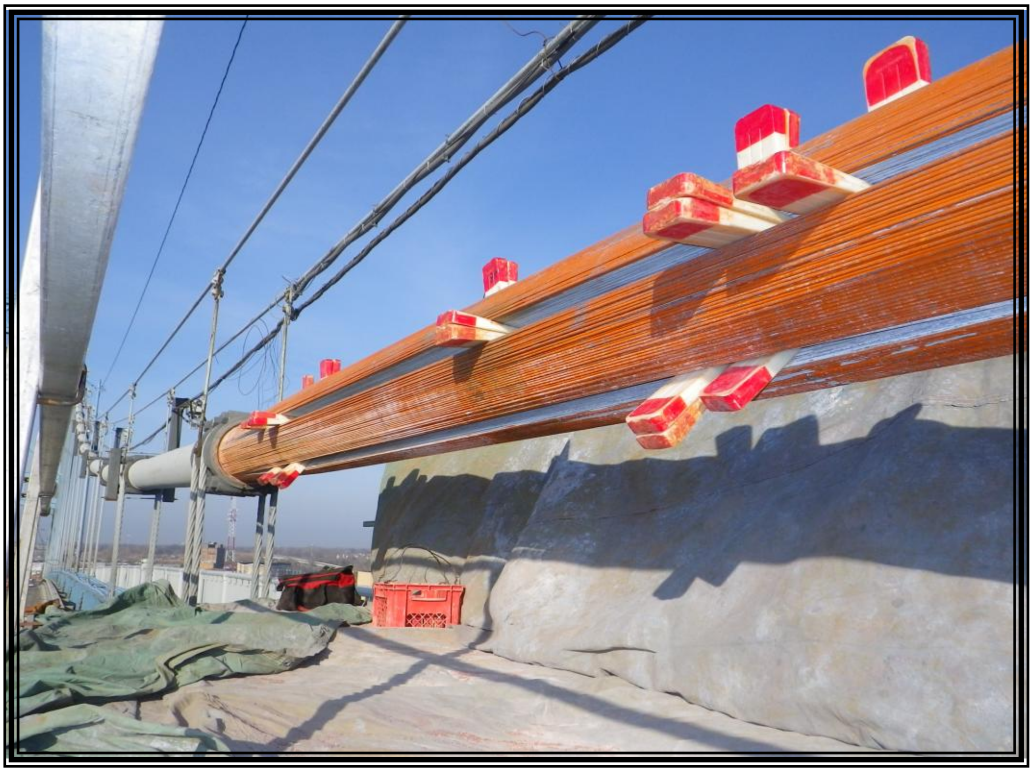
Ohio Department of Transportation

THE ANTHONY WAYNE BRIDGE

Over the Maumee River

2013 CABLE STRENGTH EVALUATION REPORT



February 2013

PREPARED BY

MODJESKI and MASTERS
Experience great bridges.

Mechanicsburg, PENNSYLVANIA

PREPARED FOR

ARCADIS

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over the
MAUMEE RIVER

2013 CABLE STRENGTH EVALUATION

REPORT

for the

OHIO DEPARTMENT OF TRANSPORTATION

Prepared by

MODJESKI AND MASTERS, INC.
CONSULTING ENGINEERS
MECHANICSBURG, PENNSYLVANIA

Prepared for

ARCADIS

Executive Summary

Introduction

Modjeski and Masters, Inc. (MM), with assistance from the Contractor, Piasecki Steel Construction Corp. and ARCADIS, conducted an investigation of both main cables on the Anthony Wayne Bridge in November 2012. The purpose of the investigation was to determine the condition of the wires and to take samples for laboratory testing. The results of the investigation and testing were subsequently used to perform a cable strength evaluation using probabilistic methods.

General Inspection Information

The Owner directed the ARCADIS Team to inspect each cable internally at one location, with the option of one additional opening per cable as the field conditions warranted.

NCHRP Report 534 "Guidelines for Inspection and Strength Evaluation of Suspension Bridge Parallel Wire Cables" (Report 534) recommends selecting locations with external signs of potential internal deterioration. A review of the 2008 Physical Condition Report was performed to identify which panels should be selected for internal inspection. This information was used in conjunction with data obtained from the acoustic monitoring system, the location of past inspection "windows" and the recommendations of Section 2.2.5 of Report 534 to identify locations for internal inspection. The following locations were chosen as primary internal inspection locations:

- PP 3 – PP 4, located four panels up from the cable hold-down in the west side span of the south cable,
- East PP 65, located in the east back span of the north cable between the cable hold-down and the cable hood where the cable passes through the sidewalk

The following locations were chosen as optional internal inspection locations:

- PP 58 – PP 59, located approximately mid-way between the east tower and the cable hold-down in the east side span of the south cable,
- PP 31 – PP 32, located near the low point of the main span north cable.

Based on a visual inspection of the wire condition, the wires were divided into the following categories, per Section 1.4.2.2 of Report 534:

- Stage 1 – spots of zinc oxidation (like-new condition),
- Stage 2 – zinc oxidation over the entire wire surface (no ferrous rust),
- Stage 3 – spots of brown rust covering up to 30% of the wire surface over a 3-inch to 6-inch length,
- Stage 4 – brown rust covering greater than 30% of the wire surface over a 3-inch to 6-inch length.

Inspection Findings

A summary of the resulting cable condition at each location is given in Table 1. In general, the cables are in fair to poor condition, with 17% to 59% of the wires at Stage 4 with no Stage 1 wires observed. An exception is Primary Opening Location PP 31 – PP 32, North, where about two-thirds are at Stage 1 or 2 and less than 10% were Stage 4. Only about 1% of the wires at this location were classified as Stage 1. No broken wires were observed at any of the inspection locations during the cable inspection.

Location	Percent of Total				No. of Broken Wires
	Stage 1	Stage 2	Stage 3	Stage 4	
Primary Opening, East PP 65, North	0%	16%	54%	30%	0
Optional Opening, PP 31 - PP 32, North	1%	62%	28%	9%	0
Primary Opening, PP 3 - PP 4, South	0%	0%	83%	17%	0
Optional Opening, PP 58 - PP 59, South	0%	0%	41%	59%	0

Table 1 – Cable Condition Summary

Calculation of Cable Strength

The wire test results were used to estimate the strength of the cable by employing two of the following three models presented in Section 5 of Report 534 – the Simplified Strength Model and the Brittle Wire Model. The testing laboratory testing did not report the ultimate strain so the Limited Ductility Model could not be calculated.

The cable strengths calculated using the Simplified and Brittle Wire models are shown in Table 2, in kips. It is important to note that the estimated percent of cracked wires at all locations except Optional Opening PP 31 – PP 32, North exceeds 10%, thereby making the Simplified Strength Model overly conservative and no longer applicable. At Optional Location PP 31 – PP 32, North, the estimated percent of cracked wires is 9% which is at the upper limits for this model to provide reasonable results.

Location	Strength Models	
	Simplified Strength (kips)	Brittle Wire (kips)
As-Built	17,800	17,900
Primary Opening, East PP 65, North	10,000	14,400
Optional Opening, PP 31 - PP 32, North	15,100	16,600
Primary Opening, PP 3 - PP 4, South	12,600	15,200
Optional Opening, PP 58 - PP 59, South	6,700	16,000

Table 2 – Cable Strength Summary

Table 3 presents the resulting factors of safety, which are determined by dividing the calculated cable strength by the calculated cable tension, also given in Table 3. The calculated cable tension is based on the rehabilitated condition with the new lightweight deck in place.

Location	Cable Tension (kips)	Simplified Strength Factor of Safety		Brittle Wire Factor of Safety	
		As-Built	As-Insp.	As-Built	As-Insp.
Primary Opening, East PP 65, North	5,984	2.97	1.67	2.99	2.41
Optional Opening, PP 31 - PP 32, North	5,712	3.12	2.64	3.13	2.91
Primary Opening, PP 3 - PP 4, South	6,241	2.85	2.02	2.87	2.44
Optional Opening, PP 58 - PP 59, South	6,422	2.77	1.04	2.79	2.49
Controlling		2.77	1.04	2.79	2.41

Table 3 – Factor of Safety Summary

The as-built cable strength, also calculated using the wire test properties assuming all wires are Stage 1, shows the reduction in cable strength since the bridge was built is between 7% and 20%, based on the more accurate Brittle Wire Models.

Section 6.4 of Report 534 recommends that immediate remedial action be taken whenever the safety factor is found to be less than 2.15. For the Anthony Wayne Bridge cables, this corresponds to a reduction in the as-built cable strength of about 22% and a further reduction from its present condition of about 11%.

Conclusion

The cable strength investigation found that the main cables are in fair to poor condition, with a factor of safety of 2.41 for the south cable and 2.44 for the north cable, based on the Brittle Wire Model. Based on the rehabilitated condition, the minimum calculated cable factor of safety of 2.41 is above the 2.15 action level referenced in Report 534. However, this factor of safety was developed with data sets less than the minimum recommended by Report 534. Therefore, the percent error in the safety factor is greater than would be expected if the recommendations of Report 534 had been followed. It should also be noted that the factor of safety of 2.41 for the rehabilitated condition falls to approximately 2.31 in the current condition without the lightweight concrete deck.

Recommendations

Based on the level of corrosion and the reduction in strength, and the guidelines given in Section 2 of Report 534, it is recommended that ODOT take additional action to obtain a higher level of confidence in the cable condition and to limit further corrosion of the cable, including the following:

- Based on the amount of Stage 4 corrosion observed during the inspection, a minimum of six additional locations per cable should be inspected in the near future (< 2 years). As part of the inspection,
    - A cable band should be removed on each cable,
    - At a minimum, a long (~half) segment in one of the backstays should be included as one of these locations. The backstays do not have cable bands, so the wrapping wire should be removed and reapplied in increments as the inspection proceeds. The addition of several cable bands should also be considered in the backstays.
    - Additional wire samples should be taken so that statistically valid samples of each stage of corrosion are obtained,

- The wires in the tower saddles should be inspected and the saddles should be sealed to ensure that water does not infiltrate the cables at their appex,
- Cable band bolts adjacent to six inspection locations should be checked and retensioned during the next internal inspection. The metalizing on the existing cable band bolts may cause problems in checking the existing tension and retensioning the bolts. New cable band bolts should be ordered in anticipation that the existing bolts will need to be replaced. If the cable band bolt tension is significantly reduced, ODOT may want to consider checking the tension in all of the cable bands,
- If severe corrosion is found to be widespread within the cable based on the six additional openings, ODOT should inspect additional locations or possibly the entire cable length.

- Cable oiling and/or the introduction of corrosion inhibitors into the cable should be considered,
- The acoustic monitoring of the bridge should continue. ODOT and MISTRAS should verify that the system is operating correctly. The system should have captured the acoustic emissions from the wire sampling process, which can be used to verify the systems ability to detect wire breaks. The system should be updated and reconfigured as required. Additional information collected from the monitoring going forward can be used in determining future inspection locations,
- Continue with all practical measures to prevent intrusion of water. Plans are already being made to replace the existing elastomeric wrap. ODOT may also want to consider cable dehumidification as an option to prevent future corrosion in conjunction with the elastomeric cable wrap replacement.

TABLE OF CONTENTS

1.0 INTRODUCTION

The Anthony Wayne Bridge carries Route 2 over the Maumee River in Toledo, Lucas County, Ohio (see Figure 1.1). The bridge is owned by the City of Toledo and is maintained by the Ohio Department of Transportation (ODOT).

The original design drawings and specifications for the bridge were prepared by Waddell and Hardesty and the superstructure was constructed by McClintic-Marshall, Co., Pittsburgh, Pennsylvania. The Anthony Wayne Bridge was opened to traffic in 1931, after a three-year construction period. The suspended main span is 785 ft. between towers, with two 233.5 ft. suspended side spans and two 203.75 ft. backstays.

The suspended main span has two parallel wire main cables comprised of 19 strands of 186 wires each for a total of 3,534 wires. Each wire is No. 6, galvanized with a steel diameter of 0.192 in. The approach spans consist primarily of girder spans with a single deck truss span adjacent to the suspended side spans.

This report details the work completed to determine the strength of the main cables under a series of contracts with ODOT. This work was performed following the recommendations given in the National Cooperative Highway Research Program (NCHRP) Report 534 (1), "Guidelines for Inspection and Strength Evaluation of Suspension Bridge Parallel Wire Cables" (Report 534). Prior to its publication in 2004, there was no nationally recognized procedure for predicting the strength of suspension bridge cables. The methods used for this purpose were developed by whoever was conducting the investigation for a particular bridge. The work documented here is one of several applications on a U.S. Bridge of the procedure established by Report 534.

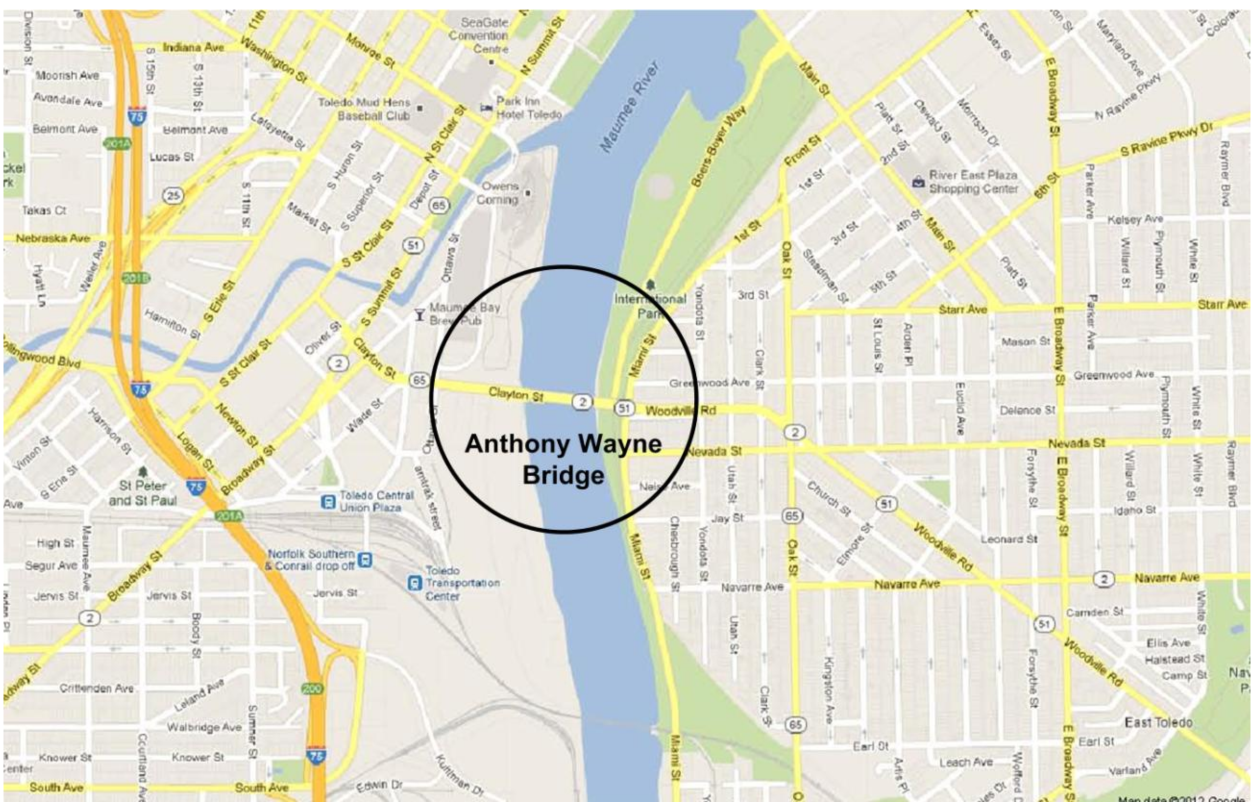


Figure 1.1 – Location Map

The first step of the evaluation was to determine which panels should be internally inspected. Next, work platforms were installed and the cables were unwrapped and wedged at these locations and the wires inspected and classified based on their condition. Typically, broken wires would be noted and repaired, where possible, by splicing in a length of new wire. No broken wires were observed during this inspection, therefore this step was not required. Samples were removed from the cable for laboratory testing at Lucius Pitkin, Inc., New York, New York. Wires from which samples were cut were repaired.

From the information gathered during the inspection, the total number of wires at each stage of corrosion was estimated along with the total number of cracked wires. No broken wires were observed. This information was combined with the laboratory test results to determine the strength of the cable at each of the inspected locations. The resulting factor of safety was then determined by dividing the calculated strength by the force in the cable at that location. Any deviations from the Report 534 procedure are discussed herein.

The following information is presented in this report:

- Section 2 gives a general description of the bridge,
- Section 3 presents the selection of the cable opening locations based on previous inspection reports from 1993 and 2008 as well as information presented in the Acoustic Emission Monitoring Report prepared by MISTRAS in May 2012,
- Section 4 discusses the internal cable inspection conducted by Modjeski and Masters, Inc. in November 2012,
- Section 5 describes the various laboratory tests performed on the wires by Lucius Pitkin, Inc. along with their results,
- Section 6 describes the various models used to calculate the strength of the cable,
- Section 7 presents the resulting cable strength and factor of safety,
- Section 8 discusses the cable band bolt retensioning,
- Section 9 presents the conclusions of the cable strength evaluation and
- Section 10 provides recommendations to ensure that the cable strength is maintained.

Modjeski and Masters, Inc. would like to thank ODOT, ARCADIS and Piasecki Steel Construction Corp. for their assistance during the inspection.

2.0 BRIDGE DESCRIPTION

The Anthony Wayne Bridge is approximately 3215 ft. long between abutments. The main suspended span is 785 ft. center-to-center of the main piers, with suspended side spans of 233.5 ft. center-to-center of the main pier and the hold-down pier. The approaches are 901.75 ft. and 1061.25 ft. long, respectively. The main span is supported by two 13-5/16 in. diameter parallel wire main cables and 76 pairs of 1-5/8 in. diameter suspender ropes. The side spans are cable supported with 22 pairs of 1-5/8 in. diameter suspender ropes and the backstays between the cable hold-down pier and the anchorage are not loaded. The cable hold-down consists of four 2-3/8 in. diameter wire ropes connected to steel struts anchored in the piers. The suspended span roadway is supported by a stringer and floorbeam floor system. A general view of the bridge is shown in Figure 2.1. Elevations of the bridge are shown in Figures 4.1 and 4.2.

The portion of each approach between the hold-down pier and the anchorage consists of a deck truss span while the approach structures between each anchorage and abutment consists of a series of plate girder spans.
The bridge roadway carries four lanes of traffic, two in each direction. The maximum deck grade on the bridge is 4.4% on the approaches and suspended side spans. The roadway width is typically 54 ft. between curbs with a 6 ft. wide sidewalk on both sides of the roadway.

The main cables consist of 19 strands, each comprising 186 No. 6 gage galvanized wires, for a total of 3,534 wires per cable. The cables were compressed to form a circular shape with a diameter of 13 in. and then coated with red lead paste. Galvanized No. 9 wire was wrapped continuously around the longitudinal cable wires and painted to form the exterior protection of the cable. The total diameter of the wrapped cable as designed is approximately 13-5/16 in.

Figure 2.1 - Southwest elevation of the bridge suspended span.

3.0 SELECTION OF INSPECTION LOCATIONS

In the Spring of 2012, a discussion was held between MM, ODOT and ARCADIS in order to identify the locations on the cable for internal inspection. As part of the discussion, it was decided that two primary locations would be opened and two optional locations would be identified for investigation. ODOT would reserve the right to open the optional locations if the conditions discovered in the primary openings warranted further inspection. ODOT did not want to remove a cable band as part of the cable inspection and expressed a desire to open locations that contained inspection windows from previous inspections. In 1978, the wire wrapping on the cable was removed for a distance 24 in. to 36 in. at two locations on each cable in order to investigate the condition of the wires. These windows exposed the surface wires and allowed wedging to inspect the first four to five layers of the cable. The windows were reopened in 1981, 1989 and 1993. Based on the 1993 report, Field Inspection of the Suspension Components of the Anthony Wayne Bridge, prepared by Modjeski and Masters, Inc. as Subconsultants for Burgess and Niple, Limited the four windows were identified as Cable Site A, Cable Site B, Cable Site C and Cable Site D. Cable Site A was located on the north cable, east of Panel Point 65, near the low point of the side span and Cable Site B was located on the north cable between Panel Points 39 and 40, part way up the east main span. Cable Site C was located on the south cable between Panel Points 25 and 26, a short distance up the west main span and Cable Site D was located on the south cable between Panel Points 3 and 4, a short distance up the west side span. Figure 3.1 shows a photograph of Cable Site D taken during the 1993 inspection.

Figure 3.1 – Cable Site D From the 1993 Inspection

ODOT also wanted to incorporate the findings from the acoustic monitoring system installed by MISTRAS in June 2011. MISTRAS reconfigured the acoustic monitoring system in October 2011 in order to identify panels with potential corrosion. The following is an excerpt from *Section 7 Bridge Shutdown – Panels with Potential Corrosion* of the *Anthony Wayne Bridge Acoustic Emission Monitoring Report*, which is included in Appendix A of this report:

Based on the channel by channel analysis, potential areas of interest for future inspection of the north side of the bridge (based on AE activity classification) is as follows: - east anchorage near deck level; west anchorage around Cable Band 1; panel(s) around Cable Band 43; and panel(s) near Cable Band 11. On the south side of the bridge, potential areas of interest include: panel(s) around Cable Band 6; east anchorage; panel(s) around Cable Band 59; and panel(s) near Cable Band 11.

In *Section 9 Concluding Discussion/Follow-Up* this report notes additional locations of interest for future inspection. An excerpt of this section is included below:

As of Thursday, July 14, 2011 – the systems and sensors on both the North and South cables have been continuously recording and monitoring the cable. As of September 10, 2011, no potential wire breaks have been recorded. However, there are several sections on both the North and South cable that have an AE signature that is different from the surrounding panels and are potential locations for future inspection. On the North cable, the section of cable between Sensors 7, 8 and 9 show a high amount of activity, with higher trending of activity between Sensors 8 & 9 (mostly frictional). Additionally, a small cluster between Sensors 14 & 15 has been observed. For the south cable, a similar trend of AE activity is located between Sensors 7 & 8 and is about three times higher than the average observed for the same section on the North cable. Additionally, a small cluster of AE activity was observed between Sensors 1 & 2.

MISTRAS also summarized this information on elevations of the bridge as shown in Figure 3.2.

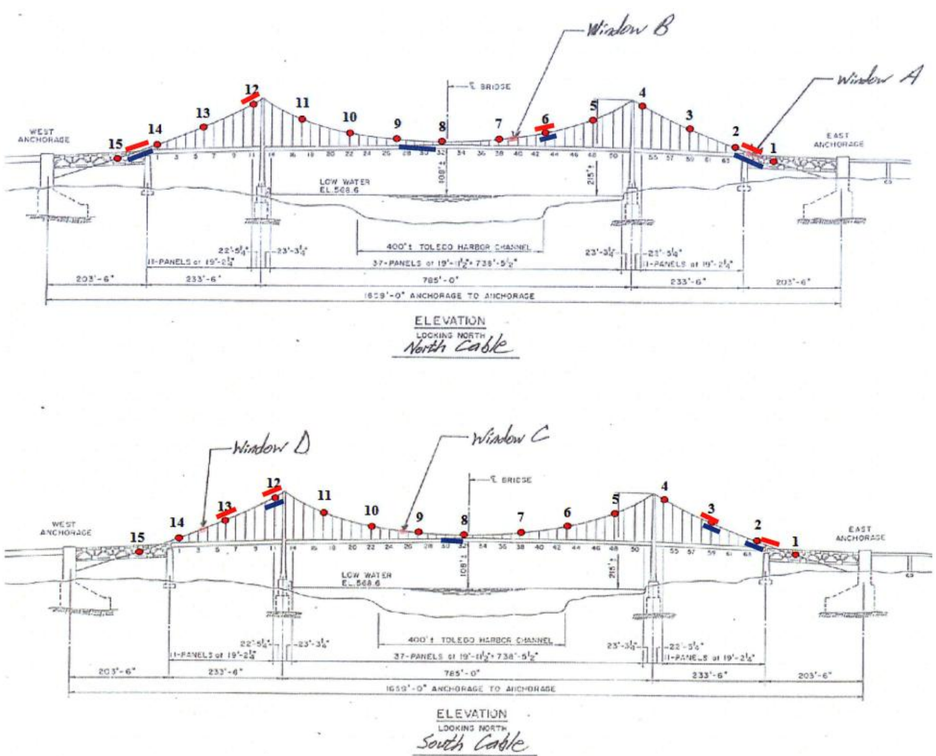


Figure 3.2- MISTRAS Figure of Areas of Potential Interest for Future Inspection

MM combined this information with the data from the 2008 inspection performed by Burgess and Niple. This report noted several deficiencies in the main cable, including areas of water retention under the elastomeric cable wrap. The following is an excerpt from the 2008 Physical Condition Report:

Specific deficiencies pertaining to the main cables include the following:

• Following is a list of cable bands at which water retention was noted under the cable wrap:

- *Downstream Cable: 5, 7-11, 14-18, 23, 25, 27, 30, 32-35, 39, 41-46, 48, 49, 51, 55-58, 60, and 63*

- *Upstream Cable: 5-8, 10, 20, 37, 41, 43, 44-47, 50, 55-60, and 62*

At the majority of these locations, the cable wrap had obvious signs of unbonded layers where precipitation has entered the cable.

- *The neoprene cable wrap was removed on the Downstream Cable near Floor Beam 33 by D.S. Brown, Inc. This location corresponded to the location that was unwrapped by the same company during a previous inspection. The soft wire wrap was found to be corroding. Also, the previous patch did not bond well with the wrap, allowing water to enter. When the wrap was removed, water drained out (seePhotograph No. 73).*

- *A 1-inch diameter drain hole through the neoprene wrap exists in both cables between Floor Beams 32 and 33. The exposed soft wire wrap at these locations is corroded.*

- *A 2-inch long tear in the wrap was observed in the Upstream Cable just west of Floor Beam 0. The tear extends through 3 layers but does not expose the soft wire wrap (see Photograph No. 74).*

- *At Cable Band 8 on the Downstream Cable, a large amount of water has collected, causing the wrap to bulge (see Photograph No. 75).*

- *At Cable Band 59 on the Upstream Cable, the water leaking out of the wrap was rust colored.*

- *Cable collars (trumpet-shaped fixtures around cable at the entrance to the anchorage)are partially buried at Pier F.*

Additionally, Section 2.2.5.1 of Report 534 states that the first internal inspection should be made at a minimum of three locations along each cable, selected as follows:

- one in each cable at a low point of the main span,
- one in each cable at or near a low point of the side span,
- one in the first cable main span, above the low point at a distance of from 30% to 70% of half the main span,
- one in the other cable in a side span, above the low point at a distance of from 30% to 70% of the side span.

Based on all of the available information, MM recommended that the primary cable locations should be located between PP 3 – PP 4 on the south cable and the area east of PP 65 on the north cable. The recommended optional locations were located between PP 58 – PP 59 on the south cable and PP 31 – PP 32 on the north cable. ODOT concurred with these recommendations.

The chosen locations are shown in Figure 3.3 for the north cable and Figure 3.4 for the south cable.

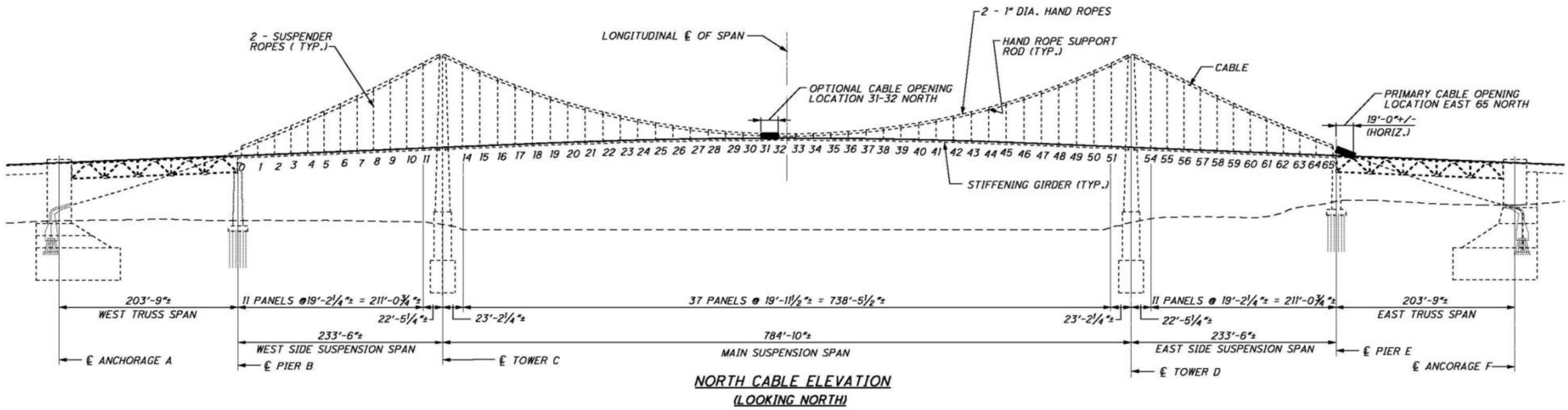


Figure 3.3 - North Cable Inspection Locations

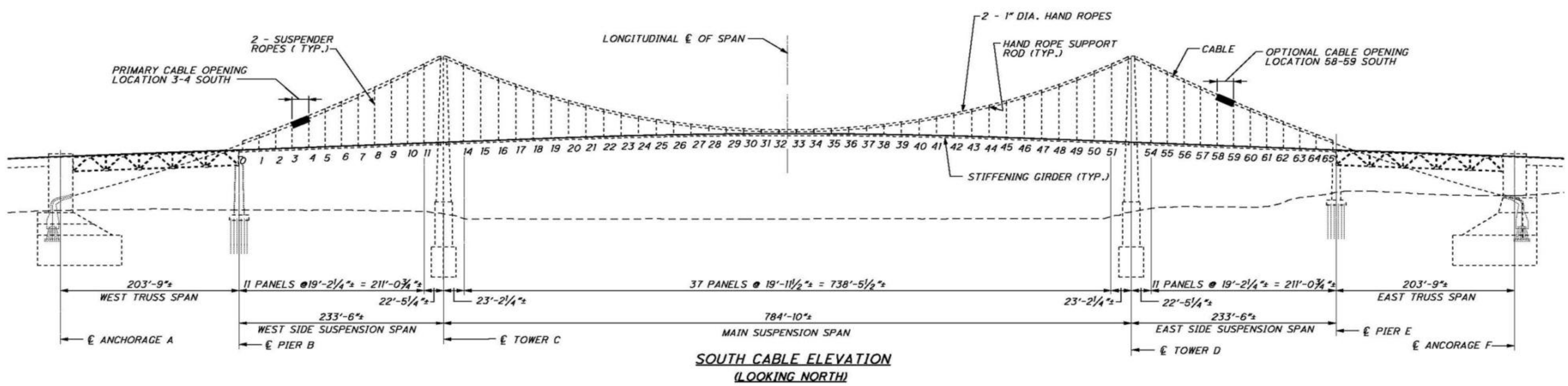


Figure 3.4- North Cable Inspection Locations

4.0 INTERNAL INSPECTION

The cables were inspected internally in November 2012 under Project No. 128038 LUC-2-18.62. The internal inspection was performed by first installing work platforms, shown in Figures 4.1 and 4.2. Next, the neoprene cable wrap and external wrapping wire was removed and plastic wedges were driven into the cables with sledgehammers. The Specifications called for six to eight wedges to be driven at the 12:00, 1:30, 3:00, 4:30, 6:00, 7:30, 9:00, and 10:30 positions, corresponding to positions 1 through 8 as shown in Figure 4.3 (the 1:30, 4:30, 7:30 or 10:30 position(s) are omitted when fewer than eight wedge lines are used).

At most of the locations, the cables were wedged over a full 20-foot (+/-) panel length. However, due to the large cable band spacing of the backstays, this was not practical at location East PP 65, North. Here the cables were opened over an approximate length of 20 ft. between the cable hold-down band and the cable hood where the cable passes through the sidewalk. A photograph of the cable wedged for inspection is shown in Figure 4.4.

Figure 4.1 – Access Platform Installation

Figure 4.2 – Access Platform Installation

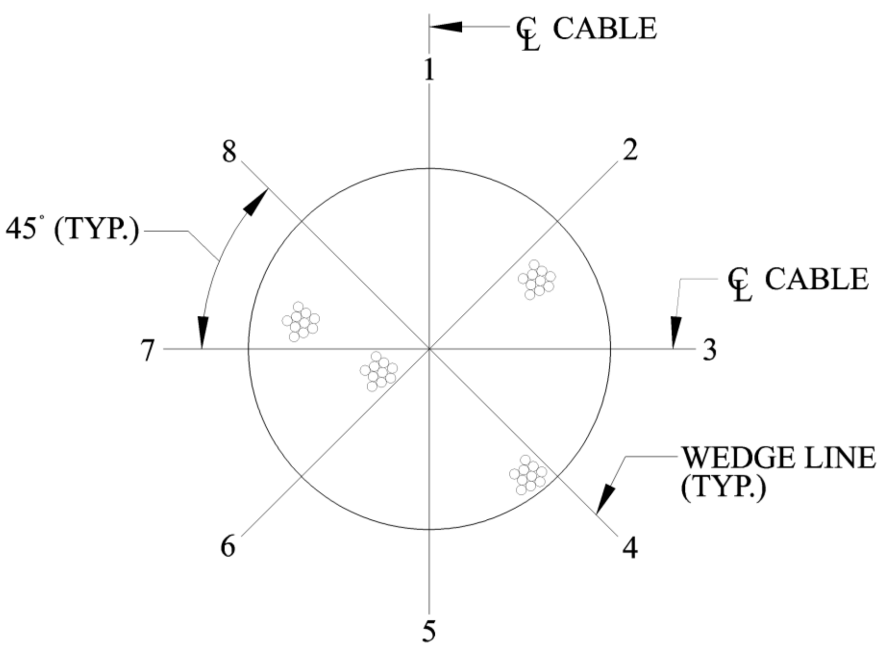


Figure 4.3 – Cable Wedge Locations, Looking Upslope

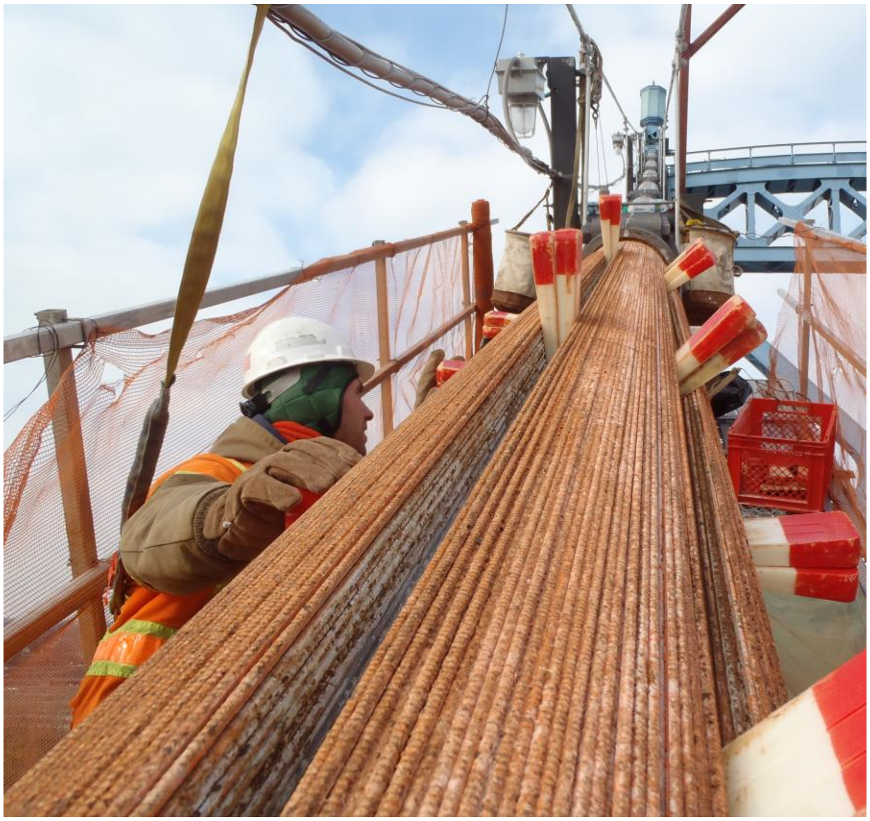


Figure 4.4– Cable Wedged for Inspection

Once the cable was opened, the condition of each of the exposed wires was classified based on the following stages (shown in Figure 1.4.2.2-1 of Report 534):

Stage 1: Spots of zinc oxidation on the wires (like-new condition),
Stage 2: Zinc oxidation over the entire wire surface (no ferrous rust),
Stage 3: Spots of brown rust covering up to 30% of the wire surface over a 3-in. to 6-in. length, and
Stage 4: Spots of brown rust covering more than 30% of the wire surface over a 3-in. to 6-in. length.

These corrosion stages are shown in Figure 4.5. The stage of each of the observed wires was recorded at three locations along the opened length, using the form shown in Figure 4.6.

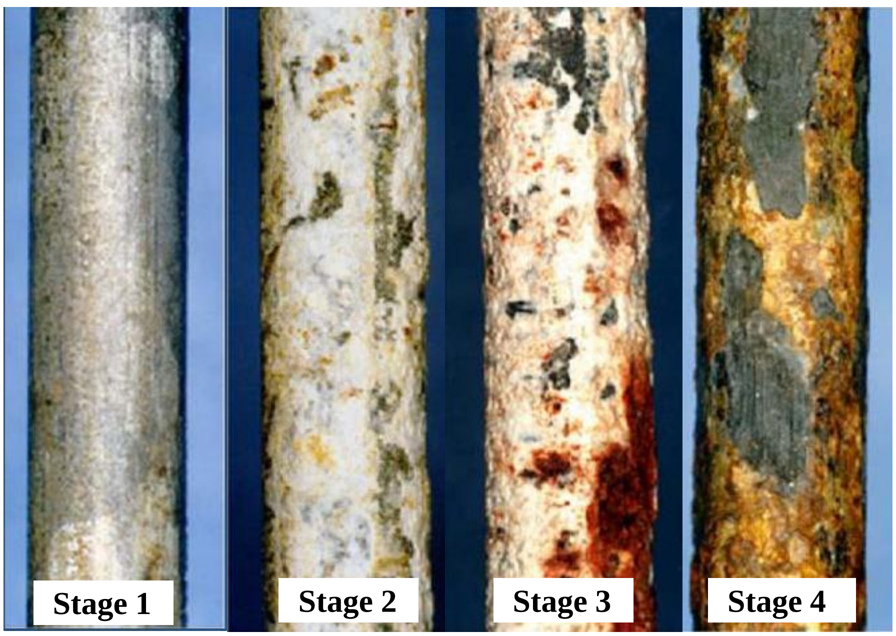


Figure 4.5- Corrosion Stages of Cable Wires (Figure 1.4.2.2-1 of NCHRP Report 534)

If broken wires are found they are also recorded, along with the gap distance between the two ends of the wire. Any accessible broken wires should be repaired by splicing a short length of new wire between the broken ends using ferrules. Wire ends are pulled together using a come-along fitted with wire grips. The force in the repaired wire is required to be within 10% of the dead load force, in accordance with Appendix D of Report 534. No broken wires were found during the cable inspection. Samples were cut from unbroken wires for laboratory testing and then repaired in a similar fashion to that described above. The location of sample wires was recorded on the form shown in Figure 4.7.

Once the inspection was completed, the cable was recompacted to its original diameter using a custom-made hydraulic compacting machine as shown in Figure 4.8. Binding straps were applied at a 12-in. to 18-in. spacing to keep the cable compacted. Next, the cable was rewrapped with an elastomeric cable wrapping. The compacted and banded cable is shown in Figure 4.9. Figure 4.10 shows the elastomeric cable wrap being installed and Figure 4.11 shows the wrap being heated to bond the elastomeric layers.

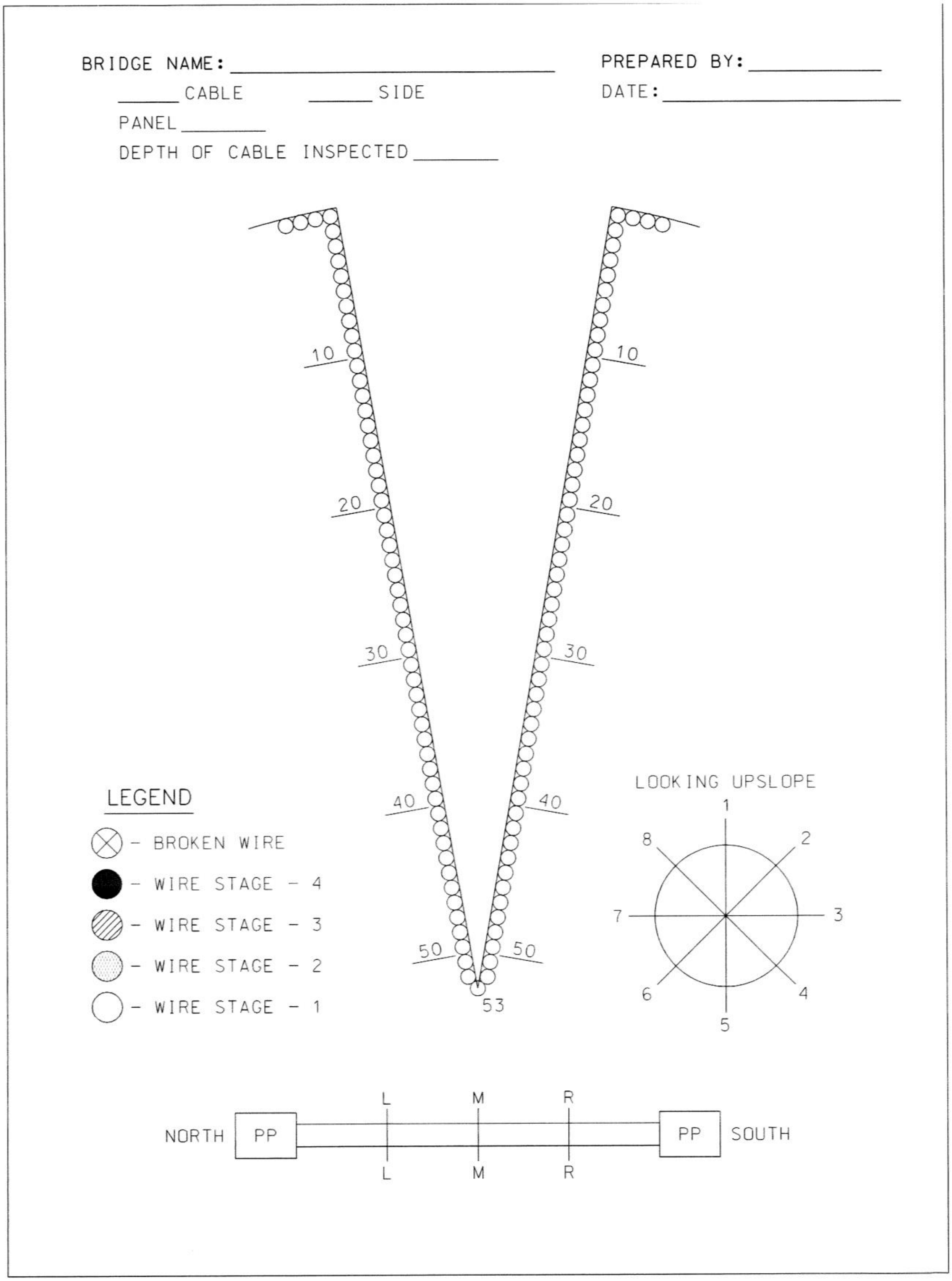


Figure 4.6– Wire Condition Form (Figure 2.3.1.2.4-2 of Report 534)

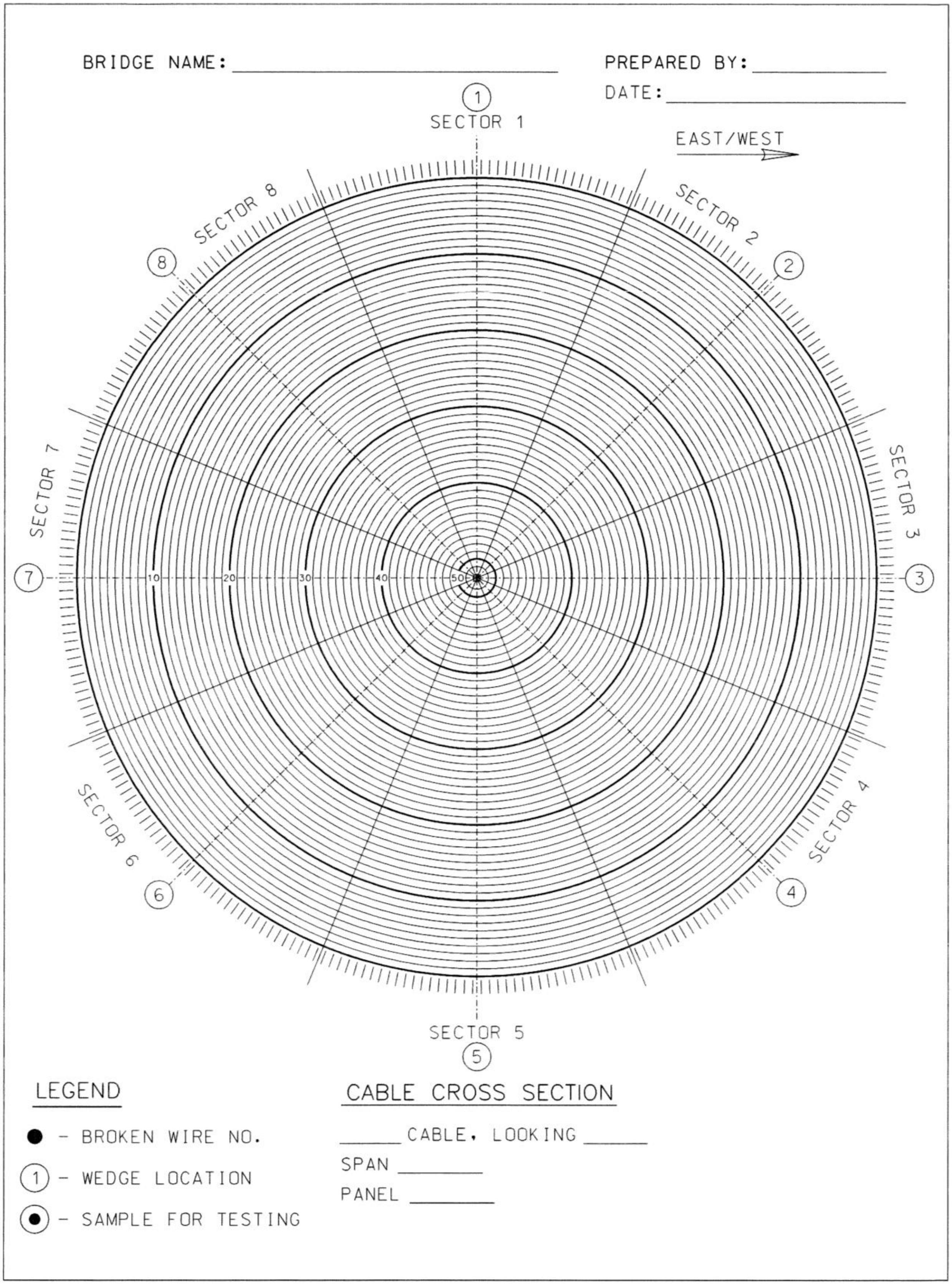


Figure 4.7 – Broken/Sample Wire Form (Figure 2.3.1.2.4-3 of Report 534)

Figure 4.8– Recompacting Cable

Figure 4.9– Recompacted Cable with Banding Straps

Figure 4.10– Neoprene Wrap Installation

Figure 4.11- Neoprene Wrap Heat-Bonding Operation

4.1 Primary Cable Opening Location PP 3 – PP 4, South

This was the first panel to be inspected (November 13, 2012). It is located on the south cable three panels up from the cable hold-down on the west side span. The cable was opened at six wedge lines, Locations 1 and 3 through 7. The inspection showed the wires to be in fair condition. The corrosion level is predominantly Stage 3. Stage 4 corrosion was found closer to the perimeter of the cable. No Stage 1 or Stage 2 wires were observed and no broken wires were found. The field notes indicated that some of the Stage 3 wires only had spot corrosion. Three sample wires, two Stage 3 and one Stage 4, were removed from the cable at this location. All sampled wires were repaired. Figure 4.12 shows the condition of the cable along wedge line 6.

Based on the information from the 1993 Field Inspection Report, this cable opening location should have encompassed the previous inspection window Cable Site D. During the cable opening it was determined that Cable Site D was actually located one panel below the opening location, between PP 2 –PP 3 of the south cable.

Figure 4.12- Primary Cable Opening Location PP 3 – PP 4, South

4.2 Optional Cable Opening Location PP 58 - PP 59, South

This was the second location to be inspected (November 14, 2012). It is located on the south cable approximately mid-way between the east tower and the east hold-down in the side span. Traces of water were observed to be leaking from the wire wrap on the underside of the cable when the existing neoprene wrapping system was removed. The cable was opened at seven of the eight wedge lines. The wires were found to be in poor condition, with a significant number of wires exhibiting Stage 4 corrosion. The remaining wires exhibited Stage 3 corrosion. No Stage 1 or Stage 2 wires were observed at this location. No broken wires were found, and three samples were taken: two Stage 4 and one Stage 3. All sampled wires were repaired. Figure 4.13 shows the condition of the cable along the bottom wedge line.

Figure 4.13- Optional Cable Opening Location PP 58 – PP 59, South

4.3 Primary Cable Opening Location East 65, North

This was the third panel to be inspected (November 15, 2012). It is located on the north cable in the east side span between the hold-down and the cable hood where the cable passes through the sidewalk. The cable was opened at six wedge lines. As previously mentioned, the cable was unwrapped and opened over an approximate length of 20 ft. between the cable-hold down at PP 65 and the cable sidewalk hood. The wires were found to be in better condition than the previous two locations, with roughly one-half of the wires being Stage 3. The number of Stage 4 wires was approximately one-third of the total wires and they were primarily confined to the outer layers of the cable. Three Stage 4 wire samples were removed from this location and all sampled wires were repaired. No broken wires were observed during the inspection. Figure 4.14 shows the condition of the cable along wedge line 5.

Based on the information in the 1993 Field Inspection Report, this location was supposed to encompass Cable Site A from the previous cable inspection windows. The 1993 report indicated that after the inspection was complete, the wires were cleaned and coated with liquid zinc. The report also noted that a galvanized metal sleeve was installed over the wrapping at Window A to discourage vandalism. The daily inspection report, prepared by ARCADIS on November 15, 2012, mentions the contractor removing sheet metal from around the cable. Figure 4.15 shows a photograph of the unwrapped cable at Primary Cable Opening Location East 65, North where remnants of the liquid zinc applied to the cable window in 1993 can be seen.

Figure 4.14- Primary Cable Opening Location East 65, North

Figure 4.15 – Cable Window from Previous Inspections

4.4 Optional Cable Opening Location PP 31 – PP 32, North

This was the fourth and last panel to be inspected (November 16, 2012). The cable was opened along six wedge lines. Even though this panel is located adjacent to the low point of the main span, it was by far in the best condition of all the locations that were inspected. Approximately two-thirds of the wires were Stage 2 with less than 10% of the wires observed at Stage 4. This was the only location where Stage 1 wires were observed at approximately 1% of the total. Four sample wires, one Stage 1, two Stage 2 and one Stage 3, were removed from this location. No broken wires were found at this location and all of the sampled wires were repaired. Figure 4.16 shows the condition of the cable along wedge line 1.

Figure 4.16- Optional Cable Opening Location PP 31 – PP 32, North

4.5 Wire Condition Summary

Table 4.1 summarizes the percentage of wires at each stage of corrosion in the cable for each of the inspection locations. Table 4.2 shows the number of wire samples removed from the cable during inspection as well as the recommended number of samples. The number of samples taken at each stage of corrosion are substantially less than the number recommended in Table 2.4.3.5.1-1 of Report 534. In most cases, the number of samples removed was almost an order of magnitude less than the recommended number of samples. Some of the stages of corrosion were not present at all of the cable opening locations, reducing the opportunity for sampling. For instance, Stage 1 corrosion was only found at one location and it represented a very small percentage of the total wires. However, the recommended sample sizes were developed to minimize the error in the calculated cable strength. Sample sizes less than the recommended result in a greater percent error in the calculated cable strength. NCHRP Project 10-57, FY 2000, Structural Safety Evaluation of Suspension Bridge Parallel Wire Cables, which was a precursor to Report 534, presents several graphs of the percent error versus the sample size. These graphs are reproduced below in Figure 4.17 for reference.

Figures 4.18 and 4.19 graphically summarize the condition of the wires for the north and south cable, respectively. Overall, the cable is in fair to poor condition at most locations. Typically, over 80% of the total wires at a given location are Stage 3 or 4, with no Stage 1 wires observed. There is, however, substantial variation in condition from one location to another. At the Optional Cable Opening Location PP 31 – PP 32, less than 10% of the wires were Stage 4 and the majority of the observed wires were Stage 2. However, this location had very few observed Stage 1 wires. No broken wires were observed at any of the locations, which is encouraging. Report 534 indicates that Stage 4 corrosion is usually accompanied by cracked and broken wires. The tensile testing revealed two Stage 4 wires with preexisting corrosion cracks. It is important to note that Report 534 recommends that a minimum of three locations along each cable be inspected during the first internal inspection. The minimum number of inspection locations is intended to increase the probability of detecting cable deterioration. This inspection did not encompass the minimum recommended number of panels and a cable band was not removed, further decreasing the probability that the worst cable condition was captured. The amount of variation between inspection locations warrants some skepticism with regard to applying the factor of safety determined herein to the entire cable. This is especially true due to the limited length of cable inspected.

Location	Percent of Total				No. of Broken Wires
	Stage 1	Stage 2	Stage 3	Stage 4	
Primary Opening, East PP 65, North	0%	16%	54%	30%	0
Optional Opening, PP 31 - PP 32, North	1%	62%	28%	9%	0
Primary Opening, PP 3 - PP 4, South	0%	0%	83%	17%	0
Optional Opening, PP 58 - PP 59, South	0%	0%	41%	59%	0

Table 4.1 – Wire Condition Summary

Location	Stage 1	Stage 2	Stage 3	Stage 4	Total
Primary Opening, East PP 65, North	0	0	0	3	3
Optional Opening, PP 31 - PP 32, North	1	2	1	0	4
Primary Opening, PP 3 - PP 4, South	0	0	2	1	3
Optional Opening, PP 58 - PP 59, South	0	0	1	2	3
Total	1	2	4	6	13
Recommended	10	15	35	60	120

Table 4.2 – No. of Wire Samples Taken by Location

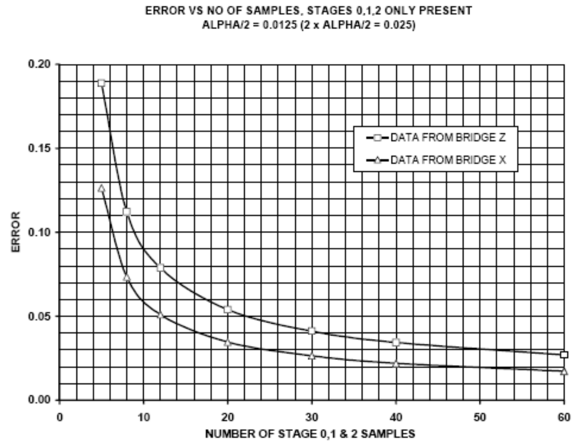


Figure 2.7-2. Error versus sample size for Stage 1 and Stage 2.

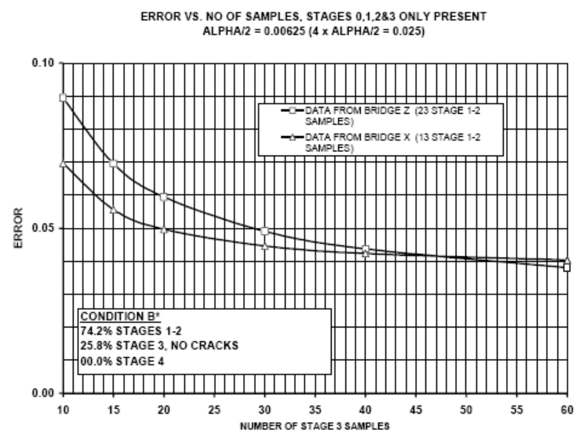


Figure 2.7-3. Error vs. number of Stage 3 samples (25 Stage 1-2 samples).

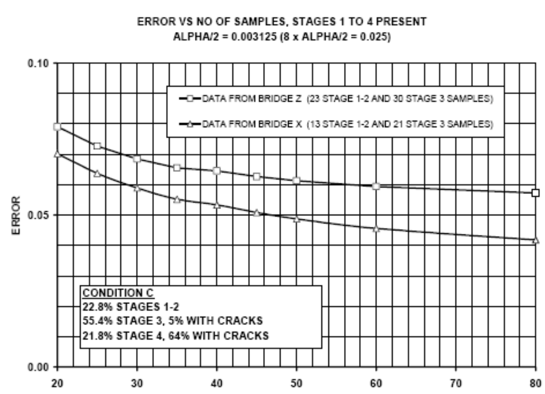


Figure 2.7-4. Error vs. number of Stage 4 samples (25 Stage 1-2 and 35 Stage 3 samples).

Figure 4.17- Error Versus Number of Sample Graphs from NCHRP Project 10-57, FY 2000

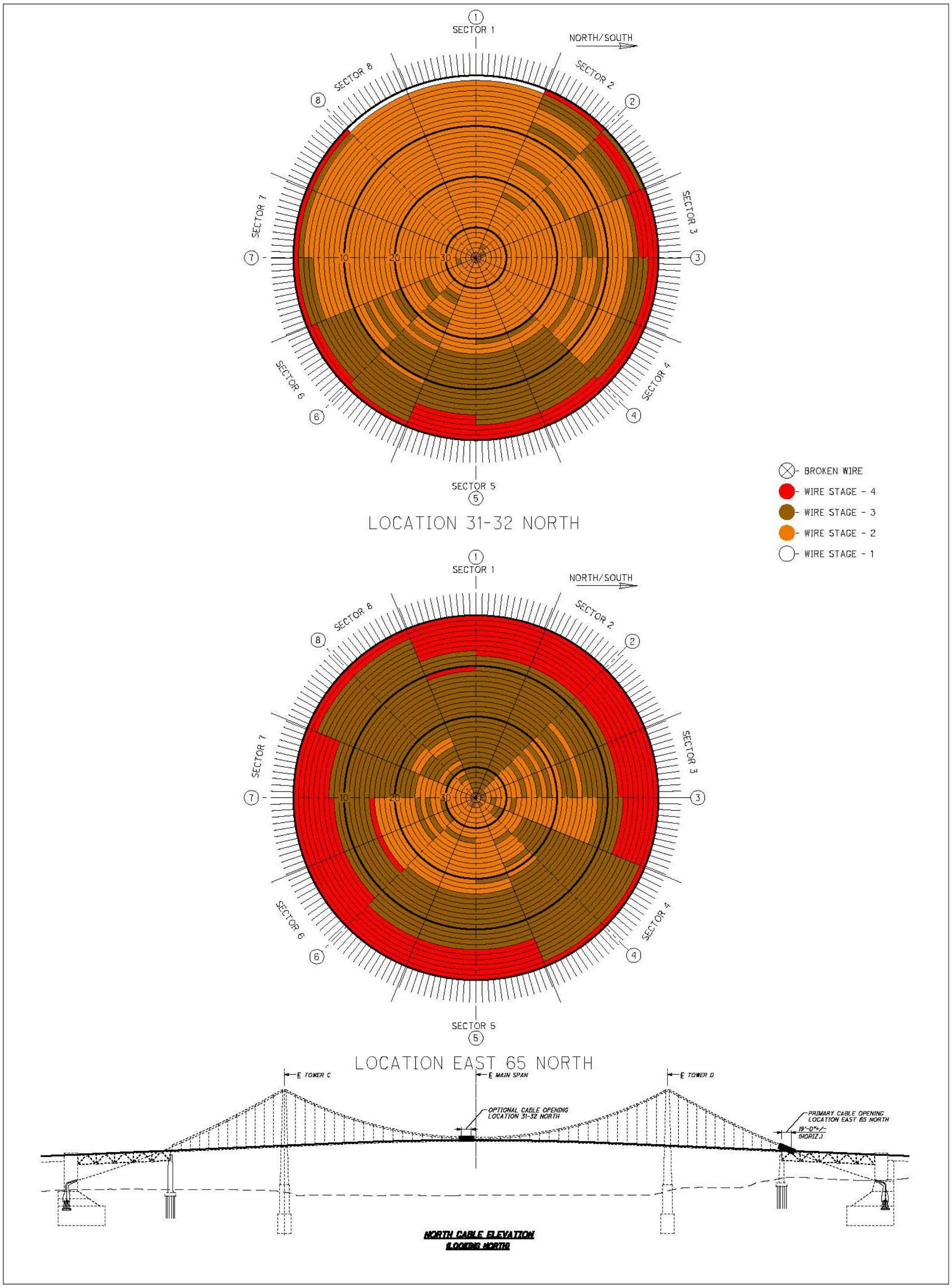


Figure 4.18 – North Cable Wire Condition

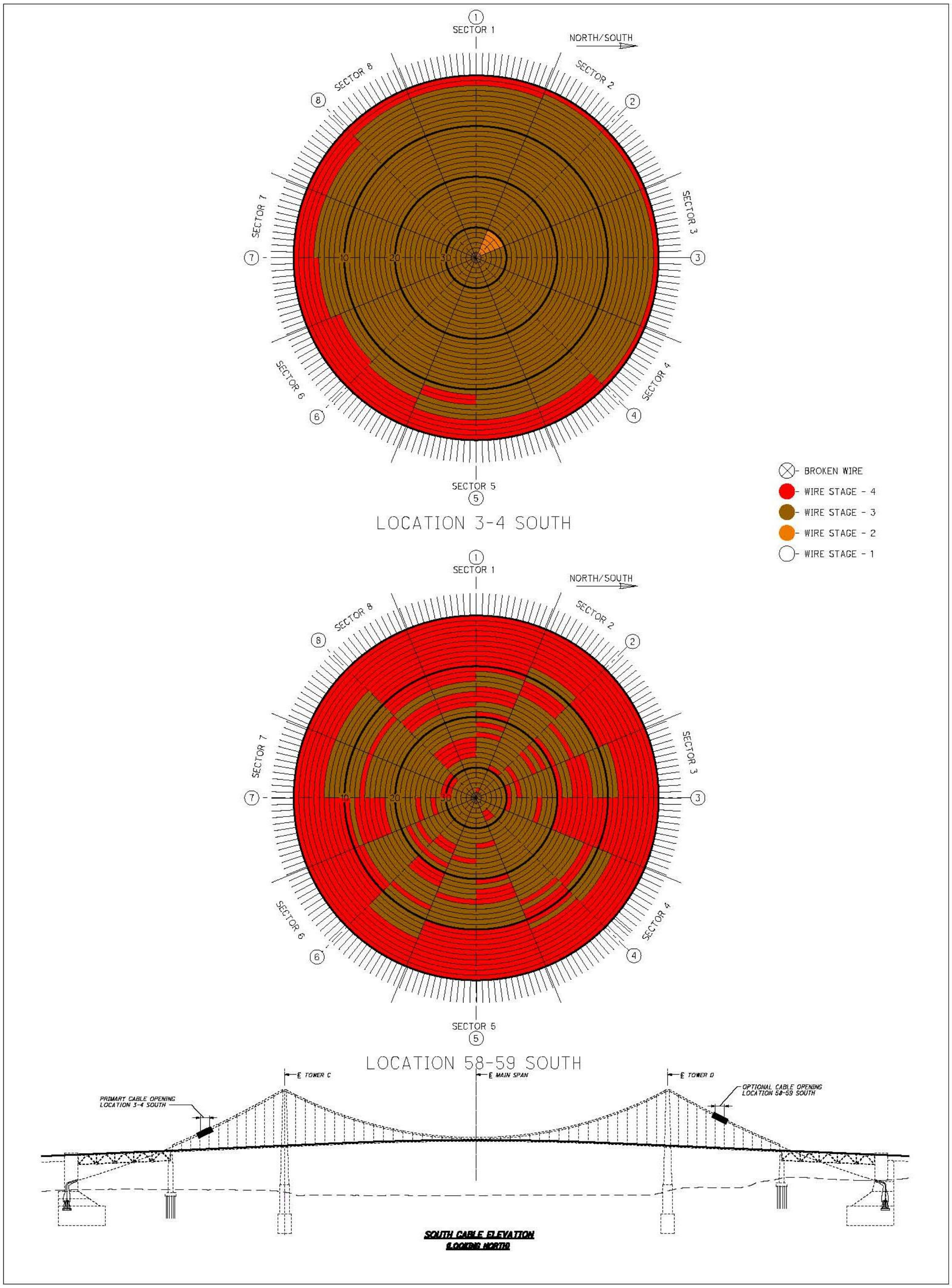


Figure 4.19 – South Cable Wire Condition

5.0 LABORATORY TEST RESULTS

The wire samples taken during the internal inspection were sent to Lucius Pitkin, Inc. for testing under a separate contract. Each wire sample was cut into 16 in. long test specimens. The following tests were conducted to determine the wire properties required for determining the strength of the cable and to assess the condition of the wires. Complete results of all testing are included in Appendix C.

5.1 Tensile Test

Tensile tests were performed in accordance with ASTM A 586 and ASTM A 370 to determine the following:

- breaking load,
- yield strength,
- tensile strength,
- elongation,
- reduction of area, and
- modulus of elasticity.

The scope of work for the project stated that in addition to the tests listed above, wire elongation will be recorded at intervals of tensile force up to maximum force preceding failure. Full stress-strain curves, or force vs. strain curves, will be developed for each specimen. After the testing was complete, it was determined that the data for the full stress-strain curves was not collected. Without the ultimate strain at failure, the calculations for the Limited Ductility Strength Model cannot be performed. The evaluation proceeded using the Simplified Strength Model and the Brittle Wire Model.

Testing was performed using a universal testing machine, shown in Figure 5.1. Force and displacement data were collected while the specimens were loaded and stress-strain curves were developed to just beyond the 2% offset for yield strength. Strains beyond this point were not recorded. Stresses were calculated based on the nominal ungalvanized wire diameter of 0.192 in. The properties of the individual specimens were then used to determine the minimum ultimate wire strength over one panel.

Figure 5.1– Tensile Test Setup

The tensile tests were also used to determine the number of specimens with pre-existing cracks. Uncracked wires fail in a ductile manner, achieving strains of about 4%. A typical stress-strain curve for an uncracked wire is shown in Figure 5.2. Their failure surface shows a reduction in the wire diameter at the failure location (necking) along with a "cup and cone" failure surface, as shown in Figure 5.3. Wires with cracks were identified by both their sudden failure at relatively low strains and their ragged failure surface, shown in Figure 5.5. Since the stress-strain curves were not generated to failure, the lower strains associated with cracked wires are not apparent in Figure 5.4. The low elongation in a 10-inch length combined with the lower ultimate tensile strength, as displayed in the information adjacent to the graphs, point to the possibility that the wire was cracked.

The presence of a crack was confirmed by microscopic analysis of the fracture surface after testing was complete.

From the testing information, the number of cracked samples was found. The percentage of cracked Stage 4 wires in the cable was then assumed equal to the percentage of cracked Stage 4 samples. No cracked Stage 3 wires were identified during the testing. Otherwise, the percentage of cracked Stage 3 wires would be assumed to be 0.33 times the number of cracked Stage 3 samples. Report 534 uses the 0.33 factor to account for the fact that, unlike Stage 4 wires, which are typically near the surface of the cable and therefore easily accessible for taking samples, Stage 3 wires are generally found deeper in the cable. Stage 3 samples, then, usually are taken from the outer region of the cable, where the wires are more likely to be cracked. Thus, without the 0.33 factor, the number of cracked Stage 3 wires would be overestimated.

The results of the tensile tests are summarized in Table 5.1 for typical panels. Note the mean tensile stress never exceeds the assumed specified minimum tensile strength of 215 ksi for cold-drawn suspension bridge wire of this era, and is further reduced for higher levels of corrosion. The results of the cracked wire tests have been separated from the rest, and are distinguished by their low strength and low ultimate strain. Only Stage 4 cracked wires were found during testing and are included in the calculation of the cracked wire properties.

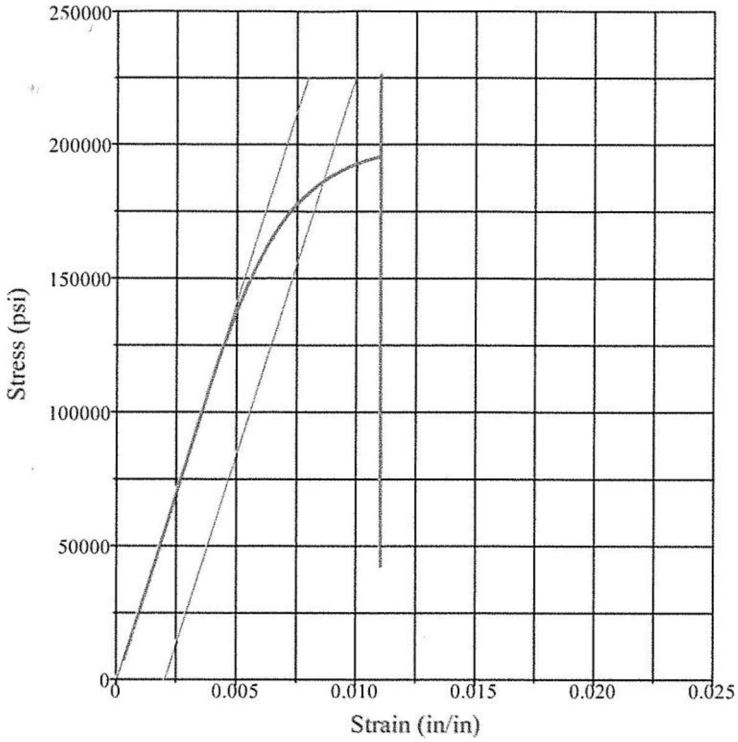
	Stage			
	1 & 2	3	4	Cracked
No. of Specimens	23	23	26	12
Mean Tensile Strength, ksi	210	193	196	199
Mean Ultimate Strain	N/A	N/A	N/A	N/A

* Two Stage 4 cracked wire samples were included in the calculation of the cracked wire properties.

Table 5.1– Summary of Tensile Test Results (Typical Panels)

The tensile test results exhibit some slight inconsistencies from what would be expected. Typically, the mean tensile strength is expected to decrease as the level of corrosion increases. The wire specimens follow this trend between Group 2 (Stage 1 and Stage 2 wires) and Group 3 (Stage 3 wires); however, there is a slight increase in the mean tensile strength in Group 4 (Stage 4 wires) and another slight increase in the mean tensile strength of Group 5 (Stage 4 cracked wires). Although this data does not follow the anticipated trend, the difference is small and can partially be attributed to the small number of samples that were taken. The standard deviation for each group is also quite large, meaning there was considerable variation in the small number of samples. Additional samples may reduce the effects of this variability.

Lucius Pitkin regraded each specimen in the laboratory after the wires were examined in a controlled environment. Past experience with other projects has shown that these inconsistencies can sometimes be eliminated with a more detailed grading performed in the laboratory rather than the grading done in the field. In this particular case, the regrading performed by Lucius Pitken resulted in similar discrepencies between the mean tensile strengths of the wire groups. Therefore, it was decided to use MM's field grading because the wires were graded based on the full exposed length which was greater than the length of the samples sent to the lab for testing.



	Test Results
Specimen Gage Length:	**10.0000** in
Diameter:	**0.1920** in
After Test Diameter:	**0.1500** in
Area:	**0.0290** in^2
After Test Area:	**0.0177** in^2
Correlation Coefficient:	**0.9999**
Tangent Modulus:	**28187** ksi
Tensile Strength:	**226** ksi
Total Elongation:	**4** %
Pretest Punch Length:	**10** in
Posttest Punch Length:	**10.378** in
Reduction of Area:	**39** %
Peak Load:	**6551.2000** lbf
Load at Offset:	**5398** lbf
Stress at Offset:	**186** ksi
Proportional Limit:	**4242.1000** lbf

Specimen 13-6

Figure 5.2– Uncracked Wire Stress-Strain Curve

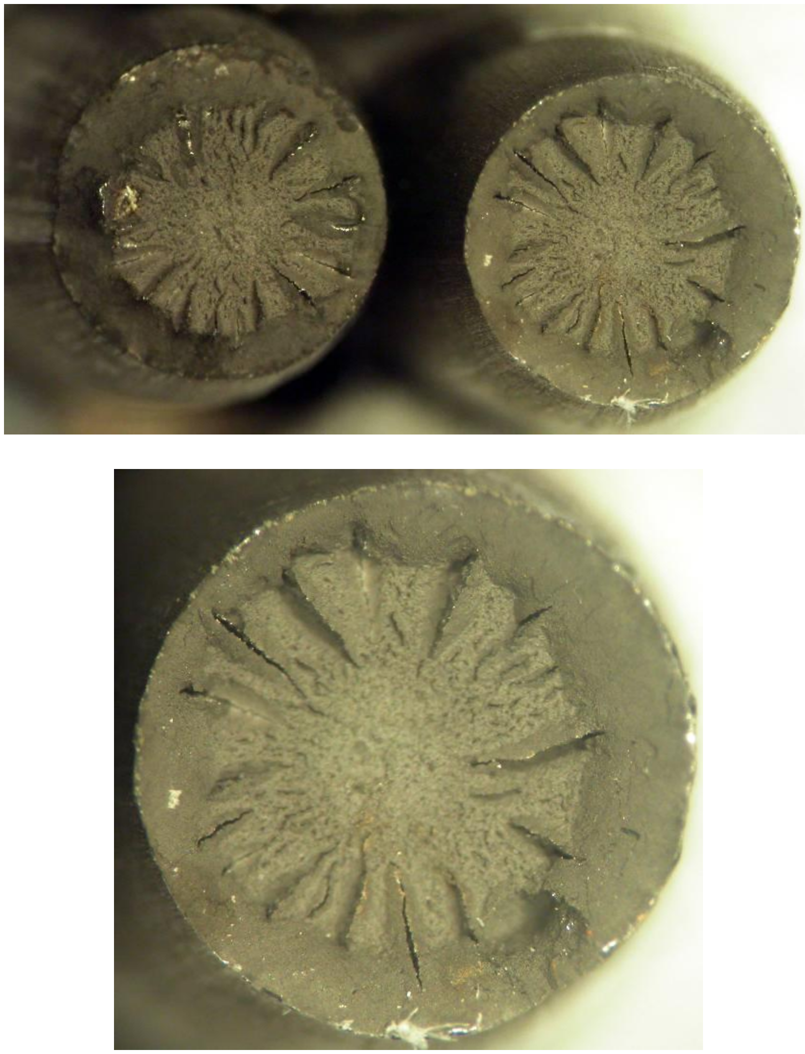
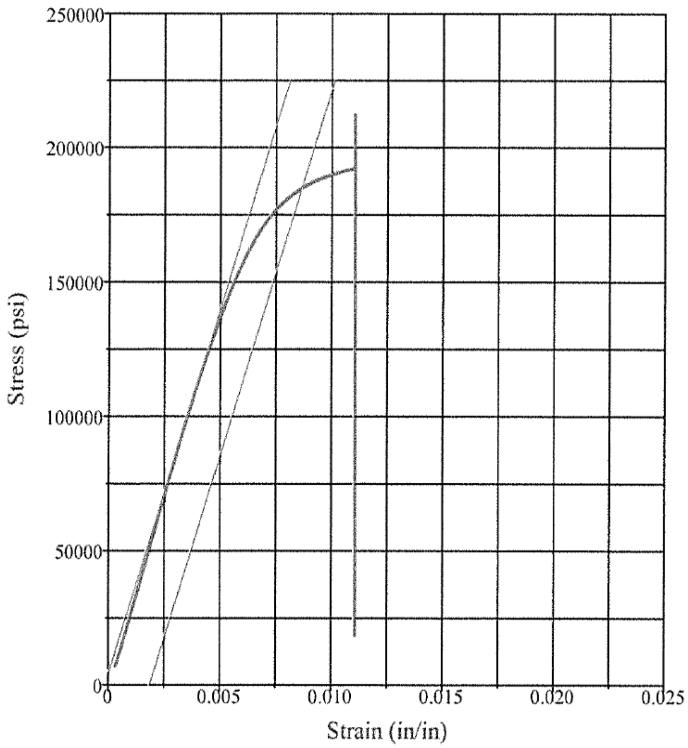


Figure 5.3– Ductile Failure (Cup and Cone)



	Test Results
Specimen Gage Length:	**10.0000** in
Diameter:	**0.1920** in
After Test Diameter:	**0.1800** in
Area:	**0.0290** in^2
After Test Area:	**0.0254** in^2
Correlation Coefficient:	**0.9998**
Tangent Modulus:	**27116** ksi
Tensile Strength:	**212** ksi
Total Elongation:	**1** %
Pretest Punch Length:	**10** in
Posttest Punch Length:	**10.076** in
Reduction of Area:	**12** %
Peak Load:	**6159.8000** lbf
Stress at Offset:	**185** ksi
Load at Offset:	**5368** lbf
Proportional Limit:	**4301.8000** lbf

Specimen 3-3

Figure 5.4– Cracked Wire Stress-Strain Curve

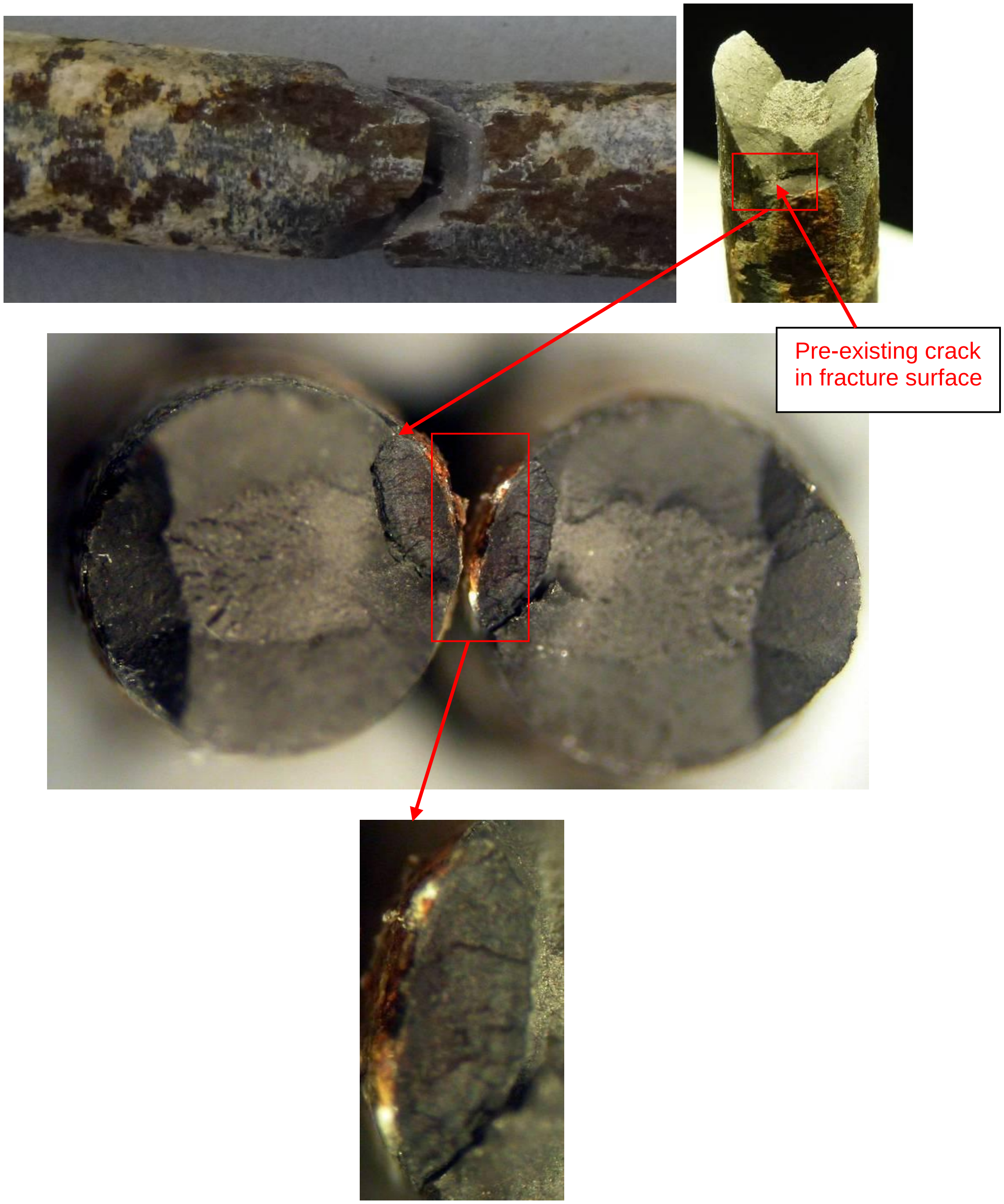


Figure 5.5– Brittle Failure

5.2 Fatigue

Fatigue testing was not performed on the wire samples.

5.3 Chemical Composition

Report 534 recommends that chemical composition be determined for wires whose composition is unknown. Five wires are recommended for testing to provide a record for future inspections. Chemical composition analysis needs to be performed only once over the life of the bridge, as the chemical makeup of the wire will not change over time. The amount of variation in chemical composition is indicative of the quality control exercised during manufacturing, and may explain any variation in the results of tensile testing.

ODOT opted to forgo the chemical composition testing during this cable opening.

5.4 Weight of Coating

The weight of coating test, ASTM A90, is used to measure the average weight of zinc coating remaining on the Stage 1 and 2 wires. The specimens are weighed, the zinc coating is removed (using some type of hydrochloric acid solution), and the specimens are weighed again. This information, collected over a period of time, can be used to estimate when the coating will be depleted.

ODOT opted to forgo the weight of coating tests during this cable opening.

5.5 Preece Testing

Preece testing is used to determine the variability of the remaining zinc coating on Stage 1 and 2 wires. Here the specimens are dipped into a copper sulfate solution multiple times. The solution attacks the coating, and, after the coating has worn away, leaves a copper deposit on the wire, simplifying identification of regions of greatest zinc loss.

ODOT opted to forgo the preece testing during this cable opening.

5.6 Hydrogen Embrittlement Tests

Hydrogen embrittlement testing is conducted to determine whether any residual trapped hydrogen within the cable wire samples is sufficient to affect their strength and fracture behavior. Tests were performed in accordance with ASTM F 1624. The samples susceptibility is determined by measuring the threshold for stable crack growth.

ODOT opted to forgo hydrogen embrittlement tests during this cable opening.

Since much of the supplemental testing was not performed, it is difficult to draw conclusions regarding the cable wire and corrosion. It is worth noting that in their report, LPI stated that the wires sustained corrosion attack with partial or complete depletion of the zinc coating and exhibited formation of corrosion products. The report also states that wires with Stage 4 corrosion exhibited fracture surfaces with non-circular cross-sections where the fracture started from surface corrosion pits. Based on the field inspection and the findings of the laboratory report, it would appear that the protection provided by the zinc coating has been consumed at certain locations of the cable and no further corrosion protection is available.

6.0 CABLE STRENGTH CALCULATION PROCEDURE

Once the cable had been inspected and laboratory testing completed, cable strength was calculated for each location as follows, in accordance with the referenced section of Report 534:

1. The total number of wires at each stage of corrosion was estimated per Section 4.3.2,
2. The total number of broken wires was estimated per Section 4.3.3,
3. Wires were sorted into groups and the number of cracked wires was estimated per Sections 4.4.1 and 4.4.2,
4. The properties of the wires composing each group were calculated in accordance with Section 4.4.3,
5. The wire redevelopment length was calculated per Section 4.5.2,
6. The cable capacity was then calculated using one of the three models described below and presented in Section 5 of Report 534.

The wires are divided into the following groups for calculating cable strength:

Group 1: samples exhibiting Stage 1 corrosion, if needed,
Group 2: samples exhibiting Stage 1 and/or Stage 2 corrosion,
Group 3: samples exhibiting Stage 3 corrosion that are not cracked,
Group 4: samples exhibiting Stage 4 corrosion that are not cracked,
Group 5: samples exhibiting Stage 3 and 4 corrosion that are cracked.

Typically, the properties of Stage 1 and Stage 2 wires are similar enough that both are designated as Group 2 wires, to simplify the calculations, and this was the case here.

The properties of the test specimens determined from the tensile tests were used to establish the ultimate strength of the wires composing each group per Section 4.4 of Report 534, as follows:

1. The ultimate strength data of all of the specimens composing a sample wire were collected,
2. The mean and standard deviation of their ultimate strengths were calculated,
3. The probable minimum ultimate strength of a length of wire equal to the cable band spacing was calculated,
4. This was repeated for all samples of a group and the mean and standard deviation of the probable minimum ultimate strength was calculated for that group,
5. The mean and standard deviations were then used to determine the Weibull distribution for the ultimate strength of each group,

For all models, the condition of any wire is assumed the same in adjacent panels as in the panel being evaluated. It is also assumed that wires at a given stage in the evaluated panel will break before wires at the same stage or better in adjacent panels. Thus, all uncracked wires are assumed to fail in the panel being evaluated. The three models used to estimate the strength of the cable at the inspected locations are called brittle wire models, as they assume that individual wires fail in a sudden, brittle manner when the stress or strain in the wire reaches a certain level. All unbroken wires are assumed to share equally in carrying the applied load. The first two models are based on stress, the third on strain. Since the ultimate strains were not reported, the strength could not be calculated based on the third model. A discussion of this model is included in this report for completeness.

6.1 Simplified Strength Model

This model is a simplification of the Brittle Wire Model, described below. Cracked and broken wires are assumed not to contribute to the strength of the cable. It is therefore, conservative and may underestimate the strength of the cable by up to 20%. Because it neglects broken and cracked wires, it should be used only where their estimated number is no greater than 10% of the total.

6.2 Brittle Wire Model

The Brittle Wire Model assumes that all of the wires have the same stress-strain curve, thus, all of the wires will have the same stress and carry equal portions of the applied load. A wire is assumed to fail immediately upon reaching its ultimate stress, at which time its share of the force is transferred equally to the remaining wires. In reality, the uncracked wires will deform plastically prior to fracture, allowing further development of the cable strength, making this model somewhat conservative.

The cable strength is calculated by first assuming a stress in the cable. The number of broken wires in each group is calculated using the cumulative Weibull distribution function of the tensile strength for that group. The assumed stress is then multiplied by the area of the remaining wires and estimates of the force in wires broken in other panels and redeveloped in the panel under consideration are added to determine the total force in the cable. The assumed stress is then varied until the maximum cable force is found. This is the estimated cable capacity. Excel's Solver add-on is used to automate this process.

Wires that are broken in adjacent panels are redeveloped in the panel under investigation through friction. Once a wire breaks, the force in that wire at the location of the break is zero. However, due to friction developed between the broken wire and those adjacent to it, the force in the wire gradually increases until it is the same as that in the surrounding wires. This friction develops due to the confining force exerted on the cable by both the wrapping wire and the cable bands.

For simplicity, Report 534 conservatively assumes that all redevelopment occurs at cable band locations, as shown in Figure 6.1. The number of cable bands required to redevelop a wire is calculated based on the size of the gap between the ends of broken wires or those cut for samples and the service force in the cable, in accordance with Section 4.5 of the Report 534. This is then used to determine the number of panels required to redevelop the wire to 95% of the mean strength of Group 2 wires on both sides of the break. This is the development length, that is, the number of panels over which a broken wire will affect the strength of the cable at the panel under investigation. For example, the cable shown in Figure 6.1 requires three cable bands to redevelop the wire, with each band developing 1/3 of the wire force. The resulting development length is five panels. For the Anthony Wayne Bridge suspended spans, four cable bands are required to redevelop a wire, resulting in an effective development length of seven panels.

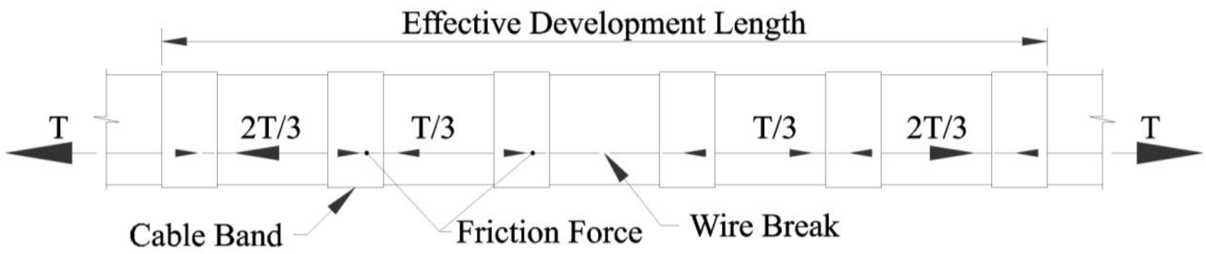


Figure 6.1 – Wire Redevelopment

The backstays were originally designed without cable bands. The spacing between the cable band at the hold-down and the cable collar at the anchorage saddle is approximately 203.75 ft., which is much larger than that of the suspended span cable bands. This increases the conservatism in the assumption that the wrapping wire does not contribute to redevelopment, as the relative amount of redevelopment contributed by the wrapping wire increases with cable band spacing and decreases with cable band size. However, for the sake of simplicity, and to minimize modifications to the Report 534 procedure, the contribution of the wrapping wires was neglected. At Primary Cable Opening 65 East, North, the resulting wire development length was calculated to be the full-length of the backstay.

The estimated force in wires broken in adjacent panels consists of two components. The first is the force in wires that are assumed to be broken in other panels over the redevelopment length. Since adjacent panels were not inspected, they were assumed to have the same number of broken wires as the inspected panel. No broken wires were found during the inspection, so this component does not affect the force. The second component is the force redeveloped in cracked wires that break as the stress in the cable is increased to the assumed value. Here again, adjacent panels within the redevelopment length were assumed to contain the same number of these as the panel being evaluated.

In the backstay location, a 20 ft. length of cable was inspected, much less than the actual spacing between the cable band at PP 65 and the cable collar at the anchorage saddle. No broken wires were observed at this location. However, if broken wires were observed the number of broken wires over the entire panel would be estimated by assuming the portion of the panel not inspected has the same number of breaks per unit length as the inspected portion.

6.3 Limited Ductility Model

The Limited Ductility Model assumes that a wire fails upon reaching its ultimate strain. The general form of this model accounts for individual differences in the stress-strain curves of the specimens tested, and must be used whenever there is appreciable variability in the experimental data. The special case of this model assumes that all wires have the same stress-strain curve, greatly simplifying the calculations. Because the consistency of the wire properties is not known from the start, this model cannot always be included in the calculations. Additionally, the laboratory testing did not include the ultimate strain at failure thereby eliminating this model from the calculations. A description of this model is provided for completeness.

The procedure for calculating cable strength is similar to that of the Brittle Wire Model; only an initial strain is assumed and varied rather than stress. The number of broken wires in each group is calculated using the cumulative Weibull distribution function of the ultimate strain. The stress in the cable is then determined using the wires' assumed stress-strain curve. Like the Brittle Wire Model, this stress is then multiplied by the area of the remaining wires and estimates of the force in wires broken in other panels and redeveloped in the panel under consideration are added to determine the total force in the cable. The assumed strain is then varied until the maximum cable force is found. This is the estimated cable capacity. Excel's Solver add-on is again used to automate this process. Wire redevelopment is treated in the same manner as the Brittle Wire model, and the same modifications would be required to the Report 534 procedure at Primary Cable Opening East PP 65, North.

The Modified Ramberg-Osgood Function, used to determine the stress in the wires at a given strain, is calculated as follows:

$$f_p = E\varepsilon_{pf}\left[A + \frac{1-A}{\left[1 + \left(B\varepsilon_{pf}\right)^C\right]^{1/C}}\right]$$

where:

f_p	= wire stress
E	= wire modulus of elasticity
ε_{pf}	= wire strain
A, B, and C	= constants

The available stress-strain curves for a number of specimens were plotted along with the calculated curve and the constants varied to approximate the calculated curve to the actual curve. The following constants were found to result in the best approximation of the data to the 2% offset:

A:	0.031
B:	145
C:	4

Figure 6.2 shows the resulting curve obtained from the limited data available.

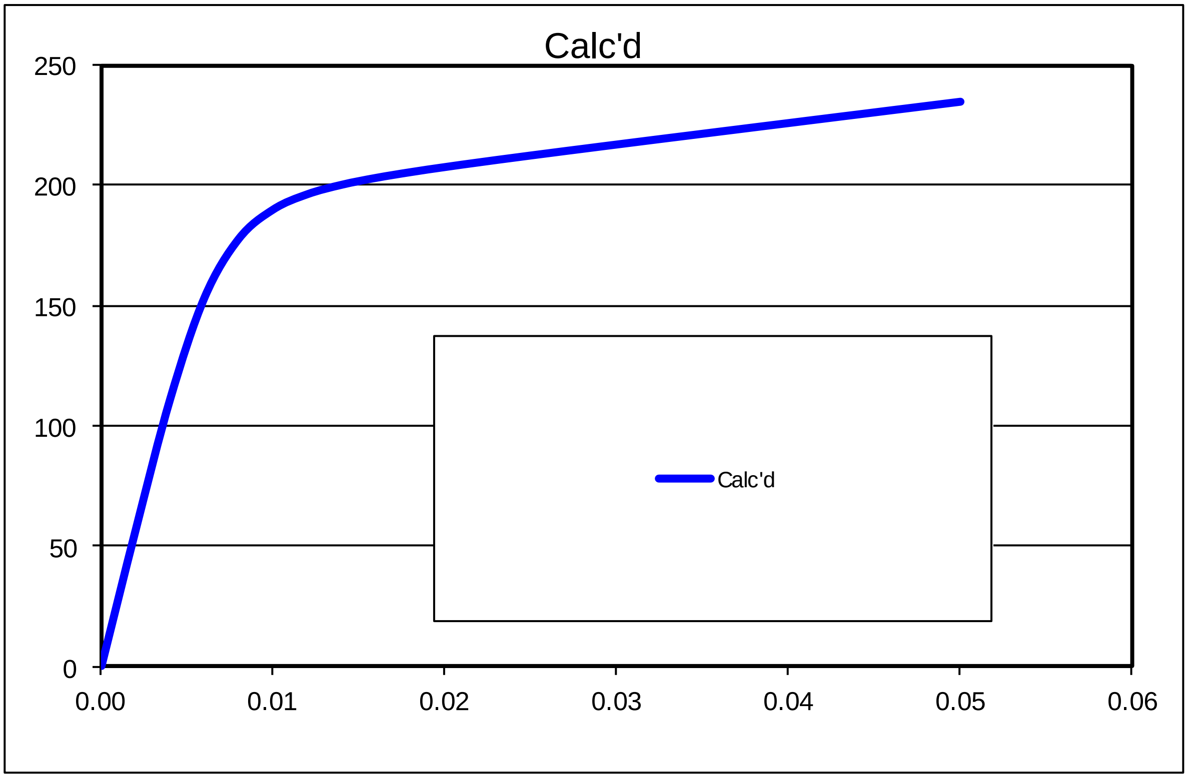


Figure 6.2 – Stress-Strain Curve

7.0 CABLE STRENGTH CALCULATION

The calculated cable strength at each location is shown in Table 7.1 in kips, for the Simplified and Brittle Wire strength models, along with the as-built capacity and percentage reduction. It is important to note that the estimated percent of cracked wires at all locations except Optional Opening PP 31 – PP 32, North exceeds 10%, thereby making the Simplified Strength Model overly conservative and no longer applicable. At Optional Location PP 31 – PP 32, North, the estimated percent of cracked wires is 9% which is at the upper limits for this model to provide reasonable results. At two locations, the reduction in cable capacity from the as-built condition is about 10% or less, based on the Brittle Wire Model. The reduction is due primarily to corrosion of the cable wires, since no broken wires were found. The locations with a reduction greater than 10% are Primary Opening PP 3 – PP4, South and Primary Opening East PP 65, North. Optional Opening PP 58 – PP 59, South has the highest degree of corrosion of the locations investigated, but the second highest strength. This is due in part to the increase in the mean average strength between Group 3 and Group 4 wires. While the mean tensile strength of Group 3 wires is 193 ksi and 196 ksi for Group 4, the percentage of Group 3 wires is much greater at Primary Opening PP 3 – PP4 and the percentage of Group 4 wire is much higher at Optional Opening PP 58 – PP 59, South, slightly skewing the results. Primary Opening East PP 65, North has less corrosion, but a long length without cable bands. The reduction in strength at location 65 East, North, was partially due to the large spacing without cable bands and the conservative assumptions used to modify the procedure of Report 534.

Location	Simplified Strength		Brittle Wire	
	Cap. (kips)	% Reduction	Cap. (kips)	% Reduction
As - Built	17,800		17,900	
Primary Opening, East PP 65, North	10,000	43.82%	14,400	19.55%
Optional Opening, PP 31 - PP 32, North	15,100	15.17%	16,600	7.26%
Primary Opening, PP 3 - PP 4, South	12,600	29.21%	15,200	15.08%
Optional Opening, PP 58 - PP 59, South	6,700	62.36%	16,000	10.61%

Table 7.1 – Cable Strength Summary

Table 7.2 shows the actual cable forces and the factors of safety at each location, for the Simplified and Brittle Wire strength models, for both the as-built and as-inspected cable strength. The Limited Ductility strength model factor of safety could not be calculated because the laboratory testing did not include the ultimate strain at failure. Cable forces were determined using a two dimensional in-house analysis software using a direct software implementation of the deflection theory of suspension bridges for the AASHTO Service IV load combination of D+L+T (Dead Load + Live Load + Temperature), using three lanes of HS20 live load. The dead load used in the analysis was taken from the original contract plans and modified to reflect modifications to the superstructure including the reductions due to the future redecking with lightweight concrete. Temperature forces are due to a temperature decrease of 80 degrees Fahrenheit.

The factor of safety at each location is simply the cable strength divided by the force in the cable at that particular location, also given in Table 7.2.

Section 6.4 of Report 534 recommends that immediate remedial action be taken whenever the safety factor is found to be less than 2.15. For the Anthony Wayne Bridge cables, this corresponds to a reduction in the as-built cable strength of about 22% and a further reduction from its rehabilitated condition of about 11%.

Location	Cable Tension (kips)	Simplified Strength Factor of Safety		Brittle Wire Factor of Safety	
		As-Built	As-Insp.	As-Built	As-Insp.
Primary Opening, East PP 65, North	5,984	2.97	1.67	2.99	2.41
Optional Opening, PP 31 - PP 32, North	5,712	3.12	2.64	3.13	2.91
Primary Opening, PP 3 - PP 4, South	6,241	2.85	2.02	2.87	2.44
Optional Opening, PP 58 - PP 59, South	6,422	2.77	1.04	2.79	2.49
Controlling		2.77	1.04	2.79	2.41

Table 7.2 – Factor of Safety Summary

8.0 CABLE BAND BOLT RETENSIONING

The cable bands are steel castings that hold the suspenders in place over the cable. They consist of two cylinder halves bolted together over the circumference of the cable. The number of bolts per cable band is dependent on the slope of the cable at the suspender attachment point. The friction from clamping against the cable provides the force that prevents the band from sliding down the cable. The steeper the cable, the more bolts are needed to prevent this sliding. In addition to their ability to transfer the tangential component of the suspender force to the cable without slipping, bolt tensions affect the capacity of the cable band to redevelop cable force in broken wires. Because the tension in the cable band bolts decreases with time due to creep of the zinc coating on the wires and/or gradual compaction of the cable, the bolt tensions are usually determined for assessing reliability against band slippage. Based on measurements taken from other suspension bridges, the loss may average as much as 65% of the original tension. While this aspect of the work is not directly related to cable capacity, it is useful to know the cable band bolt clamping force and the friction among wires that it may generate.

Initially, the bolts in the cable bands adjacent to the evaluated panels in the suspended span (six cable bands), as well as, the hold-down cable band at Panel Point 65, were specified to be measured to determine their tension and then retensioned to a minimum of 54,000 pounds. This installation force was taken from the original 1930 shop drawings.

During a field visit, the Contractor noted that the cable bands and bolts had been metalized and indicated that this would cause problems in measuring the cable band bolt tension. His concern was that the metalizing would bind the nut and prevent the loosing and re-tightening required to retension the bolts. It was the Contractor's opinion that the bolts should be replaced, or at a minimum, a supply of new bolts should be available in case problems arose during the retensioning process. Due to the lead time involved in obtaining the specialized bolt, the Contractor could not obtain a sufficient supply in the time frame allotted to complete the project. After discussing the situation with ODOT, it was decided that the cable band bolt tension would not be checked as part of this cable opening contract.

9.0 CONCLUSIONS

The investigation showed the cables to be in fair to poor condition for a bridge of this age, with a factor of safety of 2.41 for the north cable and 2.44 for the south cable, based on the Brittle Wire Model. It is important to note that the minimum calculated cable factor of safety of 2.41 is based on the rehabilitated condition. In the current condition, without the lightweight deck, the factor of safety would be approximately 2.31. The factor of safety for the rehabilitated bridge is above the 2.15 action level referenced in Report 534. However, this factor of safety was developed with smaller sample sets and fewer openings than the minimum recommended by Report 534. Therefore, the percent error in the safety factor is greater than would be expected if the recommendations of Report 534 had been followed.

The reduction in the factor of safety is primarily due to the condition of the cables, which exhibit a significant amount of corrosion at some locations. While the cables did exhibit significant corrosion, no broken wires were observed during the inspection. Based on the results of investigations conducted on other bridges, it would not be unexpected that cables of this age would have a factor of safety at or below 2.5. The current factor of safety is also less than the 2.6 currently used for most new bridge design. Based on the current condition of the cables and the scheduled maintenance repairs for the bridge, it is recommended that some type of remedial action be considered in the near future.

The results from the wire testing yielded some anomalies. First, the Stage 1 and Stage 2 wires (Group 2) had a mean tensile strength of 210 ksi, which is lower than the 215 ksi that would be the expected minimum tensile strength of cold-drawn bridge wire from this era. This may be due to a deficiency of Stage 1 wire in the Group 2 properties. Stage 1 wire was deficient in the population of observed wire during the cable inspection. This may also point to something with the original wire used for construction. Additional testing of the wires may provide a better understanding. Additionally, the Group 4 (Stage 4) and Group 5 (Stage 4 cracked wires) mean tensile strengths were slightly higher than the Group 3 wire properties. The increases are small and have a small affect on the cable strength. There was, however, a significant drop between the mean tensile strength of Group 2 and Group 3 wires. These irregularities may point to insufficient sample sizes which can skew the statistical analysis.

It is also important to keep in mind that the two locations per cable chosen for this investigation constitute less than 3% of the total cable length. There is a very high likelihood that the worst location was not found, especially given the wide variability in the condition of the cables among the locations inspected. However, it is likely that the controlling location would not have a safety factor low enough to pose a concern.

10.0 RECOMMENDATIONS

Section 2.2.5.4 of Report 534 states that when more than 10% of the wires in a cable panel are found to be Stage 4 in any inspection, the cable should be scheduled for a full internal inspection, and remedial action, such as the introduction of corrosion inhibitors, should be taken. Installation of an acoustic monitoring system is strongly recommended to listen for and locate continuing wire breaks. Based on the guidelines given in Section 2 of Report 534, we recommend the following:

- Based on the amount of Stage 4 corrosion observed during the inspection, a minimum of six additional locations per cable should be inspected in the near future (< 2 years). As part of the inspection,
    - A cable band should be removed on each cable,
    - At a minimum, a long (~half) segment in one of the backstays should be included as one of these locations. The backstays do not have cable bands, so the wrapping wire should be removed and reapplied in increments as the inspection proceeds. The addition of several cable bands should also be considered in the backstays.
    - Additional wire samples should be taken so that statistically valid samples of each stage of corrosion are obtained,
    - The wires in the tower saddles should be inspected and the saddles should be sealed to ensure that water does not infiltrate the cables at their appex,
    - Cable band bolts should be checked and retensioned during the next internal inspection. As previously discussed, the metalizing on the existing cable band bolts may cause problems in checking the existing tension and retensioning the bolts. New cable band bolts should be ordered in anticipation that the existing bolts will need to be replaced. If the cable band bolt tension is significantly reduced, ODOT may want to consider checking the tension in all of the cable bands,
    - If severe corrosion is found to be widespread within the cable based on the six additional openings, ODOT should inspect additional locations or possibly the entire cable length.

- Cable oiling and/or the introduction of corrosion inhibitors into the cable should be considered,
- The acoustic monitoring of the bridge should continue. ODOT and MISTRAS should verify that the system is operating correctly. The system should have captured the acoustic emissions from the wire sampling process, which can be used to verify the systems ability to detect wire breaks. The system should be updated and reconfigured as required. Additional information collected from the monitoring going forward can be used in determining future inspection locations,
- Continue with all practical measures to prevent intrusion of water. Plans are already being made to replace the existing elastomeric wrap. ODOT may also want to consider cable dehumidification as an option to prevent future corrosion in conjunction with the elastomeric cable wrap replacement.

The backstays should be given special attention since they have the lowest factor of safety. Inspecting a larger length panel of at least one backstay will enable a better estimate of cable strength to be made at this location. Inspecting an adjacent backstay would also be beneficial, to verify its condition. Because the wrapping wire is the primary means of wire redevelopment for the backstays, these panels should be inspected in three or four segments, with the wrapping wire removed only for the segment being inspected. Work should begin at the highest point on the panel and proceed down slope.

At this time, additional cable bands may also be installed on the backstays to limit the influence of broken wires to a shorter length of cable. It is important to keep in mind that those additional cable bands will only aid in the redevelopment of wires that break after their installation and as such should be installed while the number of broken wires likely is still small.

In calculating cable strength at the backstay locations, further modifications may be made to the Report 534 procedure to more accurately reflect differences from the conditions assumed in the report at these locations. Most notably, the contribution of the wrapping wire-to-wire development may be accounted for, greatly reducing the wire development length.

The above recommendation regarding the acoustic monitoring system shall be done as soon as practical as there seems to be some question whether the system is continually monitoring both cables. The more data that can be collected, the more likely the critical location(s) along the cables will be chosen for the next internal inspection. Detecting any weak spots early could prevent an unpleasant surprise in the future, which would require immediate and costly mitigation.

Based on the 2008 inspection report, the existing neoprene wrap is compromised in several locations. These regions should be monitored and repaired to prevent the intrusion and/or retention of water until the elastomeric wrap is replaced. Due to the level of corrosion, it would not be prudent to delay any measures that can prevent water infiltration.

11.0 REFERENCES

1. R.M. Mayrbaurl, and S. Camo. *Guidelines for Inspection and Strength Evaluation of Suspension Bridge Parallel Wire Cables*. NCHRP Report 534, Transportation Research Board, Washington, D.C., 2004.
2. *Flint and Neill Partnership Technical Audit of the Main Cable Inspection and Assessment: Final Report*. Scottish Executive Publications. http://www.scotland.gov.uk/Publications/2006/03/03154220/0 .Accessed July 30, 2007

APPENDIX A – ANTHONY WAYNE BRIDGE ACOUSTIC EMISSION MONITORING REPORT (MISTRAS)

APPENDIX B – INTERNAL CABLE INSPECTION DATA

Wire Condition Data Sheets

Cable Corrosion Plots

Daily Inspection Reports

Wire Condition Data Sheets

PRIMARY CABLE OPENING LOCATION PP 3 – PP 4, SOUTH

MODJESKI and MASTERS
Experience great bridges.

OPTIONAL CABLE OPENING LOCATION PP 58 – PP 59, SOUTH

PRIMARY CABLE OPENING LOCATION EAST 65, NORTH

MODJESKI and MASTERS
Experience great bridges.

OPTIONAL CABLE OPENING LOCATION PP 31 – PP 32, NORTH

Cable Corrosion Plots

Daily Inspection Reports

APPENDIX C – EVALUATION OF MAIN CABLE WIRES – ANTHONY WAYNE BRIDGE (LUCIUS PITKIN, INC.)

APPENDIX D –CABLE STRENGTH CALCULATIONS