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ATLSS Report No. 04-24

November 2004

ATLSS is a National Center for Engineering Research
on Advanced Technology for Large Structural Systems

117 ATLSS Drive
Bethlehem, PA 18015-4729

Phone: (610)758-3525
Fax: (610)758-5902
www.atlss.lehigh.edu
Email: inatl@lehigh.edu

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Research Engineer
ATLSS Engineering Research Center

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1.0 Introduction

The report summarizes the work that has been done at the ATLSS Center at Lehigh University to investigate the collapse of a 20-foot tall galvanized cantilevered sign structure. The collapse was the result of a crack at the welded baseplate connection which severed the entire pole section. In addition, a painted cantilevered sign structure, previously removed from service due to excessive vibration, was also examined for any signs of cracking. It was thought that the painted structure did not contain any fatigue cracks prior to this study. Both structures were delivered to the ATLSS Center in Bethlehem, PA for evaluation. The Tasks of evaluating both structures included:

- Task I – Visual inspection of all structural components of both the cracked and uncracked sign structures and documentation of the condition and damage.
- Task II – Metallographic examination at welded connections of the cracked regions.
- Task III – Evaluation of mechanical and chemical properties of the pole material and determination of weld hardness.

The critical fatigue details are at the baseplate connection of the pole, the connection of the mast-arm to the pole (i.e., flange detail), and the handhole detail. Anchor rods are also considered fatigue critical. Loose or cracked anchor rods could cause an uneven distribution of stresses among the anchor rods, and subsequently an uneven stress distribution in the baseplate. The anchor rods however were not included in the investigation.

Visual inspection of the galvanized sign structure revealed that cracks existed at two different details in the structure. The first crack was located at the baseplate detail of the pole, specifically at the upper weld toe connecting the baseplate to the pole. The crack, after substantial growth, resulted in the collapse of the structure. The baseplate was fully separated from the pole when shipped to the ATLSS Center. A second crack was found at the intersection of the connection plates at the flange detail at the mast-arm connection to the pole. Examination of both cracks indicated that fatigue was the mechanism in which the cracks initiated and propagated.

Visual inspection of the painted structure, which was thought to be uncracked, also revealed cracks at two different details in the structure. In this report, the poles referred to as “painted” are the green components in the photographs. ATLSS Researchers specially requested that the painted pole be sent to the laboratory for examination when informed that the pole exhibited significant vibrations under relatively light winds. Previous failures and cracking in similar structures studied by the researchers occurred in structures which exhibited similar behavior. As a result, it was suggested to Penn DOT that this pole be examined as well. Similar to the galvanized structure, the first crack was at the top of the weld toe connecting the baseplate to the pole. The crack at the base plate connection was rather large and was easily observed with the naked eye. The second crack was found at the connection flange detail at the termination of the longitudinal ribs and more difficult to see. Visual examination of the cracked baseplate suggests that fatigue was the cause of the cracking. Visual and metallographic examination of the cracks at the termination of the longitudinal stiffeners were found to be either in the green paint coating (i.e. no cracks in the welds or the base metal) or defects that typically form during the welding process. There was no sign of crack initiation or growth from any of the examined defects.

The cause of fatigue cracking in both structures is attributed to wind induced vibration. Wind induced vibration is usually caused by natural wind gusts, galloping, and/or vortex shedding.

2.0 Visual Inspection of the Structural Components

Prior to examining the cracked surfaces and the fatigue sensitive details, the general condition of the poles and mast arms was documented. Both, the painted and the galvanized structures are shown in Figure 2.1 and Figure 2.2. Figure 2.1 shows the poles, the mast arms, and the connection flange detail, while Figure 2.2 shows the baseplates of the poles.

Figure 2.1 – Components of sign structures delivered to the ATLSS Center
(Poles referred to as "painted" are the green components)

Figure 2.2 – Baseplates of sign poles

2.1 Cracks in Galvanized Structure

Fatigue sensitive details in the structure were thoroughly inspected for any sign of cracking. The cracks found were documented and further examined using fractographic analyses (when possible) to assess the cause of failure as will be discuss in a later section. It is important to mention that "fatigue sensitive details" refer to details that have been known to have poor fatigue resistance and to have exhibited fatigue cracking in other similar structures. It is possible that fatigue might not be the cause of the observed cracking or failure in such details. For example, the surfaces could have been cracked as a result of a strong impact upon the collapse of the structure. Thus, an apparent weld toe crack, although typically characteristic of a fatigue crack, could be due to overload which occurred during collapse. With the exception of the crack-like defect observed at the termination of the longitudinal stiffeners, subsequent examination of all crack surfaces revealed that fatigue was the cause of the observed cracks.

2.1.1 Baseplate

The cracked baseplate of the galvanized structure (Figure 2.2) was stored in a secure area inside the laboratory to assure that corrosion products would not further accumulate on the crack surface. Figure 2.3 shows a close-up view of cracked weld in the baseplate.

Figure 2.3 – Close-up view of cracked weld in baseplate

2.1.2 Connection Flanges at Mast-arm Attachment

Visual inspection was conducted on another fatigue sensitive detail referred to as the “connection flange” detail (Figure 2.4 and Figure 2.5). The connection flange area is used for connecting the vertical pole to the mast arm. The detail was removed from the pole using an acetylene torch and taken inside the laboratory for further inspection. As shown in Figure 2.4, a crack was found at the intersection of the connection plates welded to the vertical pole’s outer shell. A similar crack was found on the lower portion of the connection as indicated in Figure 2.4.

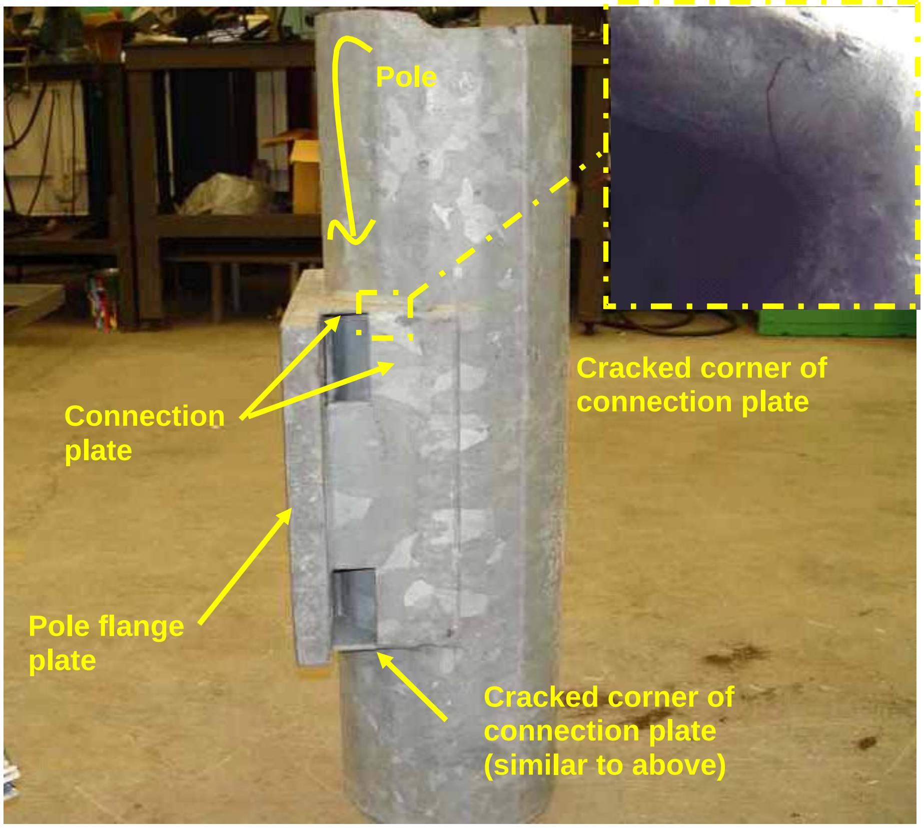

Figure 2.4 – Cracked connection flange detail of the pole

Figure 2.5 shows the mast arm flange plate detail in which the plate is fillet welded to the mast arm. Cracks, if present, would be expected along the toe of the fillet weld connecting the baseplate to the mast arm shell. Inspection did not reveal any cracks at this location.

Figure 2.5 – Uncracked connection flange detail of the mast arm

2.1.3 Handhole

The handhole detail (Figure 2.6) was also inspected for any sign of cracking. Experience has shown that cracks along the toe of the fillet used for welding the handhole to the pole are not uncommon. Typically, a lack-of-fusion plane exists where the edge of the pole wall contacts the stiffening flanges used to frame the handhole. Such lack-of-fusion defects have very poor fatigue resistance and act like embedded cracks. Close visual inspection did not reveal any cracks at this detail.

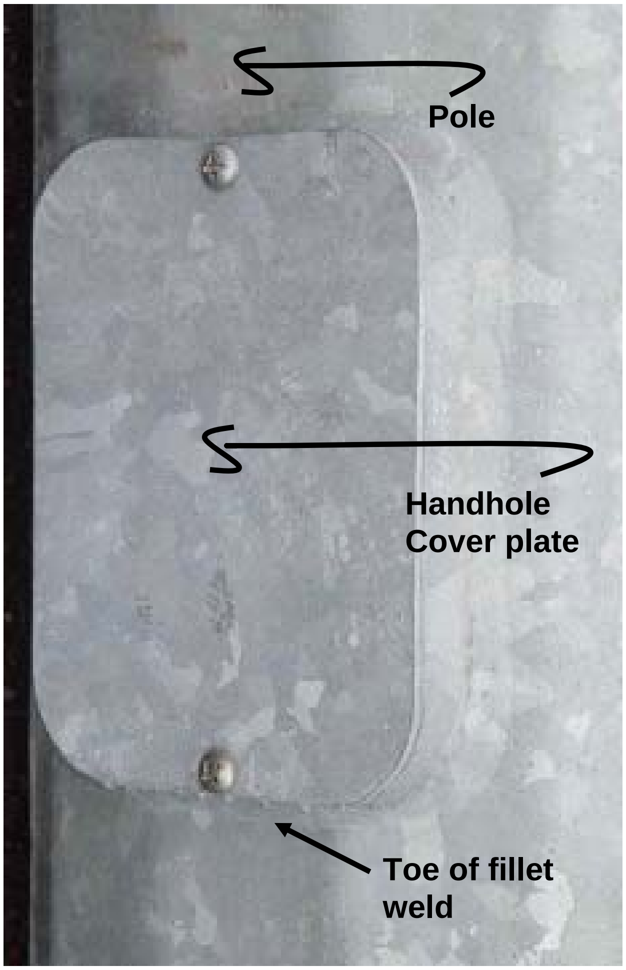

Figure 2.6 – Handhole detail

2.2 Cracks in Painted Structure

As previously stated, a considerable amount of movement was observed in this structure while it was in service. (It should be noted that a video of the movement exists and is available from Penn DOT.) Such large and steady movement prompted the removal of the structure from service. The structure was dismantled and left along the road for an extended period. Apparently, the dismantled structure was not inspected for any signs of damage due to the vibration.

To determine if any fatigue damage had occurred, ATLSS Researchers requested that the painted structure be delivered to the laboratory along with the galvanized pole, which was the focus of this investigation. Fatigue sensitive details on the painted structure were thoroughly inspected for any sign of cracking.

2.2.1 Baseplate

Although the baseplate of the painted structure was intact to the pole, visual inspection revealed a through-thickness crack at the toe of the fillet weld connecting the baseplate to the pole. Furthermore, the crack was found to be approximately 28% of the circumference of the pole (Figure 2.7). To assure that corrosion products would not further accumulate on the cracked surface, the baseplate and a portion of the pole was cut off and stored in the laboratory. The cut was made in the pole at approximately 6 inches above the cracked baseplate, as shown in Figure 2.2, so the heat from cutting and spatter would not damage the crack surface.

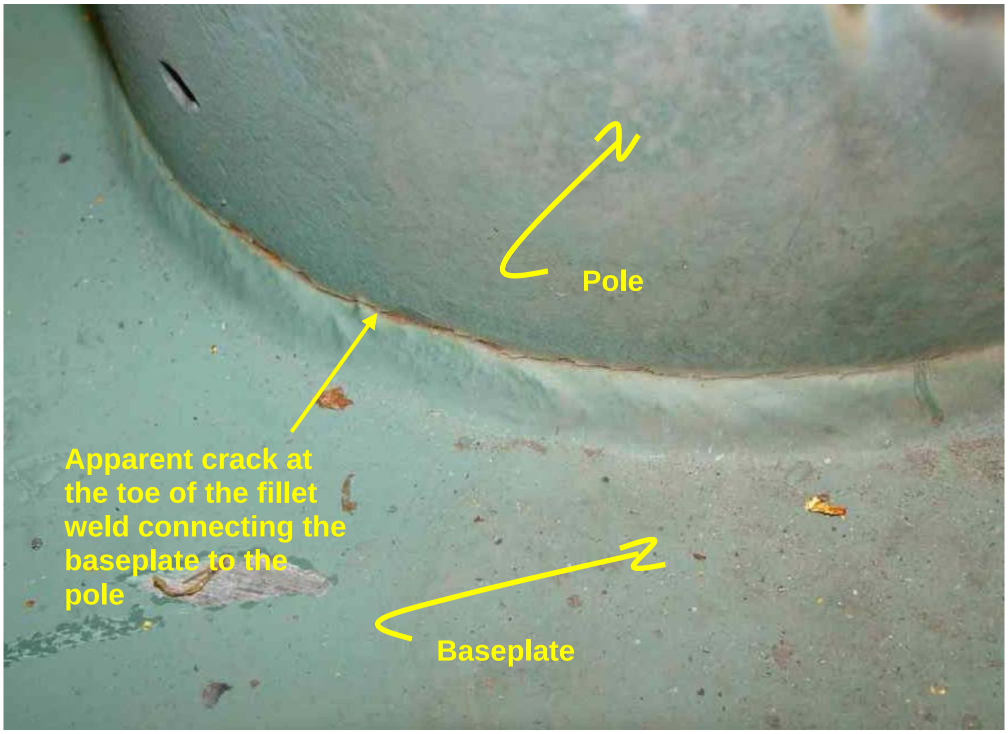

Figure 2.7 – Crack at baseplate to pole connection

2.2.2 Connection Flange

The connection flange details (Figure 2.8 and Figure 2.9) were also visually inspected for cracks. Figure 2.8 shows the connection flange detail in which the connection flange is fillet welded to the pole. There were no signs of fatigue cracking at this detail.

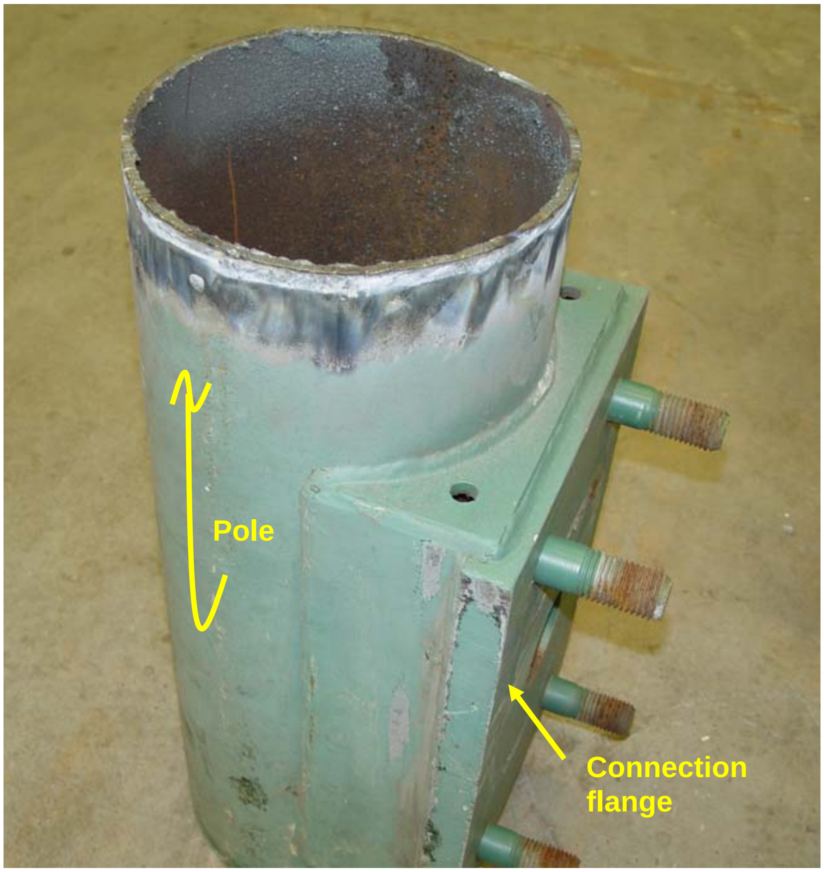

Figure 2.8 – Connection flange detail of the pole

Figure 2.9 shows the detail in which a crack was found at the weld toe at the end of the mast arm stiffener. Similar cracks were found at the termination of the other three stiffeners as indicated in Figure 2.9. The apparent cracks were found to be typical defects, which are common in welded structures. As explained later in Section 3.2. There was no sign of crack initiation or propagation from the defects into the pole's shell.

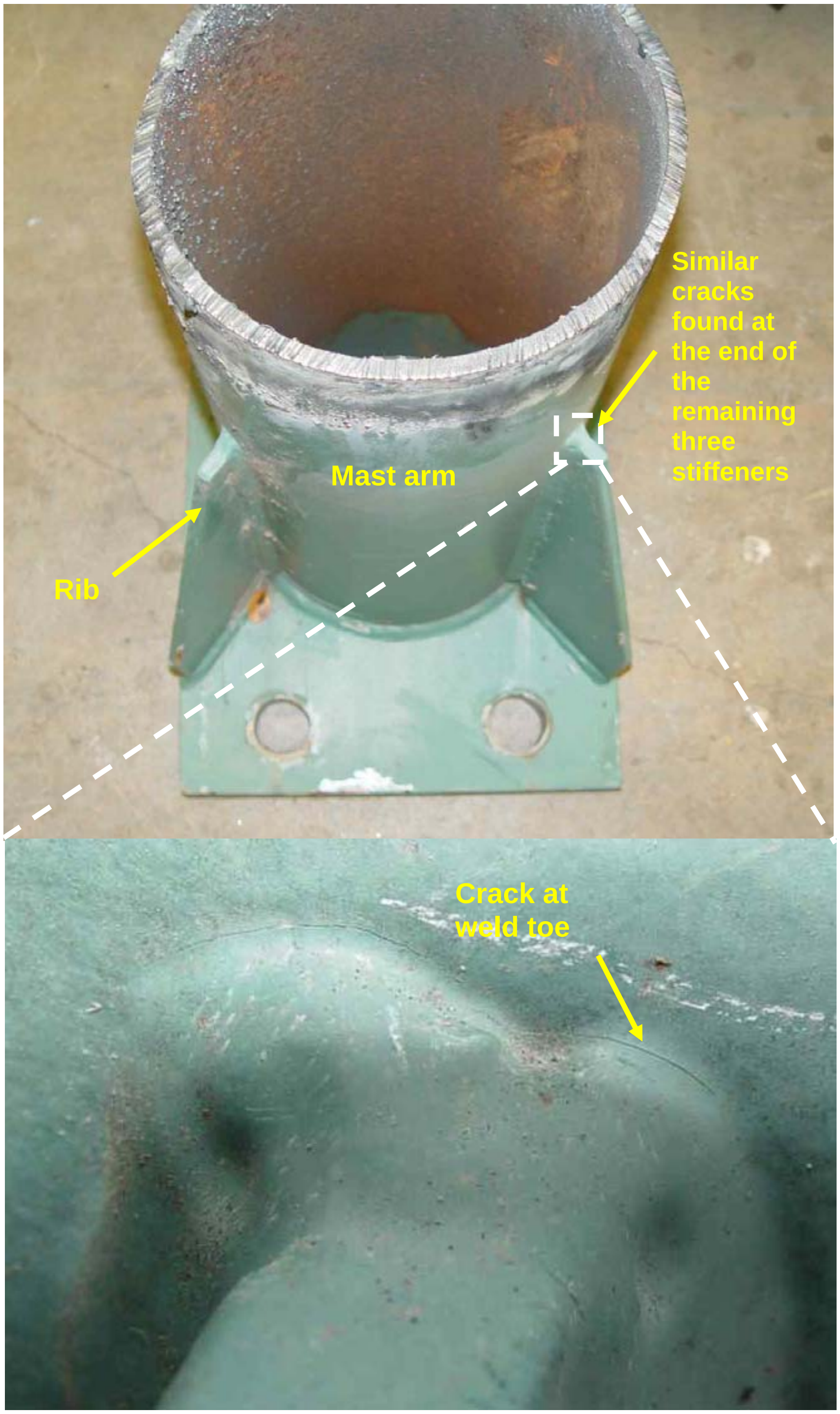

Figure 2.9 – Connection flange detail of the mast arm showing a close up of a crack found at the end of the rib that is fillet welded to the pole’s outer shell

2.2.3 Handhole

The handhole detail on the painted pole (Figure 2.10) was also visually inspected for any sign of cracking. No cracking was observed however at the detail.

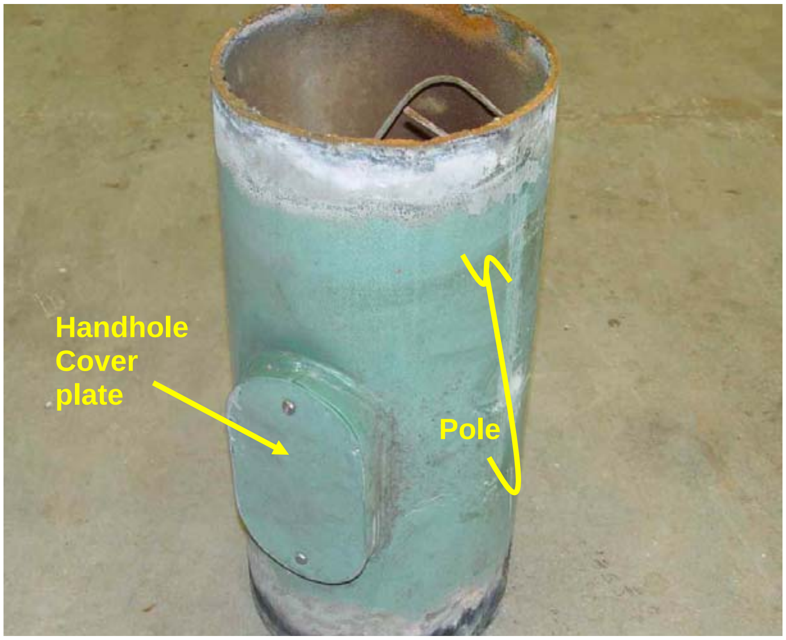

Figure 2.10 – Handhole detail

3.0 Metallographic Examination at Welded Connections of Cracked Region

3.1 Galvanized Structure

3.1.1 Connection Flanges at Mast-arm Attachment

The cracked connection flange detail of the galvanized sign structure (shown in Figure 2.4) was extracted for further investigation of the crack origin and the nature of the crack surface. The cracked surface was exposed by immersing the specimen in a liquid hydrogen bath to reduce its' fracture toughness. The specimen, while at such frigid temperature, could then be easily broken (fractured) into two pieces and facilitate exposure of the crack.

Once exposed, it was clear that the crack originated at the corner of the detail (location of a high stress concentration resulting from a change in geometry in the detail) and propagated under fatigue. A close up of the cracked surface is shown in Figure 3.1. Beach marks on the crack surface are clear indication of the successive advancement of the fatigue crack.

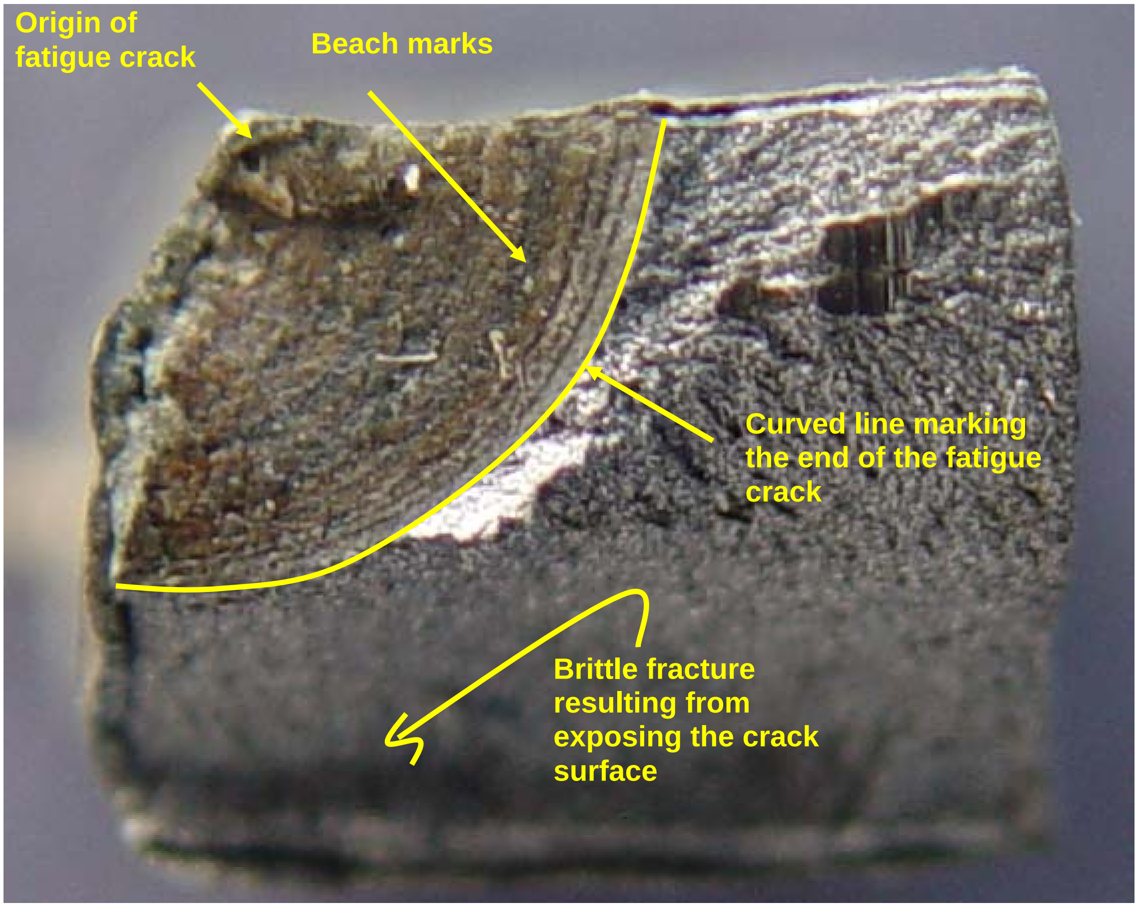

Figure 3.1 - Close up of exposed crack surface of the galvanized connection flange detail of figure 2.4 showing fatigue beach marks

More analyses were conducted using a Scanning Electron Microscope (SEM) to characterize the fracture mechanism. Figure 3.2 B is a high magnification image of Figure 3.2 A. Fatigue striations in the figure are an indication of the propagation of the crack front (indicated by the arrow on the figure). Figure 3.2 B also shows a typical appearance of fatigue fracture surface with no sign of damage to the fracture surface. Such observation indicates that the fatigue cycles were predominantly in tension (i.e., damage of the crack surface did not occur as a result of rubbing and strongly suggests that the applied stress cycles were predominantly in tension).

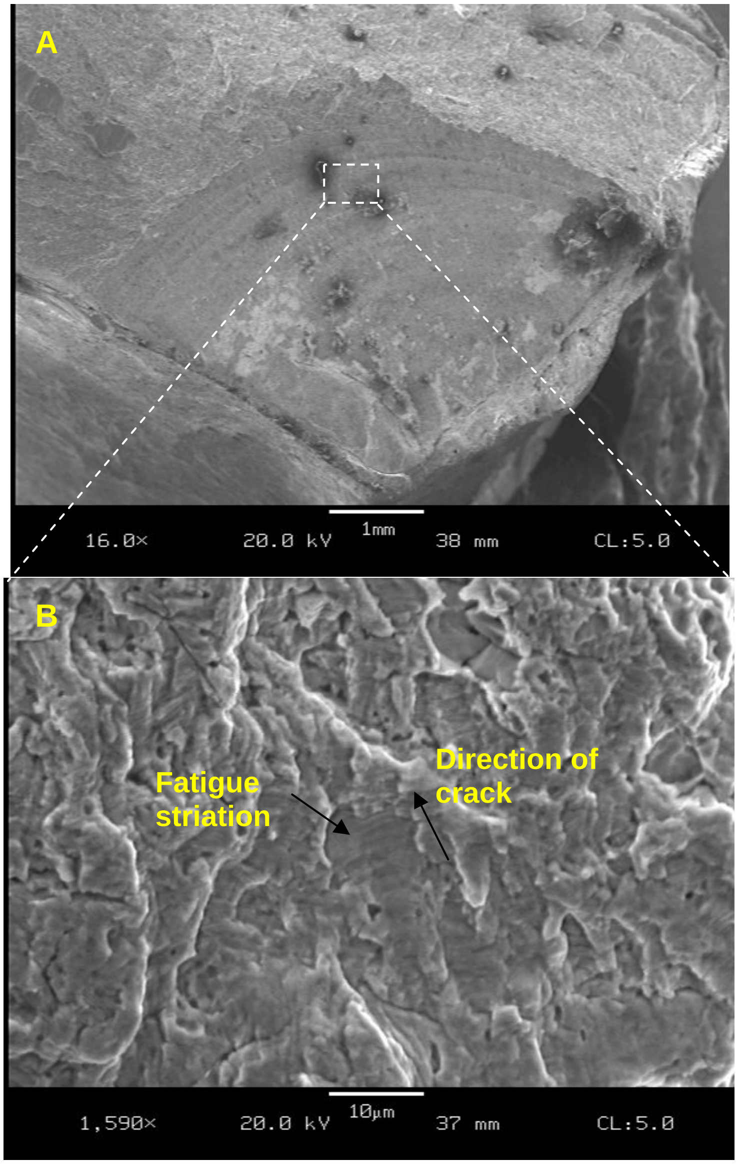

Figure 3.2 – A SEM image of cracked surface showing beach marks [Mag. 16 X]
Figure 3.2 – B shows a typical appearance of fatigue fracture surface [Mag. 1590 X]

3.1.2 Baseplate

As shown in Figure 3.3 A, the baseplate is divided into four different regions. Region 1 and region 3 were defined by visual inspection as fatigue regions (i.e. fatigue was the failure mechanism). The figure shows region 1 with more severe sign of corrosion than region 3, which suggests that cracking in region 3 did not proceed until region 1 was partially or fully cracked (i.e., region 1 was exposed to sever weathering condition for a longer period than region 3). It is also possible that the different level of corrosion could have been a result of the pole laying along the road for a long time where the heavily corroded surface of region 1 was subjected to more severe weathering conditions than the less corroded surface of region 3 (i.e. the baseplate could have been partially immersed in dirt, where the surface covered with dirt below the ground level was subjected to different weathering condition than the surface above the ground level). Unfortunately there is no evidence to support one scenario over the other.

Further inspection also reveals that a crack initiated at every bend in the plate. This suggests that the wind-induced vibration of the pole occurred from wind in multiple directions. Furthermore, multiple cracks initiated within each bend. The multiple cracks eventually joined up through tear ridges, or shear, as the crack increased in size. The presence of multiple cracks is indicated by the ratchet marks showing in Figure 3.3 B. The marks are usually present at the surface of components where a high local stress concentration is present (the bends in the pole tube).

In both fatigue regions, the multiple fatigue cracks within each bend and in the different bends eventually all joined to form two long fatigue cracks (one in each region). Failure of the pole did not take place until the length of the two fatigue cracks in region 1 and region 3 reached a critical size. The collapse region (formed during failure) of the pole is clearly shown in Figure 3.3 A and marked as region 4. Plastic collapse of the pole is clear by the presence of plastic deformation in the remaining ligament of the pole shell (attached to the baseplate). It is worth noting that fatigue region 3 tunneled under collapse region 4 for approximately 4 inches.

The fracture region (region 2) is located radialy across from the collapse region. The roughness on the surface and the slight necking of the pole shell at the fracture location is a characteristic of a ductile fracture.

The existence of corrosion products (ferrous hydroxide) on the cracked surfaces was evident in regions 1, 2, and 3. The specimens were immersed in an ultrasonic bath to remove the layers of corrosion. The Scanning Electron Microscope (SEM) analyses of the crack surface in both the fatigue regions and the fracture region did not reveal any valuable information since the accumulated corrosion products over the surface caused a great deal of damage to the surfaces. Although metallurgical analyses of the cracked region did not provide valuable information, it is clear that fatigue was the mechanism in which cracks initiated and propagated as explained above.

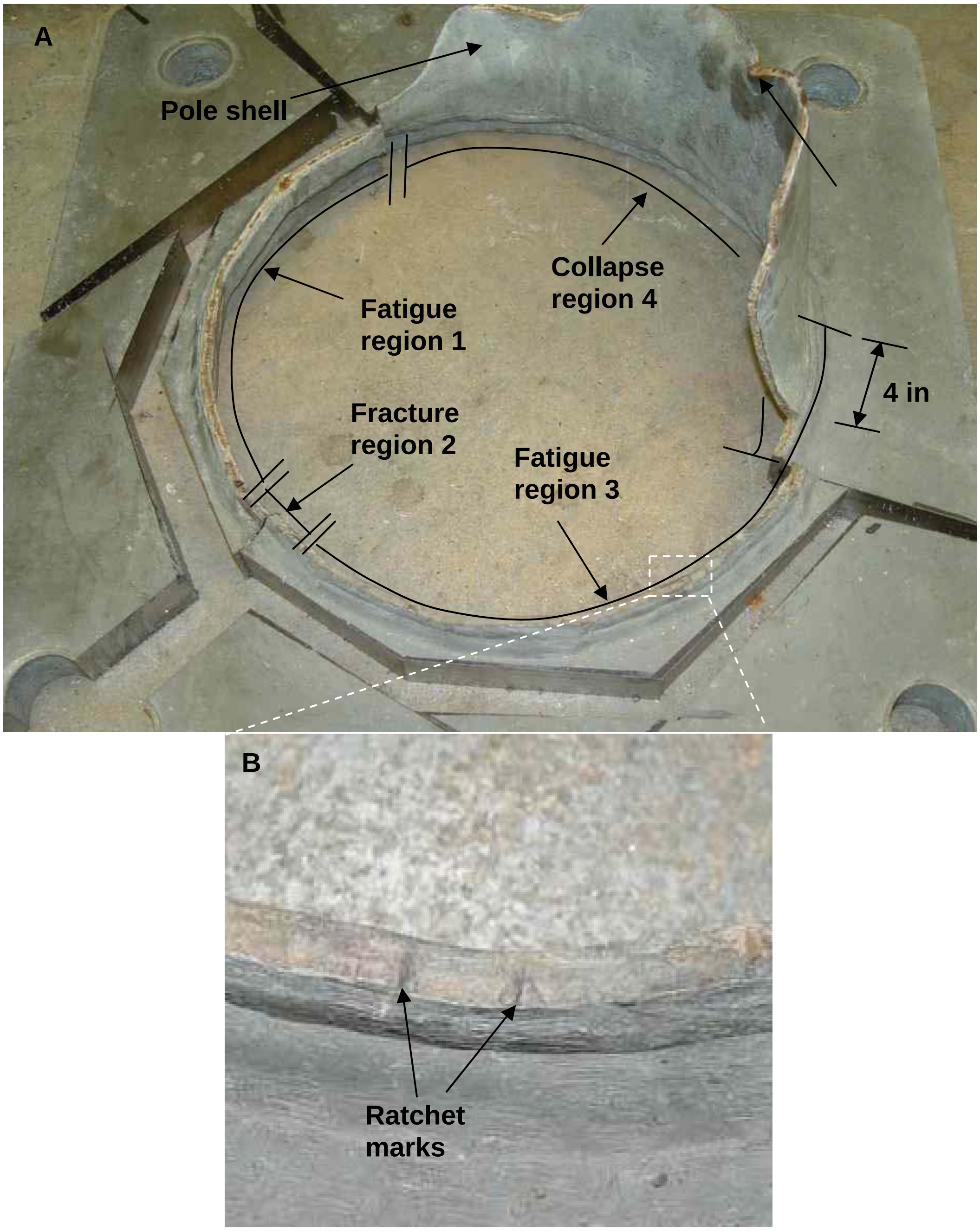

Figure 3.3 – A Cracked baseplate of galvanized pole showing four regions describing the failure mode
Figure 3.3 – B Close up of part of the cracked surface of the galvanized pole showing ratchet marks.

3.2 Painted Structure

3.2.1 Connection Flange Detail

As previously mentioned and as shown in Figure 2.9, four cracks in the paint were found at the termination of the longitudinal stiffeners welded to the pole's outer shell. Often, cracks in the paint at fatigue sensitive details are indicators of cracks in the steel below. Two out of the four regions were extracted for evaluation. Before exposing the surfaces the extracted regions were immersed in an acetone bath to remove the green paint coating on the outer surface for more thorough visual inspection. Visual inspection of the two extracted regions revealed that the first, which could be seen with the naked eye before removing the paint disappeared and was no longer visible after the removal of the paint. This indicates that the crack was only in the paint coating and did not penetrate in the base metal of the shell.

The condition at the other extracted region was however still visible after the removal of the paint coating. Exposing the possible crack was therefore necessary for further evaluation. Exposing the surface was done similar to the cracked connection flange detail in the galvanized structure by immersing the specimen in a liquid hydrogen bath to lower the fracture toughness of the metal and facilitates the separation of the surfaces. Figure 3.4 A shows a close up of the exposed surface. The figure shows a lack-of-fusion defect (also known as cold lap) between the fillet weld and the pole's shell. This could have been a result of many things including high travel speed of the welding gun such that the base metal failed to reach its melting point, unclean pole surface during welding, etc. There was no sign of cracks initiating or propagating from the defect in the thickness direction of the shell. Also shown in the figure is weld porosity, which is typically a result of dissolved gases or gases released during the welding process. SEM analysis of the weld porosity was conducted to examine if any cracks have initiated and propagated from the defect. There was no sign of crack initiation or propagation from the weld defect.

Although fatigue cracks have been known to initiate from lack-of-fusion defects and weld porosities, no cracks were found to have been initiated from neither defects discussed above.

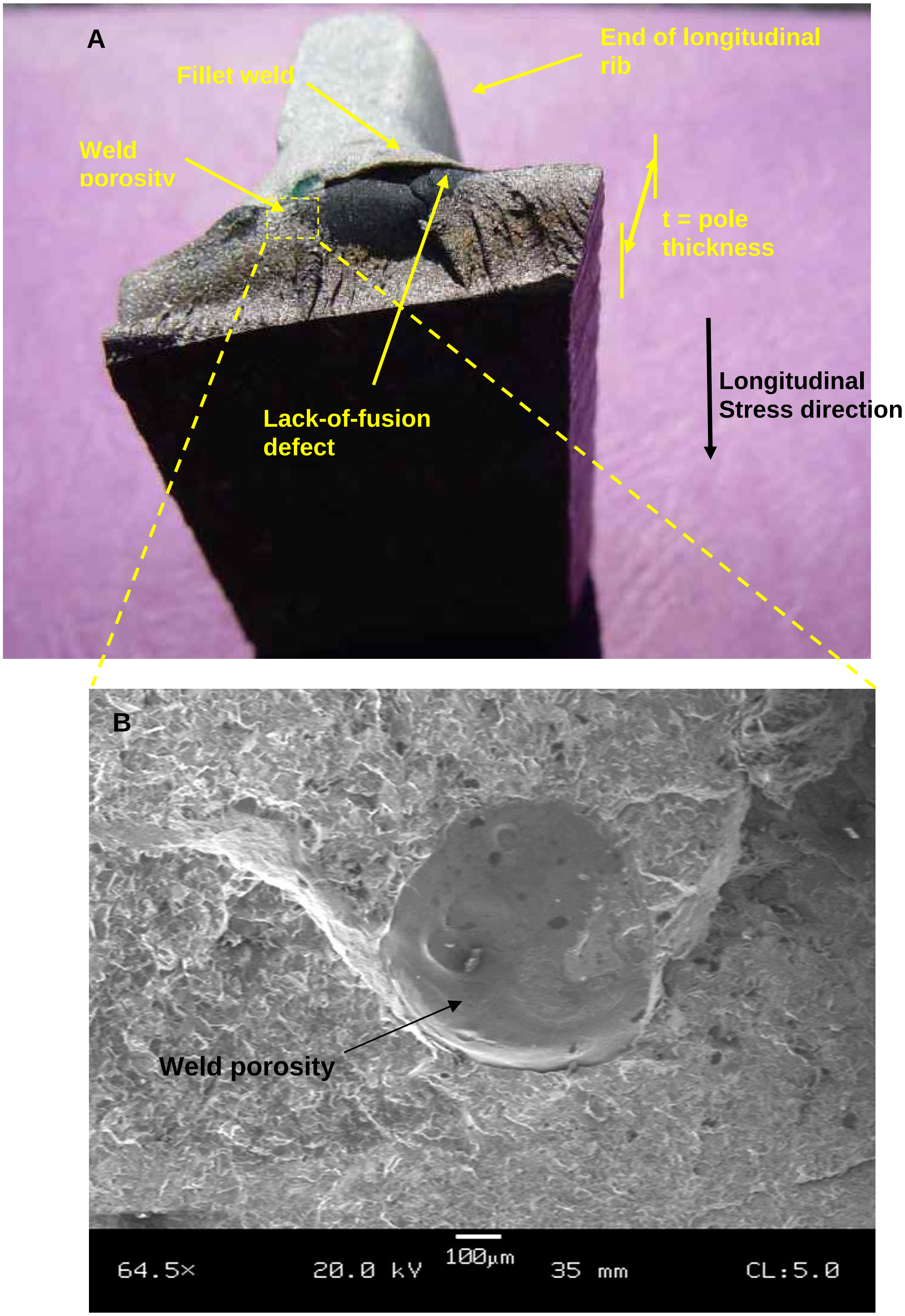

Figure 3.4 A – Exposed painted pole shell at the termination of one of the longitudinal stiffeners
Figure 3.4 B – A SEM image of the weld porosity

3.2.2 Baseplate

As previously mentioned, a large crack in the baseplate of the painted sign structure was discovered upon visual inspection of the pole at the ATLSS Research Center. The crack is approximately 28% of the circumference of the pole. As shown in Figure 3.5, a high level of corrosion is apparent on the crack surface. The severity of the corrosion indicates that the crack has existed and been exposed to weathering conditions for sometime. It is also possible that the high level of corrosion was a result of the pole laying along the highway for a long period of time.

Conducting SEM analyses of the crack surface would not yield any additional information due to the extensive damage caused by corrosion. The smoothness of the fracture surface suggests that fatigue was the failure mechanism under which the crack initiated and propagated.

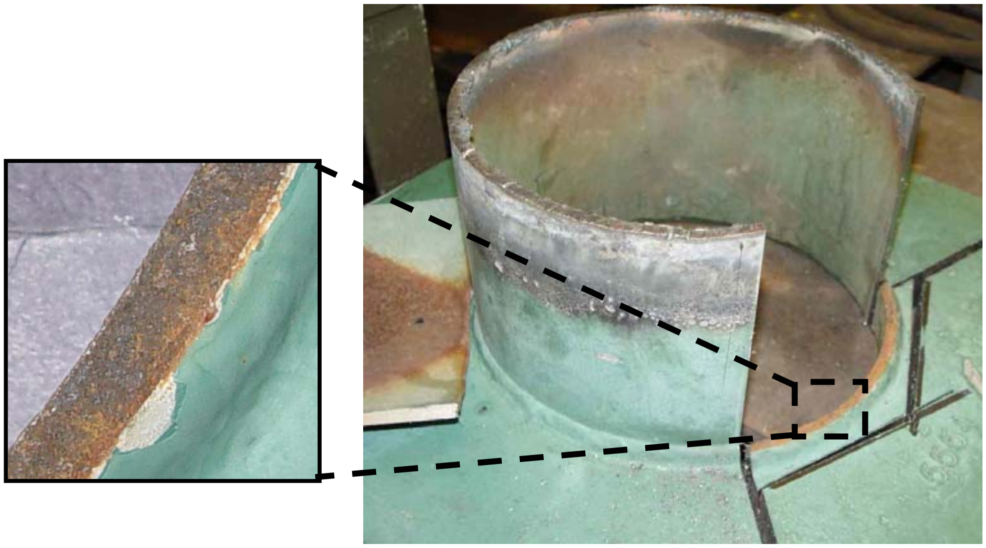

Figure 3.5 – Cracked baseplate of painted pole with a close up on the highly corroded crack surface

4.0 Mechanical and Chemical Properties and Weld Hardness

4.1 Tensile tests

Three tensile test specimens were machined from a sampling of the galvanized pole outer shell. The sampling and the testing was done in accordance with ASTM A370. The yield and tensile strengths ranged from 50.2 – 67.0 ksi and 72.1 – 87.8 ksi respectively, and were typical of Gr. 50 structural steel shapes. Table 1 below shows the results of the testing. The yield and tensile strengths ranged from 54.8 – 61.0 ksi and 72.0 – 78.4 ksi respectively, and were typical of Gr. 50 structural steel shapes.

Specimen Number	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (2") (%)	Area Reduction (%)
GS1	54.8	72.0	28.4	50.9
GS2	61.0	78.4	26.7	55.9
GS3	57.2	74.6	26.8	46.3

Table 1 – Summary of tensile test results of the pole material of the galvanized structure

4.2 Chemical Composition

The chemical analysis was conducted at Laboratory Testing Inc. of Hatfield, Pa. Results of an analysis from a sample from the pole shell are provided in a lab test report reproduced in Appendix A. The chemical compositions of the pole were found to be in conformance to UNS G10180 and are acceptable.

4.3 Weld Hardness

Hardness Rockwelll B test was conducted on the weld metal used for attaching the pole to the baseplate of the galvanized structure. The test measures the resistance of the weld to localized displacement. Five tests were conducted and an average value was calculated and further correlated for the determination of the ultimate tensile strength of the weld metal. Table 2 shows the results of the five tests, the calculated average value and the corresponding tensile strength. The tensile strength value of 96 ksi is not unusal, and indicates that an electrode E70 was most likely what was used in the welding process.

Test Number	Rockwell Number	Average of five tests	Tensile Strength (ksi)
1	96.3	93.5	96
2	90.7		
3	95.1		
4	91.3		
5	94.2		

Table 1 – Summary of hardness test results of the weld metal used for attaching the baseplate to the pole of the galvanized structure

5.0 Conclusion

Cracks in the galvanized structure were found in two details. The first cracked detail was located at the upper weld toe connecting the baseplate to the pole. The crack encompassed the whole circumference of the pole shell in which the baseplate was fully separated from the pole. The second cracked detail was located at the intersection of the connection plates at the connection flanges detail at the mast-arm connection. Cracks in both details are characteristic of fatigue cracks.

The painted structure experienced cracking at one detail. The cracked detail was located at the upper weld toe connecting the baseplate to the pole. The crack covered only 28% of the pole’s circumference. Lack-of-fusion defects and weld porosity were found in the connection flange detail at the termination of the longitudinal stiffeners welded to the outer shell of the mast arm. No fatigue crack initiation or propagation from either defect was detected.

Tensile tests, chemical composition analysis and weld hardness tests were conducted on the material of the galvanized structure to evaluate its mechanical and chemical properties. The tensile test results were found to be typical of grade 50 steel, the chemical compositions were in conformance to UNS G10180, and the weld hardness were found to be typical of what would be produced by E70 Electrodes.

6.0 Recommendations

1. Based on the investigation it is recommended that in-depth inspection to be conducted on similar sign and signal structures. At a minimum, those structures located at or near the site at which the two cracked structures were located should be inspected.

2. Inspections of these structures should include visual inspection of all welded details (i.e. baseplate, connection flange, and handhole). Inspection should be aided by dye-penetrant or magnetic-particle tests. Anchor rods should also be inspected for any sign of cracking and for proper torque.

3. If inspected structures were found to be cracked, they should be removed immediately.

4. It is also recommend that a fatigue assessment be conducted of structures with same design (geometries and cross section). This could be done through long-term monitoring of two or three structure. The monitoring will shed some light on the type and magnitude of loading experienced by the structures, which should provide greater assurance of the performance of the remaining uncracked structures.

Appendix A

Results of Chemical Composition Analysis

LABORATORY TESTING INC.
2331 Topaz Drive, Hatfield, PA 19440
Phone: 800-219-9095 • Fax: 800-219-9096

Certified Test Report

LHU001-04-09-22025-1

ACCREDITED
Cert. # 0117-01, 02, 03, 04

Nadcap
Accredited
Materials Testing Laboratory
NDT (PT, MT, UT)

SOLD TO
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Bethlehem, PA 18015
ATTN: Hussam Mahmoud

CUSTOMER P.O.	CERTIFICATION DATE	SHIP VIA
57200	9/8/2004	FAX AND MAIL

DESCRIPTION

1 pc. Test Sample, Item #2

The referenced sample was submitted to chemical content evaluation and it was found to be in conformance to UNS G10180 with the following results:

	REQUIREMENTS		
ELEMENT	**MIN**	**MAX**	**ACTUAL**
C	0.15	0.20	0.18%
Mn	0.60	0.90	0.78%
P		0.030	0.007%
S		0.050	0.004%
Si			0.020%

The services performed above were done in accordance with LTI's Quality System Program Manual Revision 16 dated 9/1/01 and ISO/IEC Guide 17025. These results relate only to the items tested and this report shall not be reproduced, except in full, without the written approval of Laboratory Testing, Inc. L.T.I. is accredited by A2LA in the Chemical, Mechanical and Nondestructive Fields of Testing. L.T.I. is accredited by NADCAP in the Material's Testing and NDT, MT, PT and UT.

MERCURY CONTAMINATION: During the testing and inspection, the product did not come in direct contact with mercury or any of its compounds nor with any mercury containing devices employing a single boundary of containment.

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Sherri L. Scheifele
QA Coordinator
By: Sherri L. Scheifele
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