figure B-6: UST QC of Span 1 Side at 85 kHz**



**Figure B-7: UST QC of Span 2 Top at 25 kHz**

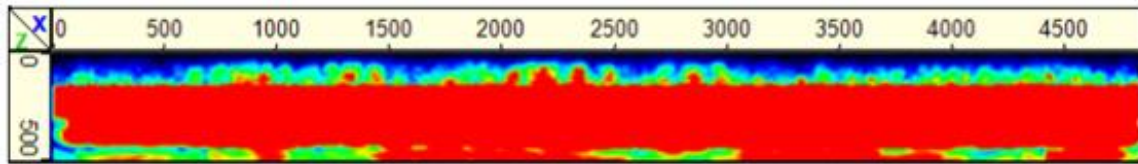


**Figure B-8: UST QC of Span 2 Top at 50 kHz**

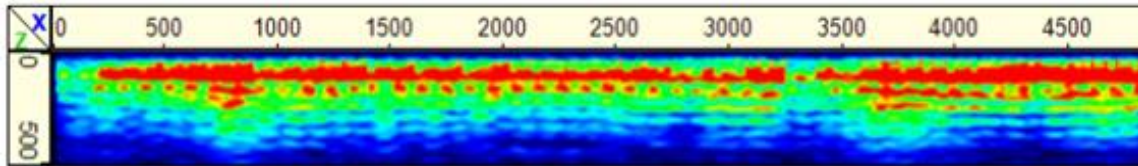


**Figure B-9: UST QC of Span 2 Top at 85 kHz**

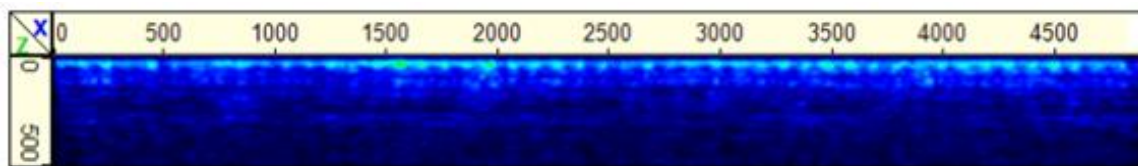




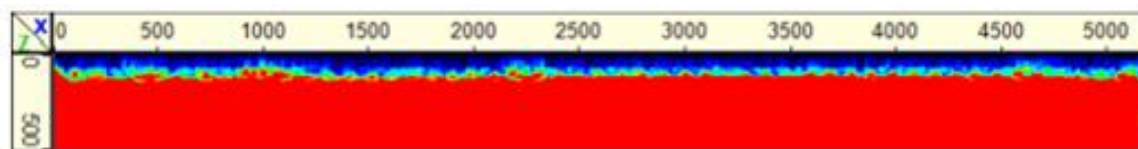
**Figure B-10: UST QC of Span 2 Side at 25 kHz**



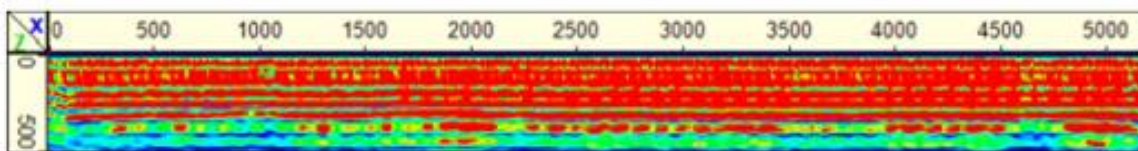
**Figure B-11: UST QC of Span 2 Side at 50 kHz**



**Figure B-12: UST QC of Span 2 Side at 85 kHz**

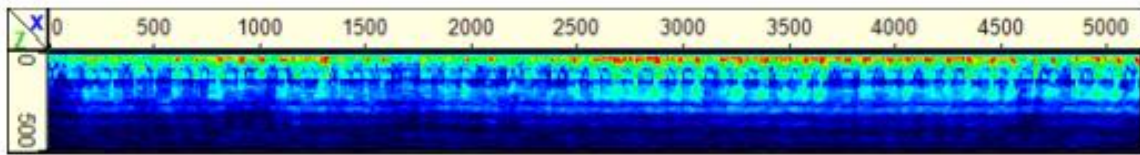


**Figure B-13: UST Inspection of Span 1 Top at 25 kHz**

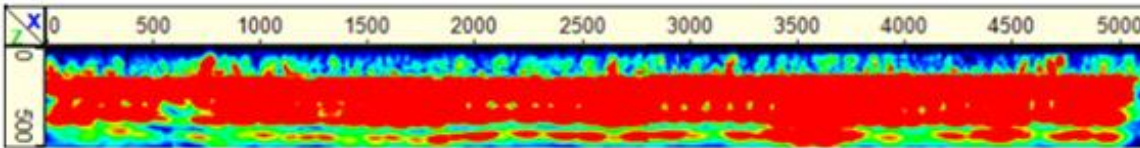


**Figure B-14: UST Inspection of Span 1 Top at 50 kHz**

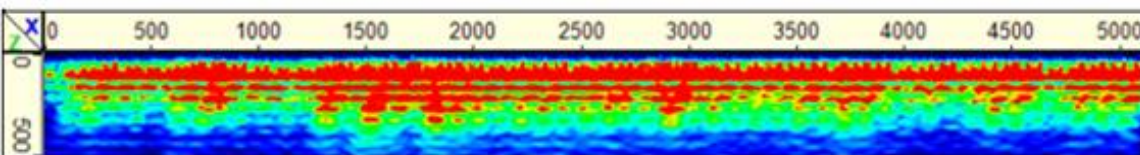




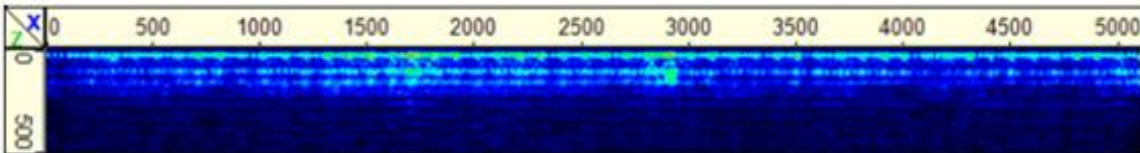
**Figure B-15: UST Inspection of Span 1 Top at 85 kHz**



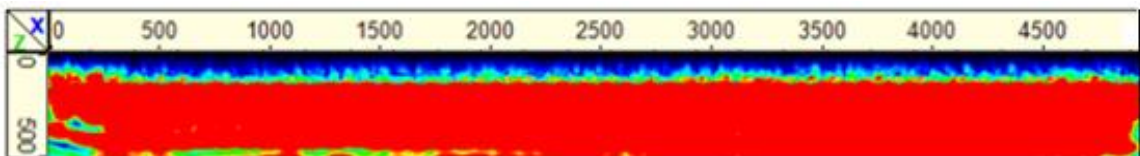
**Figure B-16: UST Inspection of Span 1 Side at 25 kHz**



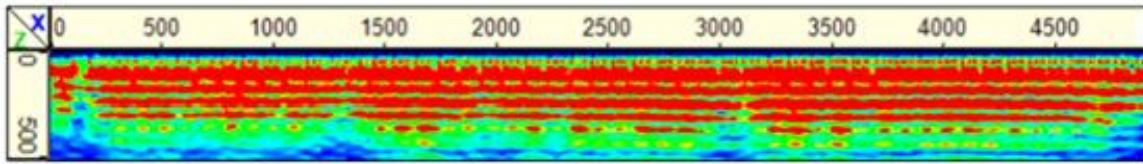
**Figure B-17: UST Inspection of Span 1 Side at 50 kHz**



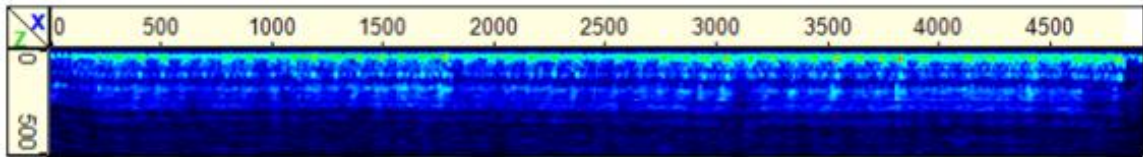
**Figure B-18: UST Inspection of Span 1 Side at 85 kHz**



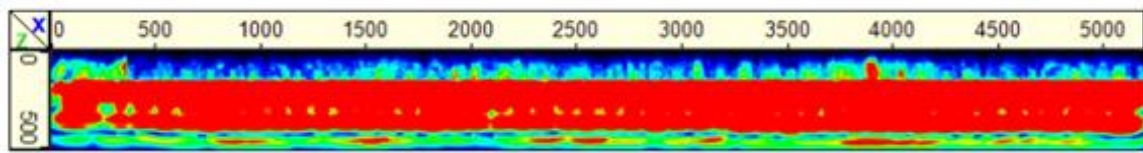
**Figure B-19: UST Inspection of Span 2 Top at 25 kHz**



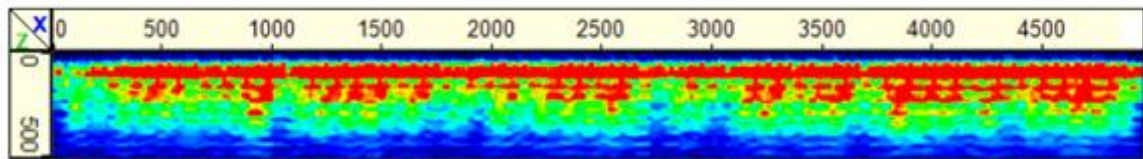
**Figure B-20: UST Inspection of Span 2 Top at 50 kHz**



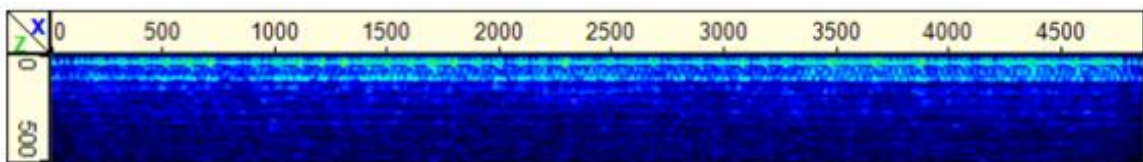
**Figure B-21: UST Inspection of Span 2 Top at 85 kHz**



**Figure B-22: UST Inspection of Span 2 Side at 25 kHz**



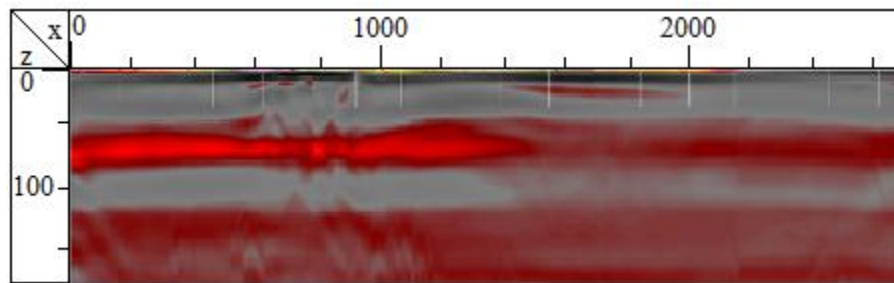
**Figure B-23: UST Inspection of Span 2 Side at 50 kHz**



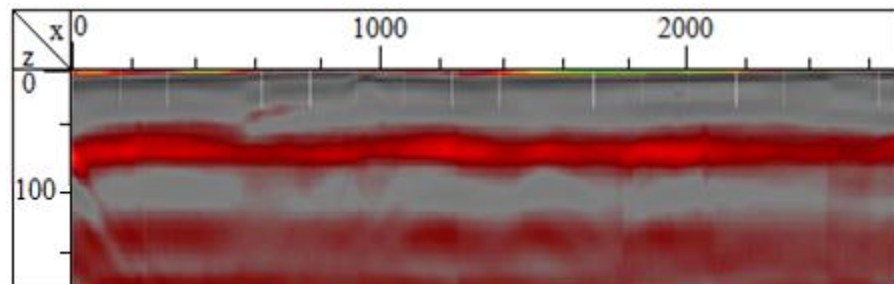
**Figure B-24: UST Inspection of Span 2 Side at 85 kHz**

## APPENDIX C: GROUND PENETRATING RADAR RESULTS

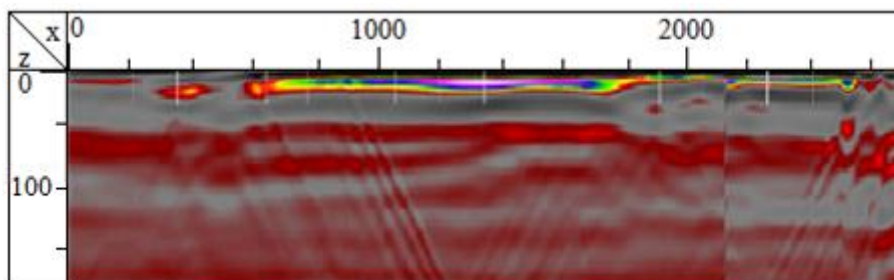
For the GPR scans shown in Figure C-1 through Figure C-16, both the x-axis and z-axis are in millimeters.



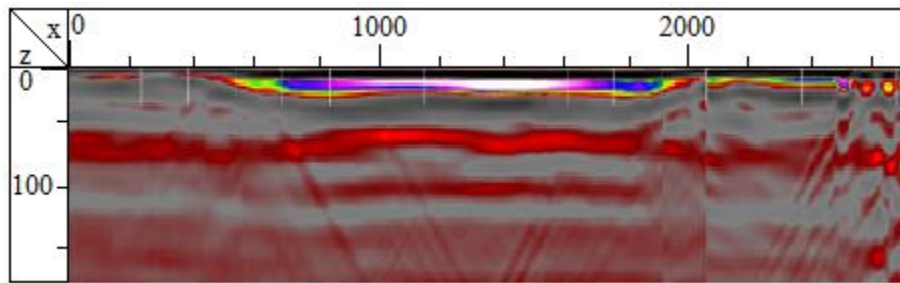
**Figure C-1: GPR QC Test A1**



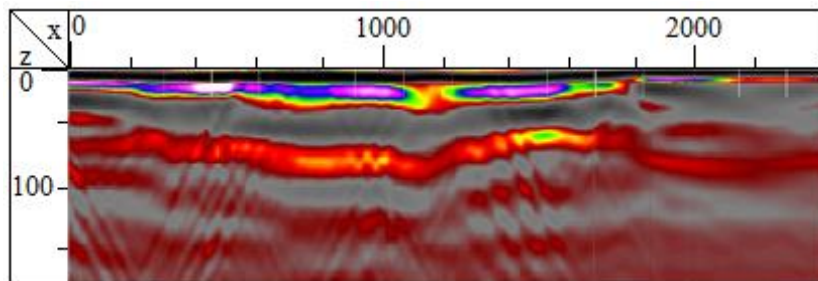
**Figure C-2: GPR QC Test A2**



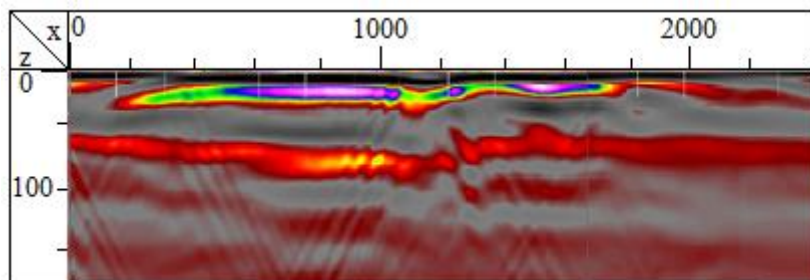
**Figure C-3: GPR QC Test B1**



**Figure C-4: GPR QC Test B2**

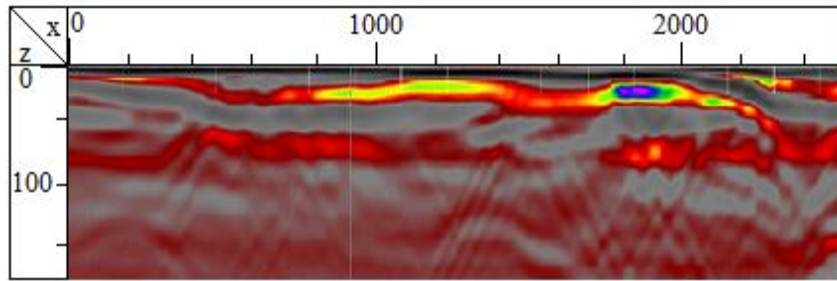


**Figure C-5: GPR QC Test C1**

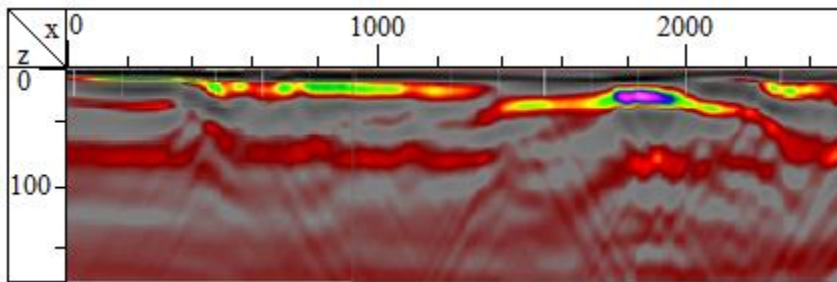


**Figure C-6: GPR QC Test C2**

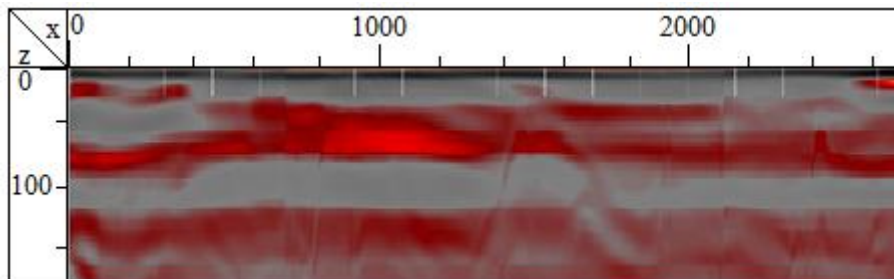




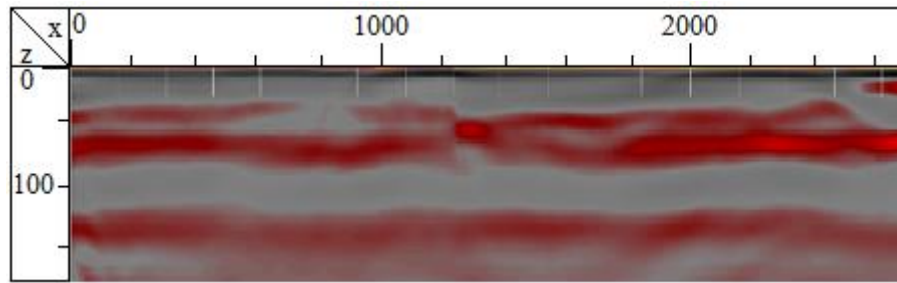
**Figure C-7: GPR QC Test D1**



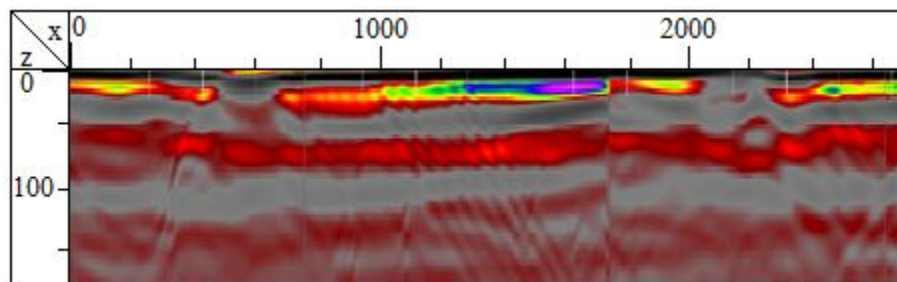
**Figure C-8: GPR QC Test D2**



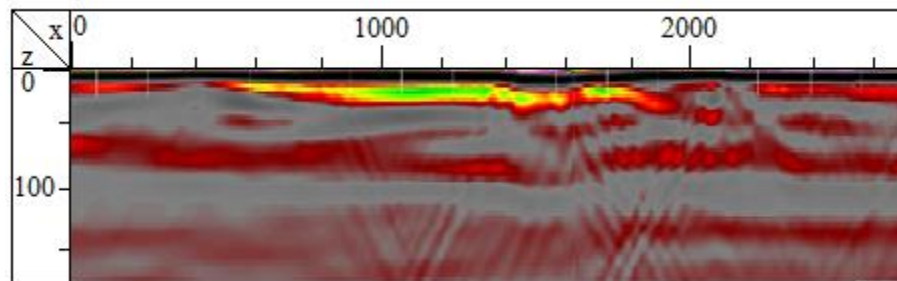
**Figure C-9: GPR Inspection Test A1**



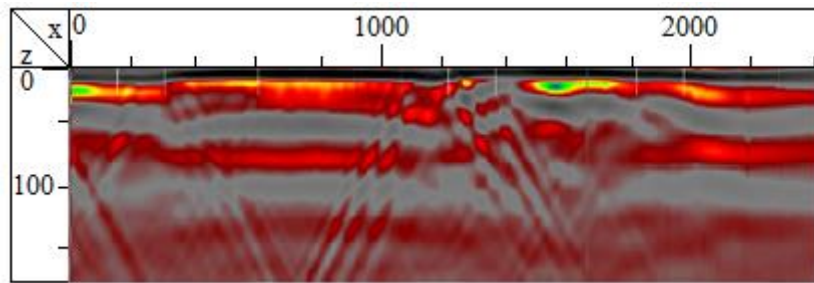
**Figure C-10: GPR Inspection Test A2**



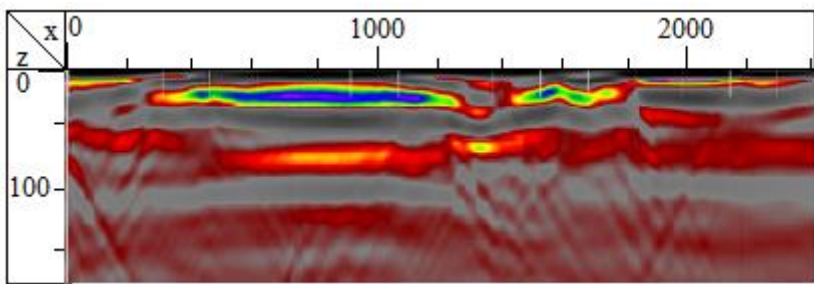
**Figure C-11: GPR Inspection Test B1**



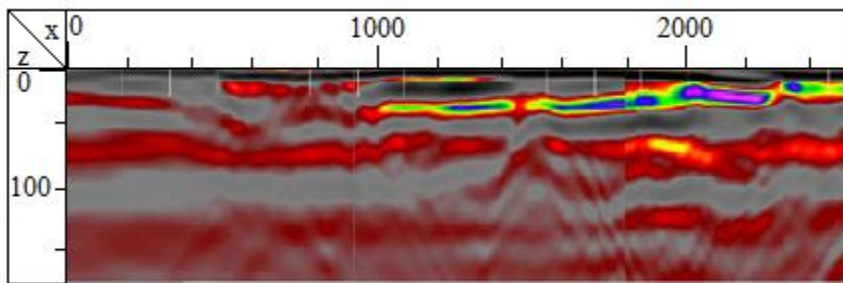
**Figure C-12: GPR Inspection Test B2**



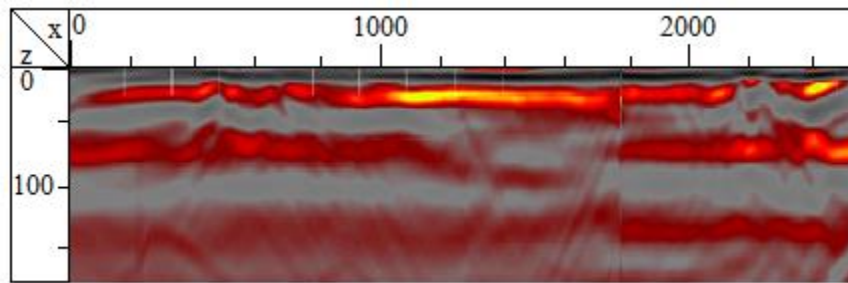
**Figure C-13: GPR Inspection Test C1**



**Figure C-14: GPR Inspection Test C2**



**Figure C-15: GPR Inspection Test D1**



**Figure C-16: GPR Inspection Test D2**



## APPENDIX D: FABRICATION OF CONDITION PROTOCOLS

### *Appendix D.1. Fabrication of Corrosion Protocol*

<b>FC001A</b>
<b>FABRICATION OF CONDITIONS CORROSION</b>
<b>Introduction</b>
<p><b>Scope:</b></p> <p>The occurrence of corrosion of the tendons in post-tensioning and stay cable systems is dependent on the environment around the steel strand surface. This environment dictates both the type and the rate of the tendon corrosion. Corrosion is an electrochemical process requiring oxygen and water that occurs as electrons are exchanged between the steel and the environment. If there is only water and oxygen present in the environment surrounding the tendon, then typically uniform corrosion occurs at a constant rate.</p> <p>The presence of other chemicals in the tendon's surrounding area can cause other types of corrosion to occur and often serve to accelerate the rate of the corrosion. Substances in the atmosphere, such as carbon dioxide, chlorine, and sulfur compounds can lead to atmospheric corrosion of the strands. This type of corrosion is highly dependent on the degree of these chemicals present in the environment and the length of the exposure time to the steel in the post-tensioning and stay cable systems.</p> <p>Pitting corrosion is a form of localized corrosion. When the passivating layer of the steel is deteriorated by means such as high chloride concentrations or acidic</p>

## FABRICATION OF CONDITIONS CORROSION

solutions, crevices are created. These small areas become anodic, while the surrounding environment becomes cathodic, leading to extremely localized corrosion and often galvanic corrosion. Galvanic corrosion occurs due to the close presence of different metals, which contain differing electrode potentials. This difference can result in galvanic coupling and therefore accelerate the rate of corrosion.

For the close alignment of the corrosion condition in the specimens to the natural occurrence of corrosion, corrosion is fabricated on steel strands using an electrolytic corrosion cell. The electrolytic corrosion cell creates a saline environment exposed to constant current for the accelerated fabrication of corrosion. If there is access to previously corroded strands, these may also be used for corrosion locations in the internal post-tensioning, external post-tensioning, and stay cable system strands. Light, moderate, and severe corrosion levels will be induced on the tendons to mimic atmospheric corrosion and on individual strands as pitting corrosion. The corrosion levels will be quantified based on the cross-sectional area loss of the entire tendon or the individual strand.

### **Terminology:**

- *Uniform corrosion.* Corrosion occurring at a constant rate in an environment of oxygen and water.
- *Atmospheric corrosion.* Corrosion in the presence of gaseous atmospheric substances such as carbon dioxide, chlorine, and sulfur compounds.
- *Pitting corrosion.* Extremely localized corrosion resulting from small depassivated areas on the steel surface.

## FABRICATION OF CONDITIONS CORROSION

- *Galvanic corrosion.* Corrosion resulting from galvanic coupling of dissimilar metals with differing electrode potentials in close proximity.
- *Electrolytic corrosion cell.* Set up of a saline environment in which voltage from a power supply forces accelerated corrosion.
- *Ampere-meter.* Instrument used to measure the electric current in a circuit.

### Significance:

The exposure of post-tensioning and stay cable tendons to environments ideal for corrosion is a critical concern in maintaining bridge structures. Although the tendons are designed to be encased in grout and duct, undesired conditions such as voids and moisture exposure are often present to facilitate corrosion. In post-tensioning and stay cable systems, corrosion of the tendons results in loss of steel cross-sectional area which directly corresponds with their loss of tensile strength. This strength loss negatively impacts the load carrying capacity of the bridge, making corrosion a significant condition to take note of during bridge inspection.

### Referenced Documents:

Fricker, S. and T. Vogel. 2007. "Site Installation and Testing of a Continuous Acoustic Monitoring." *Construction and Building Materials* Vol. 21, No. 3, pp. 501-510.

Pereira, R. M. S. 2003. "Accelerated Corrosion Testing, Evaluation and Durability Design of Bonded Post-Tensioned Concrete Tendons", University of Texas.

## FABRICATION OF CONDITIONS CORROSION

Trejo, D., M. D. Hueste, P. Gardoni, R. G. Pillai, K. Reinschmidt, S.-B. Im, S.

Kataria, S. Hurlebaus, M. Gamble and T. T. Ngo. 2009b. "Effect of Voids in Grouted, Post-Tensioned, Concrete Bridge Construction: Volume 2 - Inspection, Repair, Materials, and Risks", Research Report No. 0-4588-1 Vol. 2, Texas Transportation Institute and Texas Department of Transportation, 313 pages.

Trejo, D., M. D. Hueste, P. Gardoni, R. G. Pillai, K. Reinschmidt, S.-B. Im, S.

Kataria, S. Hurlebaus, M. Gamble and T. T. Ngo. 2009a. "Effect of Voids in Grouted, Post-Tensioned, Concrete Bridge Construction: Volume 1 – Electrochemical Testing and Reliability Assessment", Research Report No. 0-4588-1 Vol. 2, Texas Transportation Institute and Texas Department of Transportation, 342 pages.

Trejo, D., R. G. Pillai, M. B. D. Hueste, K. F. Reinschmidt and P. Gardoni. 2009c.

"Parameters Influencing Corrosion and Tension Capacity of Post-Tensioning Strands." *ACI Materials Journal* 106 (2).

Wang, Hongbin, A. A. Sagiúes, and R. G. Powers. 2005. "Corrosion of the Strand-

Anchorage System in Post-Tensioned Grouted Assemblies." *Corrosion/2005*.

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Wood, S. L., C. A. McKinstry, and J. K. Lee. 2013. "Residual Tensile Capacity of Grouted Post-Tensioned Tendons." *ACI Structural Journal* 110 (6).

Youn, S. G., S. K. Cho and E. K. Kim. 2005. "Acoustic Emission Technique for Detection of Corrosion-Induced Wire Fracture." *Key Engineering Materials* 297-300: 2040-2045.

### Procedure

#### Apparatus:

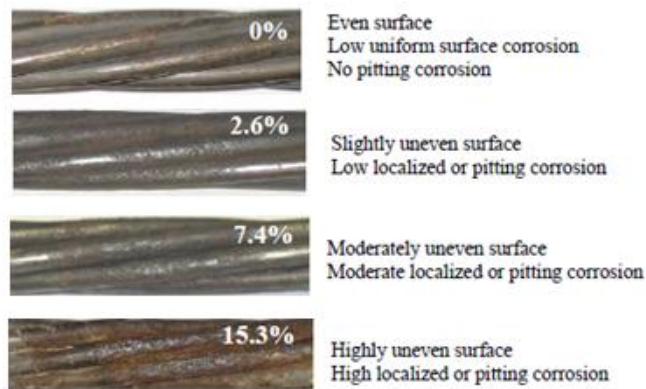
- DC Power Supply with Displayed Current (ranging from 12 V to 16 V)
- Hydrochloric Acid
- Sodium Chloride
- Water
- Plastic Container for Saline Solution
- Scale (ounces)
- Plastic ¼" Hose and Throttle
- Hose to Container Connection
- Cabling
- Resistors (ranging from 0.1 kΩ to 5 kΩ)
- Ampere-meter
- Breadboard
- Caliper
- Wedges (wood)
- Plastic Sheeting
- Plastic Tub
- Straps
- Copper Cathode

## FABRICATION OF CONDITIONS CORROSION

### Process Description:

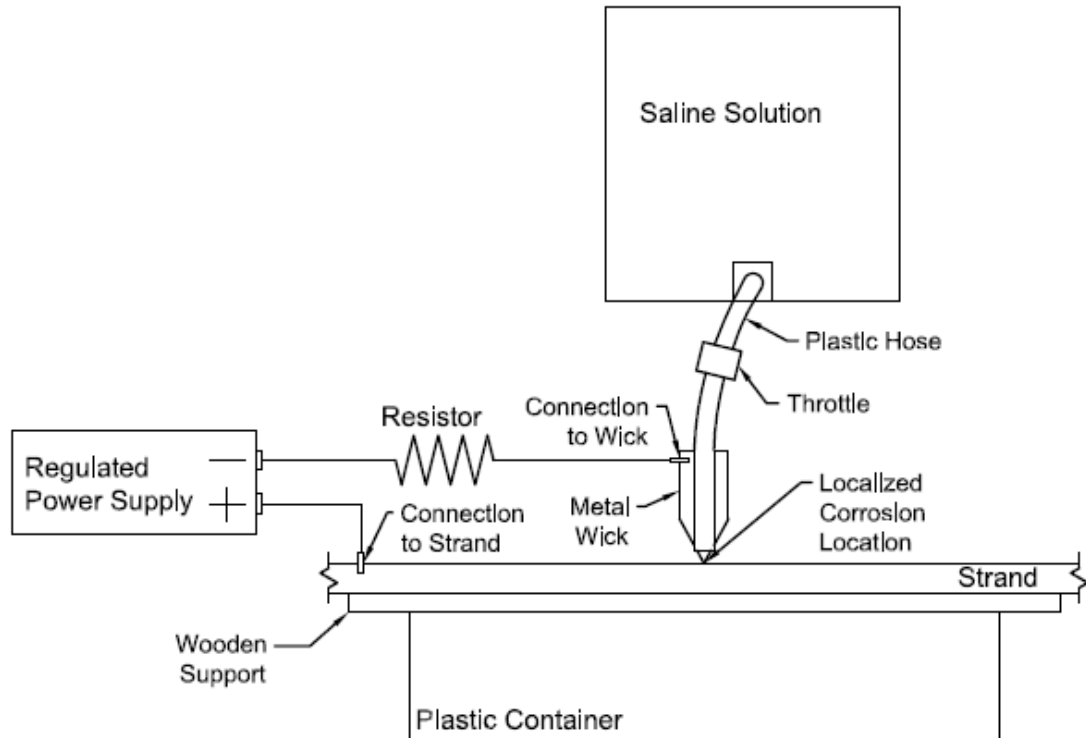
The materials for the electrolytic corrosion cell are first acquired and then the electrolytic corrosion cell is set up and tested for accuracy. It is then connected to the steel for the set amount of time and current level to induce the desired level of corrosion. Once the desired corrosion level has been reached at the particular location, the electrolytic corrosion cell is connected at the next desired location of corrosion on the tendon or individual strand and this is repeated until corrosion has been induced at all specified locations on the steel to be used in the specimen. The electrolytic corrosion cell is altered to accommodate localized corrosion at a specific point on the steel or more uniform corrosion over a length of the steel in a bath saline solution. Fabrication of Condition Methodology is provided for both set ups.

### Photos:

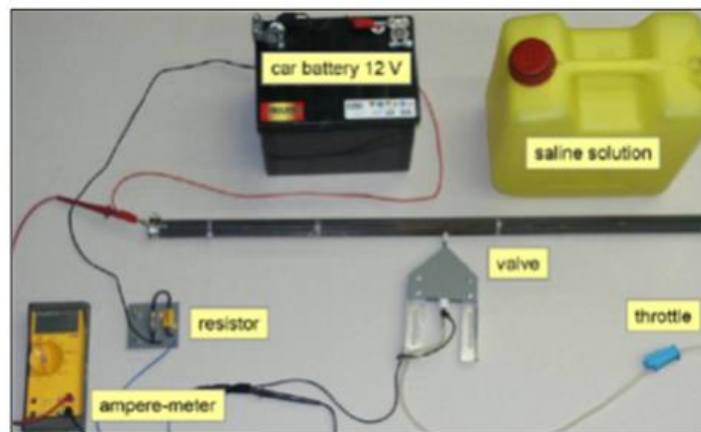


Sample of different corrosion levels with percentage of section loss (Trejo 2009)

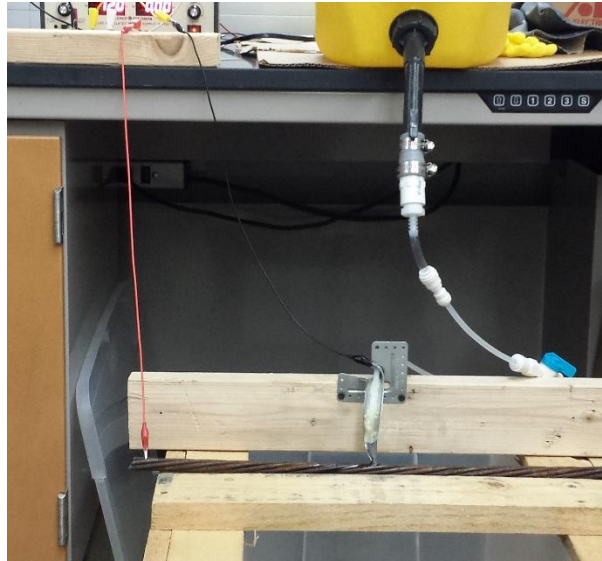
## FABRICATION OF CONDITIONS CORROSION



Set up of electrolytic corrosion cell for localized corrosion

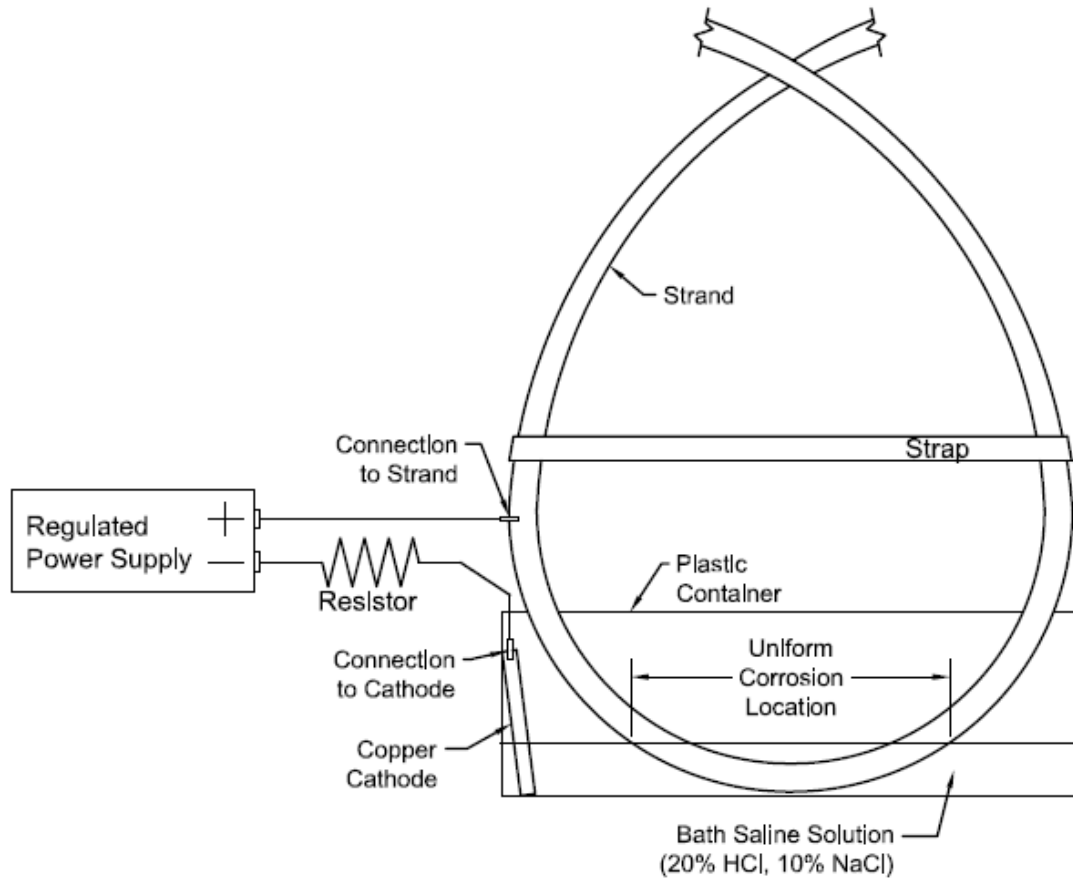


Components of electrolytic corrosion cell for localized corrosion (Fricker and Vogel 2007)

**FABRICATION OF CONDITIONS  
CORROSION**

Sample set up of electrolytic corrosion cell for localized corrosion



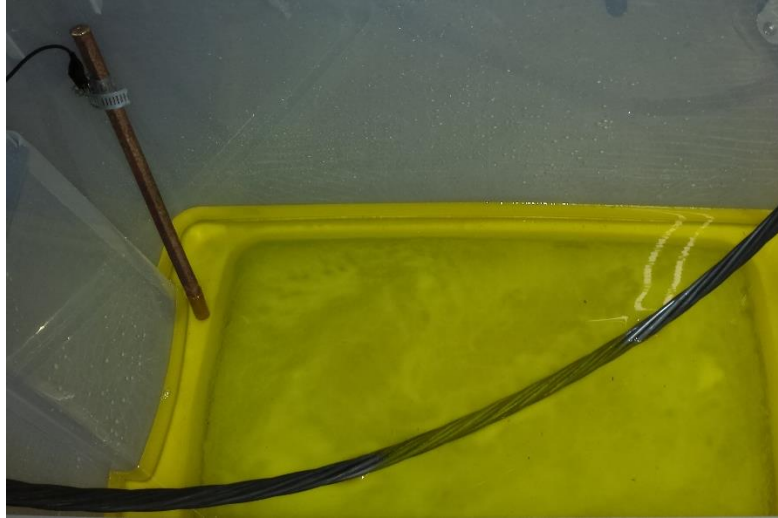
**FABRICATION OF CONDITIONS  
CORROSION**

Set up of electrolytic corrosion cell for uniform corrosion

**FABRICATION OF CONDITIONS  
CORROSION**

Sample set up of electrolytic corrosion cell for uniform corrosion

## FABRICATION OF CONDITIONS CORROSION



Strand and cathode in bath saline solution for uniform corrosion

### **Fabrication of Condition Methodology – Localized Corrosion:**

#### **PREPARATION:**

Step 1 – Connect the hose to the container for the saline solution using the connection piece and ensure the connection is sealed.

Step 2 – Connect the throttle to the hose at a location about halfway from the saline solution to the corrosion location.

Step 3 – Secure the hose end to the metal wick at the localized corrosion location, using the wooden support if necessary.

Step 4 – Pour 1 gallon of heated water into the container for the saline solution.

Step 5 – Add 2% hydrochloric acid to the water in the ratio of 1:1000.

## FABRICATION OF CONDITIONS CORROSION

Step 6 – Use the scale to measure out 7 ounces of salt.

Step 7 – Dissolve the salt in the solution to finish creating the saline solution.

Step 8 – Place the tendon on the wooden support on the plastic tub and separate the strands or wires to be corroded from the rest of the bundle using the wooden wedges and plastic sheeting.

Step 9 – Check that the power supply is turned off and connect the power supply anode to the steel segment to be corroded.

Step 10 – Connect the power supply cathode to the desired resistor using the breadboard and from the resistor to the metal wick at the location for localized corrosion on the steel strand.

Step 11 – Turn on the regulated power supply and check the current on the display. Turn off the power supply. If the desired current is flowing, continue to fabrication of condition. If not, consider using a different resistor or power supply voltage.

Note: One wire can reach failure after 20 hours using 9 mA current according to Fricker and Vogel (2007).

### FABRICATION OF CONDITION:

Step 1 – Place the container of saline solution at a location above the plastic tub in order for the solution to be gravity driven down the hose.

**FABRICATION OF CONDITIONS  
CORROSION**

Step 2 – Open the throttle to cover the steel segment to be corroded with the saline solution.

Step 3 – Turn on the power supply to enable the electrolytic corrosion cell and continually monitor that the cell current is correct by checking the current displayed on the power supply screen. Note: The current display on the power supply omits the need for a potentiostat as it can be used as a method of ensuring constant current.

Step 4 – When the desired level of corrosion has been reached, turn off the power supply and remove the electric connection from the strand.

Step 5 – Monitor the strands to ensure that the corrosion level is maintained within a reasonable tolerance level as the surface strand condition is to remain relatively constant after removal of the electrolytic corrosion cell.

Step 6 – Measure the amount of section loss in the individual strand or full tendon to verify results of the electrolytic corrosion cell. Use the caliper to measure multiple strand diameters.

Step 7 – Check that all the necessary information for the fabrication of corrosion has been clearly documented.

Step 8 – Place the strands in their specified locations by pushing or pulling them into the specimens for the internal post-tensioning, external post-tensioning, and stay cable systems.

## FABRICATION OF CONDITIONS CORROSION

### Fabrication of Condition Methodology – Uniform Corrosion:

#### PREPARATION:

Step 1 – Create a saline solution in the plastic tub of 20% hydrochloric acid and 10% sodium chloride (salt) by weight. Be careful to heat the solution so that the sodium chloride is dissolved. The amount of saline solution is to be determined by the tub size and length of strand to be immersed.

Step 2 – Place the strand in the solution using the straps to keep the strand curved so that only the length to be corroded is immersed in the saline solution.

Step 3 – Position the copper cathode partially immersed in the solution.

Step 4 – Check that the power supply is turned off and connect the power supply anode to a location on the steel strand outside of the solution.

Step 5 – Connect the power supply cathode to the desired resistor using the breadboard and from the resistor to the end of the copper cathode outside of the solution.

Step 6 – Turn on the power supply and check the current using the Ampere-meter. Turn off the power supply. If the desired current is flowing, continue to fabrication of condition. If not, consider using a different resistor or power supply voltage.

Note: One strand has 1% cross-sectional area loss every 8 hours using 100 mA current.

**FABRICATION OF CONDITIONS  
CORROSION****FABRICATION OF CONDITION:**

Step 1 – Turn on the power supply to enable the electrolytic corrosion cell and continually monitor that the cell current is correct by checking the current displayed on the power supply screen. Note: The current display on the power supply omits the need for a potentiostat as it can be used as a method of ensuring constant current.

Step 2 – When the desired level of corrosion has been reached, turn off the power supply and remove the electric connection from the strand.

Step 3 – Monitor the strands to ensure that the corrosion level is maintained within a reasonable tolerance level as the surface strand condition is to remain relatively constant after removal of the electrolytic corrosion cell.

Step 4 – Measure the amount of section loss in the individual strand or full tendon to verify results of the electrolytic corrosion cell.

Step 5 – Check that all the necessary information for the fabrication of corrosion has been clearly documented.

Step 6 – Place the strands in their specified locations by pushing or pulling them into the specimens for the internal post-tensioning, external post-tensioning, and stay cable systems.

## FABRICATION OF CONDITIONS CORROSION

### Quality Assurance:

The following are included in fabrication of the condition as a means of quality assurance:

- Current (ampere) display on the power supply – current can constantly be checked without interrupting the electrolytic corrosion cell
- Multiple strand diameters are taken, including at every inch of immersed steel for uniform corrosion, to compute the most accurate cross-sectional area loss
- After the designated corrosion level is reached with the corrosion cell, the strands are monitored for potential continuing corrosion before placement in the specimens

### Reporting

#### Condition Locations in Specimen:

The detailed location and level of corrosion in the specimen are documented. Other conditions at locations overlapping the corrosion are also documented as to take into account the influence of more than one type of fabricated condition at the same location. A visual representation of the corrosion locations on the specimen and in the duct cross sections are used along with the detailed description.



## FABRICATION OF CONDITIONS CORROSION

Necessary Information for Fabrication of Corrosion			
#	Description	Units/format	Values/Accuracy
1	State, City, Location	Text	Text
2	Personnel Performing Fabrication of Condition	List	Name(s)
3	Date	mm/dd/yyyy	Exact date
4	Start Time	hh:mm	1 min
5	End Time	hh:mm	1 min
6	Temperature	Degrees F	1 deg
7	Humidity	%	1 %
8	Specimen	Text	Text
9	Internal PT, External PT, or Stay Cable System	Text	Text
10	Tendon/Duct Number	Number	Exact number
11	Section Number	Number	Exact number
12	Specified Tendon/Duct Origin Location	Text	Text
13	Distance along Tendon/Duct from Tendon/Duct Origin	Feet, inches	Exact as possible
14	Cross-Sectional Location of Condition in Duct	Text, Sketch	Text, Sketch
15	Condition Size	Inches	Exact as possible
16	Depth of Duct in Specimen at Condition (if Internal)	Inches	1 inch
17	Other Conditions at Same Location	Text	Text
18	Specifications of Each Corrosion Level	Text, % of cross-sectional area loss	Text, %
19	Current Used to Reach Each Corrosion Level	Ampere	0.1 Ampere
20	Time Required to Reach Each Corrosion Level	hh:mm	5 sec
21	Corrosion Level at Each Location	Text	Text
22			
23			
24			

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<p align="center"><b>FABRICATION OF CONDITIONS SECTION LOSS – OPTION 1</b></p>
<p><b>Introduction</b></p>
<p><b>Scope:</b></p> <p>Section loss ensues due to the excessive corrosion or breakage of tendons in post-tensioning and stay cable systems. Corrosion induced section loss is highly dependent on the environment surrounding the steel. In the presence of oxygen and moisture, often with other substances, the strands can corrode to the extent of tendon section loss. Breakage can occur due to corrosion, fatigue loading, or over-loading of the strands and can also lead to notable section loss of the tendon.</p> <p>Steel section loss is fabricated in the tendons of the internal post-tensioning, external post-tensioning, and stay cable systems using excessive corrosion from an electrolytic corrosion cell for localized corrosion or access to already corroded strands. The section loss of the tendons is based on the loss of cross-sectional area.</p>
<p><b>Terminology:</b></p> <ul style="list-style-type: none"> <li>• <i>Section loss.</i> Loss in the cross-sectional area of the steel tendon.</li> <li>• <i>Electrolytic corrosion cell.</i> Set up of a saline environment in which voltage from a power supply forces accelerated corrosion.</li> <li>• <i>Ampere-meter.</i> Instrument used to measure the electric current in a circuit.</li> </ul>
<p><b>Significance:</b></p> <p>Section loss occurs as a result of excessive corrosion or breakage in tendons of post-tensioned and cable stayed bridge structures. Once the damage reaches the level of</p>

## FABRICATION OF CONDITIONS

### SECTION LOSS – OPTION 1

significant steel section loss in the tendons, the tensile strength of the load-bearing systems can be significantly decreased. In the case of extreme section loss, repair or rehabilitation methods are often necessary to correct the undesired condition of the steel and maintain the safety of the bridge. Therefore, tendon section loss is a vital concern during bridge inspections of post-tensioning and stay cable systems.

#### Referenced Documents:

- Fricker, S. and T. Vogel. 2007. "Site Installation and Testing of a Continuous Acoustic Monitoring." *Construction and Building Materials* Vol. 21, No. 3, pp. 501-510.
- Trejo, D., M. D. Hueste, P. Gardoni, R. G. Pillai, K. Reinschmidt, S.-B. Im, S. Kataria, S. Hurlebaus, M. Gamble and T. T. Ngo. 2009b. "Effect of Voids in Grouted, Post-Tensioned, Concrete Bridge Construction: Volume 2 - Inspection, Repair, Materials, and Risks", Research Report No. 0-4588-1 Vol. 2, Texas Transportation Institute and Texas Department of Transportation, 313 pages.
- Trejo, D., M. D. Hueste, P. Gardoni, R. G. Pillai, K. Reinschmidt, S.-B. Im, S. Kataria, S. Hurlebaus, M. Gamble and T. T. Ngo. 2009a. "Effect of Voids in Grouted, Post-Tensioned, Concrete Bridge Construction: Volume 1 – Electrochemical Testing and Reliability Assessment", Research Report No.

## FABRICATION OF CONDITIONS SECTION LOSS – OPTION 1

0-4588-1 Vol. 2, Texas Transportation Institute and Texas Department of Transportation, 342 pages.

Wood, S. L., C. A. McKinstry, and J. K. Lee. 2013. "Residual Tensile Capacity of Grouted Post-Tensioned Tendons." *ACI Structural Journal* 110 (6).

Youn, S. G., S. K. Cho and E. K. Kim. 2005. "Acoustic Emission Technique for Detection of Corrosion-Induced Wire Fracture." *Key Engineering Materials* 297-300: 2040-2045.

### Procedure

#### Apparatus:

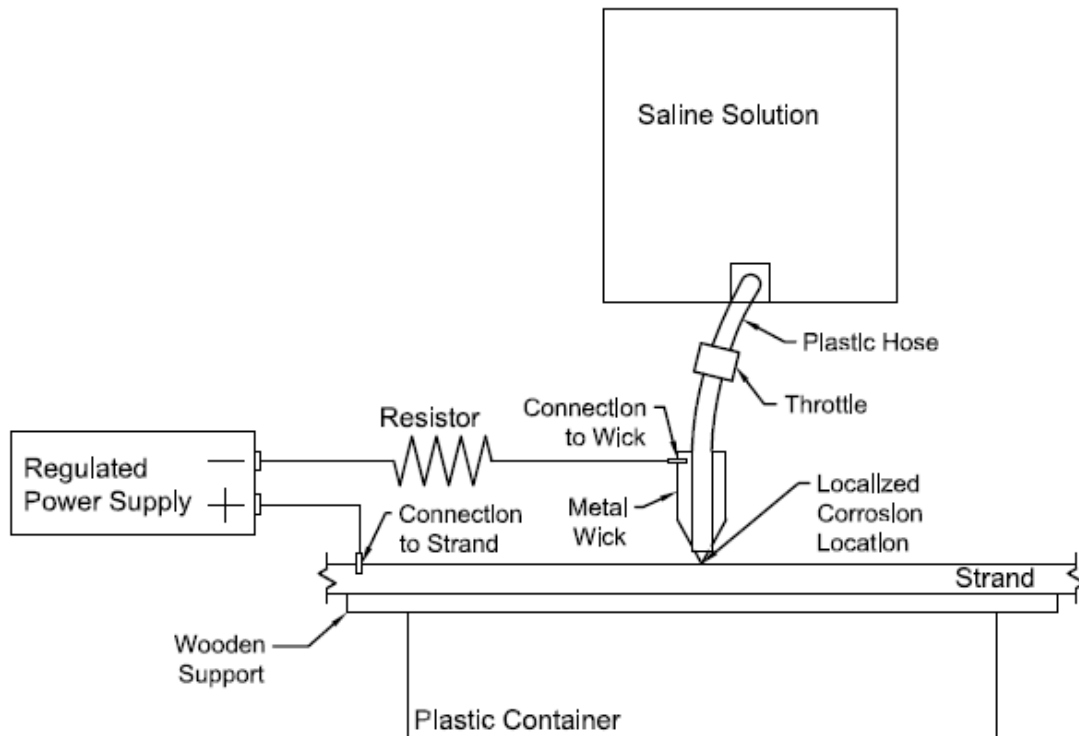
- DC Power Supply with Displayed Current (ranging from 12 V to 16 V)
- Hydrochloric Acid
- Sodium Chloride
- Water
- Container for Saline Solution
- Scale
- ¼" Hose and Valve
- Hose to Container Connection
- Cabling
- Resistors (ranging from 0.1 kΩ to 5 kΩ)
- Ampere-meter
- Breadboard
- Caliper
- Wedges (wood)
- Plastic Sheeting
- Plastic Tub

**FABRICATION OF CONDITIONS  
SECTION LOSS – OPTION 1****Process Description:**

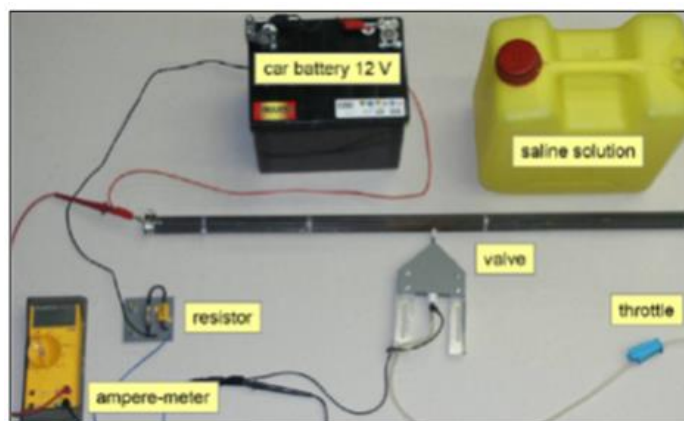
The materials for the electrolytic corrosion cell are first acquired and then the electrolytic corrosion cell is set up and tested for accuracy. It is then connected to a steel tendon for the set amount of time and current level to induce the desired level of excessive corrosion and therefore section loss in the tendon. Once the designated level of section loss has been reached at the location, the electrolytic corrosion cell is connected at the next desired location of tendon section loss and this is repeated until section loss has been induced at all specified locations on all tendons to be used in the specimen.

## FABRICATION OF CONDITIONS SECTION LOSS – OPTION 1

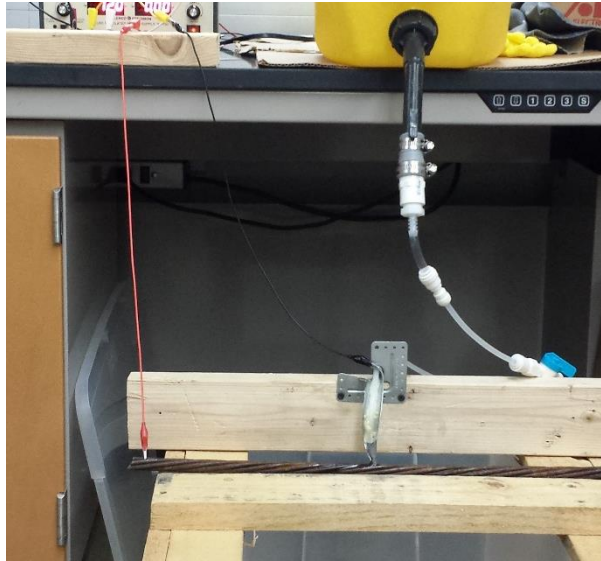
**Photos:**



Set up of electrolytic corrosion cell for localized corrosion



Components of electrolytic corrosion cell (Fricker and Vogel 2007)

**FABRICATION OF CONDITIONS  
SECTION LOSS – OPTION 1**

Sample set up of electrolytic corrosion cell for localized corrosion



Sample application of corrosion cell (Fricker and Vogel 2007)

**FABRICATION OF CONDITIONS  
SECTION LOSS – OPTION 1**

Sample of section loss condition due to corrosion cell (Fricker and Vogel 2007)

**Fabrication of Condition Methodology:****PREPARATION:**

- Step 1 – Connect the hose to the container for the saline solution using the connection piece and ensure the connection is sealed.
- Step 2 – Connect the throttle to the hose at a location about halfway from the saline solution to the section loss location.
- Step 3 – Secure the hose end to the metal wick at the localized corrosion for section loss location, using the wooden support if necessary.
- Step 4 – Pour 1 gallon of heated water into the container for the saline solution.
- Step 5 – Add 2% hydrochloric acid to the water in the ratio of 1:1000.
- Step 6 – Use the scale to measure out 7 ounces of salt.
- Step 7 – Dissolve the salt in the solution to finish creating the saline solution.



## FABRICATION OF CONDITIONS

### SECTION LOSS – OPTION 1

Step 8 – Place the tendon on the wooden support on the plastic tub and separate the strands or wires to be corroded from the rest of the bundle using the wooden wedges and plastic sheeting.

Step 9 – Check that the power supply is turned off and connect the power supply anode to the steel segment to undergo section loss.

Step 10 – Connect the power supply cathode to the desired resistor using the breadboard and from the resistor to the metal wick at the location for localized section loss of the steel strand.

Step 11 – Turn on the regulated power supply and check the current on the display. Turn off the power supply. If the desired current is flowing, continue to fabrication of condition. If not, consider using a different resistor or power supply voltage.

Note: One wire can reach failure after 20 hours using 9 mA current according to Fricker and Vogel (2007).

#### FABRICATION OF CONDITION:

Step 1 – Place the container of saline solution at a location above the plastic tub in order for the solution to be gravity driven down the hose.

Step 2 – Open the throttle to cover the location on the tendon for section loss with the saline solution.

**FABRICATION OF CONDITIONS  
SECTION LOSS – OPTION 1**

Step 3 – Turn on the power supply to enable the electrolytic corrosion cell and continually monitor that the cell current is correct by checking the current displayed on the power supply screen. Note: The current display on the power supply omits the need for a potentiostat as it can be used as a method of ensuring constant current.

Step 4 – When the desired level of section loss has been reached, turn off the power supply and remove the electric connection from the strand.

Step 5 – Monitor the strands to ensure that the section loss level is maintained within a reasonable tolerance level as the surface strand condition is to remain relatively constant after removal of the electrolytic corrosion cell.

Step 6 – Measure the amount of section loss in the tendon to verify results of the electrolytic corrosion cell.

Step 7 – Check that all the necessary information for the fabrication of section loss by the electrolytic corrosion cell has been clearly documented.

Step 8 – Place the strands in their specified locations by pushing or pulling them into the specimens for the internal post-tensioning, external post-tensioning, and stay cable systems.

**FABRICATION OF CONDITIONS  
SECTION LOSS – OPTION 1****Quality Assurance:**

The following are included in fabrication of the condition as a means of quality assurance:

- Current (ampere) display on the power supply – current can constantly be checked without interrupting the electrolytic corrosion cell
- Multiple strand diameters are taken to compute the most accurate cross-sectional area loss
- After the designated section loss level is reached with the corrosion cell, the strands are monitored for potential continuing corrosion before placement in the specimens

**Reporting****Condition Locations in Specimen:**

The detailed location and size of the section loss in the specimen is documented. Other conditions at locations overlapping the section loss are also documented as to take into account the influence of more than one type of fabricated condition at the same location. A visual representation of the section loss locations on the specimen and in the duct cross sections is used along with the detailed description.

**FABRICATION OF CONDITIONS**  
**SECTION LOSS – OPTION 1**

**Necessary Information for Fabrication of Section Loss**

#	Description	Units/format	Values/Accuracy
1	State, City, Location	Text	Text
2	Personnel Performing Fabrication of Condition	List	Name(s)
3	Date	mm/dd/yyyy	Exact date
4	Start Time	hh:mm	1 min
5	End Time	hh:mm	1 min
6	Temperature	Degrees F	1 deg
7	Humidity	%	1 %
8	Specimen	Text	Text
9	Internal PT, External PT, or Stay Cable System	Text	Text
10	Tendon/Duct Number	Number	Exact number
11	Section Number	Number	Exact number
12	Specified Tendon/Duct Origin Location	Text	Text
13	Distance along Tendon/Duct from Tendon/Duct Origin	Feet, inches	Exact as possible
14	Cross-Sectional Location of Condition in Duct	Text, Sketch	Text, Sketch
15	Section Loss	% of cross-sectional area	%
16	Depth of Duct in Specimen at Condition (if Internal)	Inches	1 inch
17	Other Conditions at Same Location	Text	Text
18	Specifications of Each Section Loss Level	Text, % of cross-sectional area	Text, %
19	Current Used to Reach Level of Section Loss	Ampere	0.1 Ampere
20	Time Required to Reach Level of Section Loss	hh:mm	5 sec
21	Degree of Section Loss at each Location	Text	Text
22			
23			

## FABRICATION OF CONDITIONS SECTION LOSS – OPTION 2

### Introduction

#### Scope:

Section loss ensues due to the excessive corrosion or breakage of tendons in post-tensioning and stay cable systems. Corrosion induced section loss is highly dependent on the environment surrounding the steel. In the presence of oxygen and moisture, often with other substances, the strands can corrode to the extent of tendon section loss. Breakage can occur due to corrosion, fatigue loading, or over-loading of the strands and can also lead to notable section loss of the tendon.

Steel section loss is fabricated in the tendons of the internal post-tensioning, external post-tensioning, and stay cable systems by grinding the strands to remove material at designated locations before the strands are pushed or pulled through the ducts. The section loss of the tendons is based on the loss of cross-sectional area.

#### Terminology:

- *Section loss.* Loss of the cross-sectional area of the steel tendon.

#### Significance:

Section loss occurs as a result of excessive corrosion or breakage in tendons of post-tensioned and cable stayed bridge structures. Once the damage reaches the level of significant steel section loss in the tendons, the tensile strength of the load-bearing systems can be significantly decreased. In the case of extreme section loss, repair

## FABRICATION OF CONDITIONS SECTION LOSS – OPTION 2

or rehabilitation methods are often necessary to correct the undesired condition of the steel and maintain the safety of the bridge. Therefore, tendon section loss is a vital concern during bridge inspections of post-tensioning and stay cable systems.

### Referenced Documents:

DaSilva, M., S. Javidi, A. Yakel and A. Aziznamini. 2009. "Nondestructive Method to Detect Corrosion of Steel Elements in Concrete".

Vill, M., Eichinger, E. M., and Kollegger, J. 2006. "Assessment of Damaged Post-Tensioning Tendons" *Structural Engineering International*, 16(1), 44-48.

### Procedure

#### Apparatus:

- Instrument to grind strands (i.e., grinder, cutoff wheel)
- Wedges (Wood)
- Glue

#### Process Description:

The grinder will be applied to the designated amount of steel strands at each determined section loss location. These wires/strands with section loss are then pushed or pulled through the ducts of the specimen. Previously corroded or damaged strands that have already experienced section loss may also be used.

**FABRICATION OF CONDITIONS  
SECTION LOSS – OPTION 2****Photos:**

Strand Section Loss

**Fabrication of Condition Methodology:****PREPARATION:**

Step 1 – If necessary, position the wooden wedges on each side of the section loss location on the tendon to separate the strands to experience section loss from those that will remain intact.

**FABRICATION OF CONDITION:**

Step 1 – Use the cutting instrument to grind the desired strands at the determined location for section loss. Note: Using a grinder, tapered strands can also be fabricated.

Step 2 – Measure the amount of section loss in the tendon to verify results.

Step 3 – Check that all the necessary information for the fabrication of section loss by cutting the strands has been clearly documented.

Step 4 – Glue or clamp the wires in the tendon if necessary to prevent fraying.

## FABRICATION OF CONDITIONS

### SECTION LOSS – OPTION 2

Step 5 – Place the strands in their specified locations by pushing or pulling them into the specimens for the internal post-tensioning, external post-tensioning, and stay cable systems.

#### **Quality Assurance:**

The following are included in fabrication of the condition as a means of quality assurance:

- Wooden wedges are positioned to separate the strands or wires to experience section loss from the strands or wires to remain intact
- Multiple strand diameters are taken to compute the most accurate cross-sectional area loss
- After fabrication of section loss, the strands are monitored before placement in the specimens

#### **Reporting**

##### **Condition Locations in Specimen:**

The detailed location and amount of tendon section loss in the specimen is documented. Other conditions at locations overlapping the section loss are also documented as to take into account the influence of more than one type of fabricated condition at the same location. A visual representation of the section loss locations on the specimen and in the duct cross sections are used along with the detailed description.



**FABRICATION OF CONDITIONS**  
**SECTION LOSS – OPTION 2**

<b>Necessary Information for Fabrication of Section Loss</b>			
#	Description	Units/format	Values/Accuracy
1	State, City, Location	Text	Text
2	Personnel Performing Fabrication of Condition	List	Name(s)
3	Date	mm/dd/yyyy	Exact date
4	Start Time	hh:mm	1 min
5	End Time	hh:mm	1 min
6	Temperature	Degrees F	1 deg
7	Humidity	%	1 %
8	Specimen	Text	Text
9	Internal PT, External PT, or Stay Cable System	Text	Text
10	Tendon/Duct Number	Number	Exact number
11	Section Number	Number	Exact number
12	Specified Tendon/Duct Origin Location	Text	Text
13	Distance along Tendon/Duct from Tendon/Duct Origin	Feet, inches	Exact as possible
14	Cross-Sectional Location of Condition in Duct	Text, Sketch	Text, Sketch
15	Number of Strands Cut at Each Location	Number	Exact number
16	Depth of Duct in Specimen at Condition (if Internal)	Inches	1 inch
17	Other Conditions at Same Location	Text	Text
18			
19			
20			
21			
22			
23			
24			

## FABRICATION OF CONDITIONS BREAKAGE

### Introduction

#### Scope:

Strand or wire breakage can occur as a result of corrosion, fatigue loading, or overloading in the post-tensioning and stay cable systems of bridge structures. Corrosion induced breakage is highly dependent on the environment surrounding the steel. In the presence of oxygen and moisture, often with other substances, the wires or strands corrode resulting in breakage. Breakage due to fatigue loading can occur as fatigue of the individual wires or by fretting fatigue. When the strands are in contact with other strands or the wall of the duct and are also subject to the dynamic loading on a bridge, breakage from fatigue fretting is possible.

Steel strand or wire breakage is fabricated in the tendons of internal post-tensioning, external post-tensioning, and stay cable system specimens by cutting the strands at designated locations before the strands are pushed or pulled through the ducts.

#### Terminology:

- *Breakage.* Fracture of the wires or strands of a steel tendon.

#### Significance:

Wire and strand breakage in the tendons of post-tensioning and stay cable systems is significant in that it can be a precursor to section loss of the entire tendon. Locating

## FABRICATION OF CONDITIONS BREAKAGE

breakage during bridge inspections can enable preemptive repair or rehabilitation to prevent noteworthy loss in tensile strength of the load carrying systems.

### Referenced Documents:

DaSilva, M., S. Javidi, A. Yakel and A. Azizinamini. 2009. "Nondestructive Method to Detect Corrosion of Steel Elements in Concrete".

FDOT. 2002. "New Directions for Florida Post-Tensioned Bridges". Florida Department of Transportation, Corven Engineering, Inc., Tallahassee, FL.

Suzuki, N., H. Takamatsu, S. Kawashima, K. I. Sugii and M. Iwasaki. 1988. "Ultrasonic Detection Method for Wire Breakage." *Kobelco Technology Review* (4): 23-26.

Vill, M., Eichinger, E. M., and Kollegger, J. 2006. "Assessment of Damaged Post-Tensioning Tendons" *Structural Engineering International*, 16(1), 44-48.

Wollman, G. P., D. L. Yates, and J. E. Breen. 1988. "Fretting Fatigue in Post-Tensioned Concrete."

### Procedure

#### Apparatus:

- Instrument to cut wires or strands (i.e., grinder, cutoff wheel)
- Wedges (Wood)
- Glue

**FABRICATION OF CONDITIONS  
BREAKAGE****Process Description:**

The designated amount of steel wires or full strands will be cut at each determined breakage location. These cut wires/strands are then pushed or pulled through the ducts of the specimen. Corroded or damaged strands that have already experienced breakage may also be used.

**Photos:**

Broken wires of a steel tendon

**Fabrication of Condition Methodology:****PREPARATION:**

Step 1 – Position the wooden wedges on each side of the breakage location on the tendon to separate the wires or strands to be cut from those that will remain intact. If necessary, take care when unwinding the strand so that it does not permanently frag.

## FABRICATION OF CONDITIONS BREAKAGE

### FABRICATION OF CONDITION:

Step 1 – Use the cutting instrument to cut the desired wires or strands at the determined location for breakage. Note: Using a grinder, tapered strands can also be fabricated.

Step 2 – Measure the amount of section loss in the tendon to verify the breakage results.

Step 3 – Check that all the necessary information for the fabrication of breakage by cutting the strands has been clearly documented.

Step 4 – Glue or clamp the wires in the tendon if necessary to prevent fraying.

Step 5 – Place the strands in their specified locations by pushing or pulling them into the specimens for the internal post-tensioning, external post-tensioning, and stay cable systems.

### Quality Assurance:

The following are included in fabrication of the condition as a means of quality assurance:

- Wooden wedges are positioned to separate the strands or wires to be cut from the strands or wires to remain intact
- Multiple strand diameters are taken to compute the most accurate cross-sectional area loss

**FABRICATION OF CONDITIONS  
BREAKAGE**

- After fabrication of breakage, the strands are monitored before placement in the specimens

**Reporting****Condition Locations in Specimen:**

The detailed location and amount of strand or individual wire breakage in the specimen is documented. Other conditions at locations overlapping the breakage are also documented as to take into account the influence of more than one type of fabricated condition at the same location. A visual representation of the breakage locations on the specimen and in the duct cross sections are used along with the detailed description.

## FABRICATION OF CONDITIONS BREAKAGE

Necessary Information for Fabrication of Breakage			
#	Description	Units/format	Values/Accuracy
1	State, City, Location	Text	Text
2	Personnel Performing Fabrication of Condition	List	Name(s)
3	Date	mm/dd/yyyy	Exact date
4	Start Time	hh:mm	1 min
5	End Time	hh:mm	1 min
6	Temperature	Degrees F	1 deg
7	Humidity	%	1 %
8	Specimen	Text	Text
9	Internal PT, External PT, or Stay Cable System	Text	Text
10	Tendon/Duct Number	Number	Exact number
11	Section Number	Number	Exact number
12	Specified Tendon/Duct Origin Location	Text	Text
13	Distance along Tendon/Duct from Tendon/Duct Origin	Feet, inches	Exact as possible
14	Cross-Sectional Location of Condition in Duct	Text, Sketch	Text, Sketch
15	Number of Wires/Strands Cut at Each Location	Number	Exact number
16	Depth of Duct in Specimen at Condition (if Internal)	Inches	1 inch
17	Other Conditions at Same Location	Text	Text
18			
19			
20			
21			

<b>FC003A</b>
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FABRICATION OF CONDITIONS BREAKAGE			
22			
23			
24			



FC004A

## FABRICATION OF CONDITIONS GROUT CONDITIONS

### Introduction

#### Scope:

Poor grout conditions such as segregated grout, white paste, soft grout, un-hydrated grout, and gassed grout are possible to occur during the grouting process of post-tensioning and stay cable systems. Segregated grout, white paste, and soft grout can be the result of excess water in the grout. Un-hydrated grout results from not enough water in the grout mix and gassed grout can be the result of gas being introduced into the grout mix during grout placement.

Grout conditions are fabricated in the ducts of the internal post-tensioning and external post-tensioning of the bridge girder specimen as well as in the stay cable specimen. The grout conditions are created by pumping fresh grout out of the duct by a vacuum pump and then replacing it with the same volume of compromised grout. The vacuum pump is connected to tubes which are connected to saddle taps on the ducts allowing for grout removal. There are two saddle taps for each grout condition location to allow for the removal of grout and confirmation of compromised grout placement. The amount of compromised grout is characterized by the volume of grout removed and subsequently replaced at each location.

#### Terminology:

- *Vacuum pump.* The device used to pump grout from the duct.
- *Saddle tap.* The piece connected to the duct with an outlet to allow for grout removal.

## FABRICATION OF CONDITIONS GROUT CONDITIONS

### Significance:

Compromised grout can occur in large amounts at particular regions in the ducts during grout placement and can be detrimental to the bridge structure. Without the presence of good grout between the steel tendons and the duct walls, proper bonding does not occur and other detrimental conditions such as water infiltration can follow.

### Referenced Documents:

- Corven, J., and A. Moreton. 2004. "Post-Tensioning Tendon Installation and Grouting Manual."
- Im, S. B., S. Hurlebaus and D. Trejo. 2010. "Effective Repair Grouting Methods and Materials for Filling Voids in External Posttensioned Tendons." *Transportation Research Record: Journal of the Transportation Research Board* 2172(-1): 3-10.
- Im, S. B. 2009 "Inspection, Assessment, and Repair of Grouted Ducts in Post-Tensioned Bridge", Texas A&M University, College Station, TX.
- Trejo, D., M. D. Hueste, P. Gardoni, R. G. Pillai, K. Reinschmidt, S.-B. Im, S. Kataria, S. Hurlebaus, M. Gamble and T. T. Ngo. 2009a. "Effect of Voids in Grouted, Post-Tensioned, Concrete Bridge Construction: Volume 1 – Electrochemical Testing and Reliability Assessment", Research Report No. 0-4588-1 Vol. 2, Texas Transportation Institute and Texas Department of Transportation, 342 pages.

## FABRICATION OF CONDITIONS GROUT CONDITIONS

### Procedure

#### Apparatus:

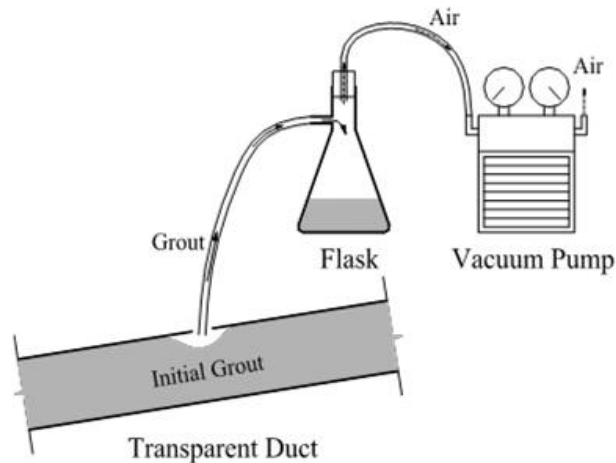
- Saddle Tap
- $\frac{3}{4}$ " Tubes
- Vacuum Pump
- Flask
- Scale
- Air Supply
- Water
- Soft/White Paste/Segregated Grout
- Un-hydrated Grout
- Gassed Grout
- Drill (1")

#### Process Description:

The saddle taps and tubes must first be set up prior to grouting at the locations along the duct desired for the fabrication of grout conditions. In the case of the internal post-tensioning ducts, the concrete is placed before the initial grout placement and replacement with the bad grout. The vacuum pump device is connected to the tubes and the desired volume of fresh grout is pumped out of the ducts. Then, a form of the compromised grout is injected into that location in the duct.

## FABRICATION OF CONDITIONS GROUT CONDITIONS

### Photos:



Schematic showing the set up for the vacuum pump (Im 2009)

### Fabrication of Condition Methodology:

#### PREPARATION:

Step 1 – At the locations desired for the grout conditions, drill a 1” hole in the duct and properly connect the saddle tap to the duct, sealing the drilled hole.

Step 2 – Attach the tubes to extend from the saddle taps, specifically to outside of the designated concrete area for the internal post-tensioning ducts.

Step 3 – In the case of the internal post-tensioning, place and cure the concrete in the formwork.

## **FABRICATION OF CONDITIONS GROUT CONDITIONS**

### **FABRICATION OF CONDITION:**

Step 1 – Mix the uncompromised standard grout to be used in the ducts.

Step 2 – Fabricate the necessary amount of each compromised grout. Form the soft grout, white paste, and segregated grout types by adding excess water to the mix.

Form the un-hydrated grout by decreasing the water content of the mix. Create the gassed grout by introducing gas into the grout.

Step 3 – With the steel tendons in place, inject the uncompromised standard grout in the ducts following proper grouting procedures.

Step 4 – Connect the vacuum pump device to the tubes and extract the designated grout volume from each grout condition location 2 hours after grouting.

Step 5 – Collect the grout pumped from the specimen at each location in a flask and measure the volume of extracted uncompromised grout.

Step 6 – Inject the same volume of compromised grout into the grout condition location. Use a second saddle tap for verification of bad grout placement if possible.

Step 7 – Check that all the necessary information for the fabrication of grout conditions has been clearly documented.

Step 8 – A heat shrink wrap can be used at locations along external HDPE duct to seal and obscure grout condition locations.

**FABRICATION OF CONDITIONS  
GROUT CONDITIONS****Quality Assurance:**

The following are included in fabrication of the condition as a means of quality assurance:

- Abundant information is recorded on the type of compromised grout used in each location
- Volume of the uncompromised grout extracted from the specimen at each grout condition location is measured with the best possible accuracy
- Care is taken so that no void space remains with the compromised grout

**Reporting****Condition Locations in Specimen:**

The detailed location and volume of the grout condition in the specimen are documented. Other conditions at locations overlapping the grout conditions are also documented as to take into account the influence of more than one type of fabricated condition at the same location.

FABRICATION OF CONDITIONS GROUT CONDITIONS			
Necessary Information for Fabrication of Grout Conditions			
#	Description	Units/format	Values/Accuracy
1	State, City, Location	Text	Text
2	Personnel Performing Fabrication of Condition	List	Name(s)
3	Date	mm/dd/yyyy	Exact date
4	Start Time	hh:mm	1 min
5	End Time	hh:mm	1 min
6	Temperature	Degrees F	1 deg
7	Humidity	%	1 %
8	Specimen	Text	Text
9	Internal PT, External PT, or Stay Cable System	Text	Text
10	Tendon/Duct Number	Number	Exact number
11	Section Number	Number	Exact number
12	Specified Tendon/Duct Origin Location	Text	Text
13	Distance along Tendon/Duct from Tendon/Duct Origin	Feet, inches	Exact as possible
14	Volume of Grout Removed	Cubic Inches	Exact as possible
15	Compromised Grout Type	Text	Text
16	Depth of Duct in Specimen at Condition (if Internal)	Feet, inches	1 inch
17	Other Conditions at Same Location	Text	Text
18			
19			
20			
21			
22			
23			
24			
25			
26			

## FABRICATION OF CONDITIONS VOIDS – OPTION 1

### Introduction

#### Scope:

Voids can occur during the grouting process of post-tensioning and stay cable systems due to improper grout mixing and placement procedures. Improper grouting procedures may include not injecting grout at the low point of the tendon profile, the direction the grout is injected, and improper grouting pressure.

Various void types and sizes are fabricated by attaching artificial void material to the tendons or interior duct surfaces at specified locations before the tendons are pushed or pulled through the ducts. The artificial voids are able to be applied to the interior duct surfaces at locations accessible from the duct openings. Possible material for the artificial voids includes extruded polystyrene foam and an expanding spray polymer such as polyurethane plastic foam. Voids can exist in several geometries and locations including on the interior surface of the duct, on the tendon surface, and reaching from the interior surface of the duct to the tendon surface. The voids are fabricated for the ducts of the internal post-tensioning, external post-tensioning, and stay cable systems.

#### Terminology:

- *Extruded polystyrene foam.* A rigid foam material.
- *Polyurethane plastic foam.* A flexible foam material than can expand up to several times of its original liquid volume.



## FABRICATION OF CONDITIONS VOIDS – OPTION 1

### Significance:

Voids in post-tensioning and stay cable systems at locations within the ducts can be detrimental to the bridge structure because it prevents proper bonding of the materials.

Voids can also facilitate an environment prone to corrosion by the presence of oxygen and potentially other gaseous substances.

### Referenced Documents:

Corven, J. and A. Moreton. 2004. "Post-Tensioning Tendon Installation and Grouting Manual"

Im, S. B. 2013. "Inspection, Assessment, and Repair of Grouted Ducts in Post-Tensioned Bridge", Texas A&M University, College Station, TX.

Trejo, D., M. D. Hueste, P. Gardoni, R. G. Pillai, K. Reinschmidt, S.-B. Im, S. Kataria, S. Hurlebaus, M. Gamble and T. T. Ngo. 2009b. "Effect of Voids in Grouted, Post-Tensioned, Concrete Bridge Construction: Volume 2 - Inspection, Repair, Materials, and Risks", Research Report No. 0-4588-1 Vol. 2, Texas Transportation Institute and Texas Department of Transportation, 313 pages.

Trejo, D., M. D. Hueste, P. Gardoni, R. G. Pillai, K. Reinschmidt, S.-B. Im, S. Kataria, S. Hurlebaus, M. Gamble and T. T. Ngo. 2009a. "Effect of Voids in

## FABRICATION OF CONDITIONS VOIDS – OPTION 1

Grouted, Post-Tensioned, Concrete Bridge Construction: Volume 1 – Electrochemical Testing and Reliability Assessment", Research Report No. 0-4588-1 Vol. 2, Texas Transportation Institute and Texas Department of Transportation, 342 pages.

Trejo, D., S. B. Im, R. G. Pillai, M. B. D. Hueste, P. Gardoni, S. Hurlebaus and M. Gamble. 2009d. "Effect of Voids in Grouted Post-Tensioned Concrete Bridge Construction: Inspection and Repair Manual for External Tendons in Segmental, Post-Tensioned Bridges", Texas Transportation Institute, Texas A&M University System.

### Procedure

#### Apparatus:

- Extruded polystyrene foam
- Expanding spray polymer (polyurethane plastic foam)
- Adhesive
- Cutting knife
- Borescope

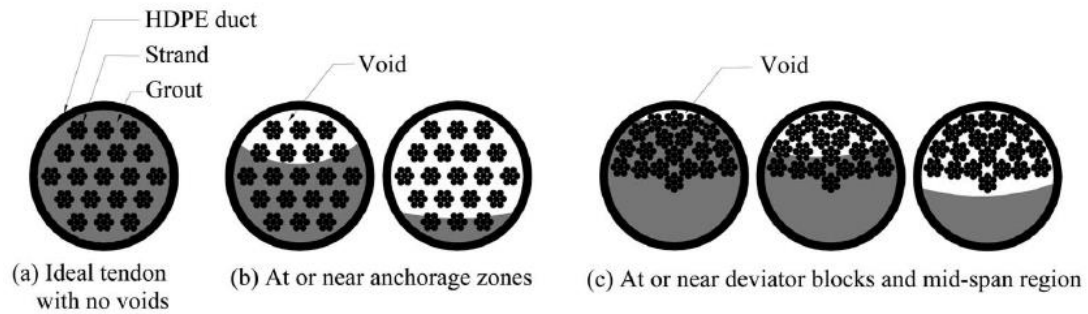
#### Process Description:

The internal post-tensioning ducts are placed and concrete is poured. The artificial voids are attached to the tendons or interior duct surfaces at the desired void locations before the tendons are pushed or pulled through the ducts. Care must be taken to

## FABRICATION OF CONDITIONS VOIDS – OPTION 1

check the final location prior to grouting. The borescope can be used to aid in visual confirmation of the artificial void locations.

### Photos:



Cross sections of typical no-void and void conditions inside a PT duct (Trejo et al. 2009a)

### Fabrication of Condition Methodology:

#### PREPARATION:

Step 1 – Set up the desired formwork for the specimen.

Step 2 – Properly position the stay cable and post-tensioning ducts in their correct locations.

Step 3 – Place and cure the concrete surrounding the internal post-tensioning ducts in the formwork.

## FABRICATION OF CONDITIONS VOIDS – OPTION 1

### FABRICATION OF CONDITION:

Step 1 – Create the artificial voids of appropriate size using the extruded polystyrene foam and cutting knife.

Step 2 – Attach the cut out extruded polystyrene foam with the adhesive to the tendons or accessible interior duct surfaces or use the expanding spray polymer at the desired void locations.

Step 3 – Push or pull the steel tendons through the ducts taking as much care as possible not to damage the foam void locations.

Step 4 – Visually inspect the ducts as much as possible to verify the location of the artificial voids after the tendons have been pushed or pulled through the ducts. A borescope can also be used to verify the void locations.

Step 5 – Inject the grout into the ducts after artificial void placement. Use vacuum grouting procedures to ensure that the grout is fully surrounding the planted voids.

Step 6 – Check that all the necessary information for the fabrication of voids using foam has been clearly documented.

### Quality Assurance:

The following are included in fabrication of the condition as a means of quality assurance:

- Location of the polystyrene foam is verified with a borescope before grout placement

**FABRICATION OF CONDITIONS  
VOIDS – OPTION 1**

- Care is taken so that there is no void space around the foam after grout placement

**Reporting****Condition Locations in Specimen:**

The detailed location and size of the voids in the specimen are documented. Other conditions at locations overlapping the voids are also documented as to take into account the influence of more than one type of fabricated condition at the same location. A visual representation of the void locations on the specimen and in the duct cross sections is used along with the detailed description.

**FABRICATION OF CONDITIONS  
VOIDS – OPTION 1**

**Necessary Information for Fabrication of Voids – Option 1**

#	Description	Units/format	Values/Accuracy
1	State, City, Location	Text	Text
2	Personnel Performing Fabrication of Condition	List	Name(s)
3	Date	mm/dd/yyyy	Exact date
4	Start Time	hh:mm	1 min
5	End Time	hh:mm	1 min
6	Temperature	Degrees F	1 deg
7	Humidity	%	1 %
8	Specimen	Text	Text
9	Internal PT, External PT, or Stay Cable System	Text	Text
10	Tendon/Duct Number	Number	Exact number
11	Section Number	Number	Exact number
12	Specified Tendon/Duct Origin Location	Text	Text
13	Distance along Tendon/Duct from Tendon/Duct Origin	Feet, inches	Exact as possible
14	Cross-Sectional Location of Condition in Duct	Text, Sketch	Text, Sketch
15	Condition Size	Inches	Exact as possible
16	Artificial Void Material	Text	Text
17	Depth of Duct in Specimen at Condition (if Internal)	Inches	1 inch
18	Other Conditions at Same Location	Text	Text
19	Adhesive Material	Text	Text
20			
21			
22			
23			
24			
25			
26			

## FABRICATION OF CONDITIONS VOIDS – OPTION 2

### Introduction

#### Scope:

Voids can occur during the grouting process of post-tensioning and stay cable systems due to improper grout mixing and placement procedures. Improper grouting procedures may include not injecting grout at the low point of the tendon profile, the direction the grout is injected, and improper grouting pressure.

Voids are fabricated in the ducts of the internal post-tensioning and external post-tensioning of the bridge girder specimen as well as in the stay cable specimen. The voids are created by pumping grout out of the duct by a vacuum pump. The vacuum pump is connected to tubes which will be connected to saddle taps on the ducts allowing for grout removal. The size of the voids are characterized by the volume of grout removed at each location.

#### Terminology:

- *Vacuum pump.* The device used to pump grout from the duct.
- *Saddle tap.* The piece connected to the duct with an outlet to allow for grout removal.

#### Significance:

Voids in post-tensioning and stay cable systems at locations within the ducts can be detrimental to the bridge structure because it prevents proper bonding of the materials.

Voids can also facilitate an environment prone to corrosion by the presence of oxygen and potentially other gaseous substances.

## FABRICATION OF CONDITIONS VOIDS – OPTION 2

### Referenced Documents:

- Corven, J. and A. Moreton. 2004. "Post-Tensioning Tendon Installation and Grouting Manual"
- Im, S. B. 2013. "Inspection, Assessment, and Repair of Grouted Ducts in Post-Tensioned Bridge", Texas A&M University, College Station, TX.
- Trejo, D., M. D. Hueste, P. Gardoni, R. G. Pillai, K. Reinschmidt, S.-B. Im, S. Kataria, S. Hurlebaus, M. Gamble and T. T. Ngo. 2009b. "Effect of Voids in Grouted, Post-Tensioned, Concrete Bridge Construction: Volume 2 - Inspection, Repair, Materials, and Risks", Research Report No. 0-4588-1 Vol. 2, Texas Transportation Institute and Texas Department of Transportation, 313 pages.
- Trejo, D., M. D. Hueste, P. Gardoni, R. G. Pillai, K. Reinschmidt, S.-B. Im, S. Kataria, S. Hurlebaus, M. Gamble and T. T. Ngo. 2009a. "Effect of Voids in Grouted, Post-Tensioned, Concrete Bridge Construction: Volume 1 – Electrochemical Testing and Reliability Assessment", Research Report No. 0-4588-1 Vol. 2, Texas Transportation Institute and Texas Department of Transportation, 342 pages.



## FABRICATION OF CONDITIONS VOIDS – OPTION 2

Trejo, D., S. B. Im, R. G. Pillai, M. B. D. Hueste, P. Gardoni, S. Hurlebaus and M.

Gamble. 2009d. "Effect of Voids in Grouted Post-Tensioned Concrete

Bridge Construction: Inspection and Repair Manual for External Tendons in

Segmental, Post-Tensioned Bridges", Texas Transportation Institute, Texas

A&M University System.

### Procedure

#### Apparatus:

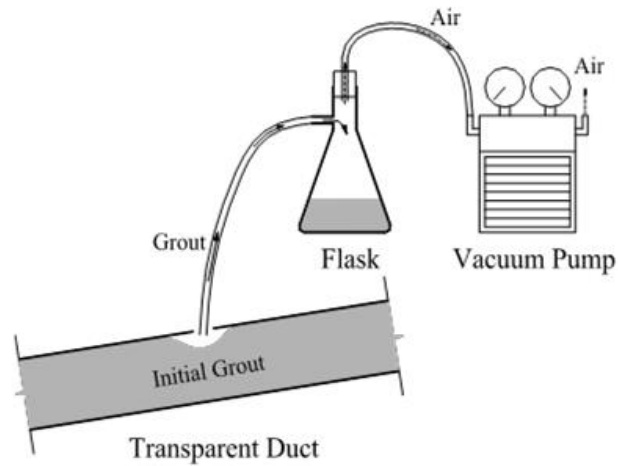
- Saddle Tap
- $\frac{3}{4}$ " Tubes
- Vacuum Pump
- Flask
- Scale
- Air Supply

#### Process Description:

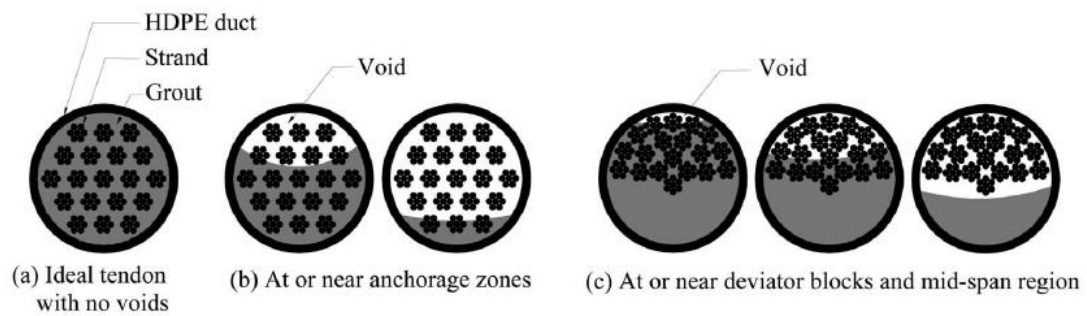
The saddle taps and tubes must first be set up at the locations along the duct desired for fabrication of voids. In the case of the internal post-tensioning ducts, the surrounding concrete is placed before the grout placement and removal. The vacuum pump device is then connected to the tubes and the desired volume of grout is pumped out of the ducts. The grout removed from the duct is placed in the flasks to measure volume.

## FABRICATION OF CONDITIONS VOIDS – OPTION 2

**Photos:**



Schematic showing the set up for making artificial voids (Im 2009)



Cross sections of typical no-void and void conditions inside a PT duct (Trejo et al. 2009a)

## FABRICATION OF CONDITIONS VOIDS – OPTION 2

### Fabrication of Condition Methodology:

#### PREPARATION:

Step 1 – At the locations desired for the voids, drill a 1” hole in the duct and properly connect the saddle tap to the duct, sealing the drilled hole.

Step 2 – Attach the tubes to extend from the saddle taps, specifically to outside of the designated concrete area for the internal post-tensioning ducts.

Step 3 – In the case of the internal post-tensioning, place and cure the concrete in the formwork.

#### FABRICATION OF CONDITION:

Step 1 – Mix the grout to be used in the ducts.

Step 2 – With the steel tendons in place, inject the grout in the ducts following proper grouting procedures.

Step 3 – Connect the vacuum pump device to the tubes and extract the designated grout volume from each artificial void location 2 hours after grouting.

Step 5 – Collect the grout pumped from the specimen at each location in a flask and measure the volume of extracted grout.

Step 6 – Check that all the necessary information for the fabrication of voids has been clearly documented.

## FABRICATION OF CONDITIONS VOIDS – OPTION 2

Step 7 – A heat shrink wrap can be used at locations along external HDPE duct to seal and obscure void locations.

### **Quality Assurance:**

The following are included in fabrication of the condition as a means of quality assurance:

- Volume of the uncompromised grout extracted from the specimen at each void location is measured with the best possible accuracy
- Void shape is examined as much as possible with borescope before sealing duct

### **Reporting**

#### **Condition Locations in Specimen:**

The detailed location and volume of the voids in the specimen are documented. Other conditions at locations overlapping the voids are also documented as to take into account the influence of more than one type of fabricated condition at the same location. A visual representation of the void locations on the specimen and in the duct cross sections is used along with the detailed description. The location of the voids in the duct cross sections are documented by specifying their longitudinal placement (beginning and end) and radial distribution, along with their depth in the cross section.

**FABRICATION OF CONDITIONS  
VOIDS – OPTION 2**

**Necessary Information for Fabrication of Voids – Option 2**

#	Description	Units/format	Values/Accuracy
1	State, City, Location	Text	Text
2	Personnel Performing Fabrication of Condition	List	Name(s)
3	Date	mm/dd/yyyy	Exact date
4	Start Time	hh:mm	1 min
5	End Time	hh:mm	1 min
6	Temperature	Degrees F	1 deg
7	Humidity	%	1 %
8	Specimen	Text	Text
9	Internal PT, External PT, or Stay Cable System	Text	Text
10	Tendon/Duct Number	Number	Exact number
11	Section Number	Number	Exact number
12	Specified Tendon/Duct Origin Location	Text	Text
13	Distance along Tendon/Duct from Tendon/Duct Origin	Feet, inches	Exact as possible
14	Cross-Sectional Location of Condition in Duct	Text, Sketch	Text, Sketch
15	Volume of Grout Removed	Cubic Inches	Exact as possible
16	Depth of Duct in Specimen at Condition (if Internal)	Feet, inches	1 inch
17	Other Conditions at Same Location	Text	Text
18			
19			
20			
21			
22			
23			
24			
25			

FC006A

## FABRICATION OF CONDITIONS WATER INFILTRATION

### Introduction

#### Scope:

The water infiltration condition is usually focused near the anchorage regions of post-tensioning and stay cable systems due to access points, but will be fabricated at locations throughout the specimens. This condition is fabricated in the ducts of the internal post-tensioning and external post-tensioning of the bridge girder specimen as well as in the stay cable specimen. The water infiltration is created by pumping fresh grout out of the duct by a vacuum pump and then replacing it with the same volume of water. The vacuum pump is connected to tubes which are connected to saddle taps on the ducts allowing for grout removal. There are two saddle taps for each grout condition location to allow for the removal of grout and confirmation of the placement of the water infiltration. The amount of water is characterized by the volume of grout removed and subsequently replaced at each location.

The water infiltration into the specimen ducts is also fabricated by pouring a designated amount of water into the grout air vent holes at specified anchorage regions of the specimens. The water is injected into the ducts both during the curing of the grout and after the grout has cured.

#### Terminology:

- *Vacuum pump.* The device used to pump grout from the duct.
- *Saddle tap.* The piece connected to the duct with an outlet to allow for grout removal.

## FABRICATION OF CONDITIONS WATER INFILTRATION

- *Grout air vent hole.* The location at which air can escape from the ducts during grout placement.

### Significance:

Water infiltration into the ducts of post-tensioning and stay cable systems can cause problems in its interaction with the grout and steel. Moisture is needed for corrosion to initiate and propagate and therefore water infiltration can be an early warning sign for the onset of corrosion. Depending on the state of the grout at the time of water infiltration, compromised grout can be formed from the excess water in the duct. The grout could form into soft grout, white paste, or segregated grout.

### Referenced Documents:

- Corven, J., and A. Moreton. 2004. "Post-Tensioning Tendon Installation and Grouting Manual."
- Im, S. B., S. Hurlebaus and D. Trejo. 2010. "Effective Repair Grouting Methods and Materials for Filling Voids in External Posttensioned Tendons." *Transportation Research Record: Journal of the Transportation Research Board* 2172(-1): 3-10.
- Im, S. B. 2009 "Inspection, Assessment, and Repair of Grouted Ducts in Post-Tensioned Bridge", Texas A&M University, College Station, TX.
- Trejo, D., M. D. Hueste, P. Gardoni, R. G. Pillai, K. Reinschmidt, S.-B. Im, S. Kataria, S. Hurlebaus, M. Gamble and T. T. Ngo. 2009a. "Effect of Voids in

## FABRICATION OF CONDITIONS WATER INFILTRATION

Grouted, Post-Tensioned, Concrete Bridge Construction: Volume 1 –  
Electrochemical Testing and Reliability Assessment", Research Report No.  
0-4588-1 Vol. 2, Texas Transportation Institute and Texas Department of  
Transportation, 342 pages.

### Procedure

#### Apparatus:

- Saddle Tap
- 3/4" Tubes
- Vacuum Pump
- Flask
- Scale
- Air Supply
- Water
- Beaker

#### Process Description:

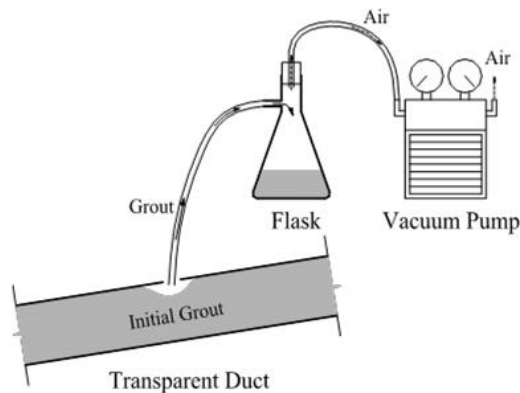
The saddle taps and tubes must first be set up prior to grouting at the locations along the duct desired for the fabrication of grout conditions. In the case of the internal post-tensioning ducts, the concrete is placed before the initial grout placement and replacement with the bad grout. The vacuum pump device is connected to the tubes and the desired volume of fresh grout is pumped out of the ducts. Then, the water is injected into that location in the duct. Also, water is injected through the grout air



## FABRICATION OF CONDITIONS WATER INFILTRATION

vent holes at the anchorage parts of the specimen. The water will infiltrate the ducts resulting in the water infiltration condition.

### Photos:



Schematic showing the set up for making artificial voids (Im 2009)

### Fabrication of Condition Methodology:

#### PREPARATION:

Step 1 – At the locations desired for the water infiltration, drill a 1” hole in the duct and properly connect the saddle tap to the duct, sealing the drilled hole.

Step 2 – Attach the tubes to extend from the saddle taps, specifically to outside of the designated concrete area for the internal post-tensioning ducts.

## FABRICATION OF CONDITIONS WATER INFILTRATION

Step 3 – In the case of the internal post-tensioning, place and cure the concrete in the formwork.

### FABRICATION OF CONDITION:

Step 1 – Mix the grout to be used in the ducts.

Step 2 – With the steel tendons in place, inject the grout in the ducts following proper grouting procedures except to only partially fill the grout area at the grout air vent holes in the anchorage regions.

Step 3– Connect the vacuum pump device to the tubes and extract the designated grout volume from each water infiltration location along the specimens 2 hours after grouting.

Step 4 – Collect the grout pumped from the specimen at each location in a flask and measure the volume of extracted grout.

Step 5 – Inject the same volume of water into the water infiltration location as specified either during or after grout curing. Use a second saddle tap for verification of water placement if possible.

Step 6 – At the anchorage part of the specimen, inject the water through the grout air vent holes as specified either during or after grout curing.

Step 7 – Check that all the necessary information for the fabrication of water infiltration has been clearly documented.

## FABRICATION OF CONDITIONS WATER INFILTRATION

Step 8 – A heat shrink wrap can be used at locations along external HDPE duct to seal and obscure water infiltration locations.

### **Quality Assurance:**

The following are included in fabrication of the condition as a means of quality assurance:

- Volume of the grout extracted from the specimen at each water infiltration location is measured with the best possible accuracy
- Void shape is examined as much as possible with borescope before water infiltration
- Care is taken so that no void space remains with the water infiltration

### **Reporting**

#### **Condition Locations in Specimen:**

The detailed location and amount of water infiltration in the specimen are documented. Other conditions at locations overlapping the water infiltration are also documented as to take into account the influence of more than one type of fabricated condition at the same location. A visual representation of the water infiltration locations on the specimen and in the duct cross sections are used along with the detailed description.

## FABRICATION OF CONDITIONS WATER INFILTRATION

### Necessary Information for Fabrication of Water Infiltration

#	Description	Units/format	Values/Accuracy
1	State, City, Location	Text	Text
2	Personnel Performing Fabrication of Condition	List	Name(s)
3	Date	mm/dd/yyyy	Exact date
4	Start Time	hh:mm	1 min
5	End Time	hh:mm	1 min
6	Temperature	Degrees F	1 deg
7	Humidity	%	1 %
8	Specimen	Text	Text
9	Internal PT, External PT, or Stay Cable System	Text	Text
10	Tendon/Duct Number	Number	Exact number
11	Section Number	Number	Exact number
12	Specified Tendon/Duct Origin Location	Text	Text
13	Distance along Tendon/Duct from Tendon/Duct Origin	Feet, inches	Exact as possible
14	Cross-Sectional Location of Condition in Duct/Anchorage	Text, Sketch	Text, Sketch
15	Amount of Water	Volume units	Exact as possible
16	Amount of Grout Curing Before Water Infiltration	Text, hh:mm	Text, 1 min
17	Depth of Duct in Specimen at Condition (if Internal)	Inches	1 inch
18	Other Conditions at Same Location	Text	Text
19			
20			
21			
22			
23			
24			
25			
26			

**FC007A**

## **FABRICATION OF TENDON DETERIORATION IN THE ANCHORAGE SYSTEMS**

### **Introduction**

#### **Scope:**

Tendon deterioration in the anchorage systems may include several of the conditions to be planted in the specimens, including strand breakage, corrosion, steel section loss, water infiltration, voids and grout conditions.

#### **Terminology:**

See FC001A, FC002A, FC002B, FC003A, FC004A, FC005A, FC005B, and FC006A as applicable.

#### **Significance:**

Strand breakage, corrosion, steel section loss, water infiltration, voids and grout conditions primarily occur in a large degree in the anchorage region of post-tensioning and stay cable systems. The secure anchorage of the post-tensioning and stay cable tendons is critical to carrying the load of the bridge and should be thoroughly examined during bridge inspections.

#### **Referenced Documents:**

See FC001A, FC002A, FC002B, FC003A, FC004A, FC005A, FC005B, and FC006A as applicable.

## FABRICATION OF TENDON DETERIORATION IN THE ANCHORAGE SYSTEMS

### Procedure

#### Apparatus:

See FC001A, FC002A, FC002B, FC003A, FC004A, FC005A, FC005B, and FC006A as applicable.

#### Process Description:

See FC001A, FC002A, FC002B, FC003A, FC004A, FC005A, FC005B, and FC006A as applicable.

#### Photos:

See FC001A, FC002A, FC002B, FC003A, FC004A, FC005A, FC005B, and FC006A as applicable.

#### Fabrication of Condition Methodology:

##### PREPARATION:

Step 1 – Construct the specimen to the degree necessary before fabrication of condition.

##### FABRICATION OF CONDITION:

Step 1 – Fabricate the designated condition or combination of conditions according to FC001A, FC002A, FC002B, FC003A, FC004A, FC005A, FC005B, and FC006A as applicable.

**FABRICATION OF TENDON DETERIORATION IN THE ANCHORAGE SYSTEMS****Quality Assurance:**

The following are included in fabrication of the condition as a means of quality assurance:

- See FC001A, FC002A, FC002B, FC003A, FC004A, FC005A, FC005B, and FC006A as applicable.

**Reporting****Condition Locations in Specimen:**

The detailed location and type of condition(s) to be part of the tendon deterioration in the anchorage region of the specimen are documented. The combination of conditions at those locations in the anchorage regions are documented as to take into account the influence of more than one type of fabricated condition at the same location. A visual representation of the tendon deterioration locations on the specimen and in the anchorage cross sections are used along with the detailed description.

## FABRICATION OF TENDON DETERIORATION IN THE ANCHORAGE SYSTEMS

### Necessary Information for Fabrication of Tendon Deterioration in the Anchorage System

#	Description	Units/format	Values/Accuracy
1	State, City, Location	Text	Text
2	Personnel Performing Fabrication of Condition	List	Name(s)
3	Date	mm/dd/yyyy	Exact date
4	Start Time	hh:mm	1 min
5	End Time	hh:mm	1 min
6	Temperature	Degrees F	1 deg
7	Humidity	%	1 %
8	Specimen	Text	Text
9	Internal PT, External PT, or Stay Cable System	Text	Text
10	Tendon/Duct Number	Number	Exact number
11	Section Number	Number	Exact number
12	Specified Tendon/Duct Origin Location	Text	Text
13	Distance along Tendon/Duct from Tendon/Duct Origin	Feet, inches	Exact as possible
14	Cross-Sectional Location of Condition in Duct/Anchorage	Text, Sketch	Text, Sketch
15	Condition Size	Inches	Exact as possible
16	Depth of Duct in Specimen at Condition (if Internal)	Inches	1 inch
17	Conditions included in Tendon Deterioration	Text	Text
18			
19			
20			
21			
22			
23			
24			
25			