FATIGUE BEHAVIOR OF THE REINFORCED ELECTRICAL ACCESS HOLE IN ALUMINUM LIGHT SUPPORT STRUCTURES

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FATIGUE BEHAVIOR OF THE REINFORCED ELECTRICAL ACCESS HOLE IN ALUMINUM LIGHT SUPPORT STRUCTURES

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ABSTRACT

Aluminum light poles are constructed from extruded aluminum tube in order to minimize the use of material. This in turn makes the pole lighter and allows for the electrical wires for the light to be hidden inside the pole. These wires must still be accessed for installation and maintenance purposes. An electrical access hole with a cover is placed near the bottom of the pole to make the wires accessible.

This electrical access hole is a point of structural weakness in the pole; therefore, the electrical access hole is often reinforced. This reinforcing may solve potential static load problems, but the disruption in the load path is a potential fatigue crack initiation point. This research centered on how fatigue failure occurs in cast reinforced electrical access holes.

The majority of the experimental research consisted of the cyclical bending of tubes with the electrical access holes centered in the extreme tension fiber. Ten poles with electrical access holes were broken in fatigue. The stress range applied to these varied from 63 MPa (9.1 ksi) at the highest to 17 MPa (2.5 ksi) at the lowest. Three tensile tests and a high shear fatigue test were conducted to supplement what could not be observed from the cyclical bending tests.

Finite element models were developed to understand the mechanical response of the electrical access hole. These were similar to the bending and tensile samples. A finite element model in a cantilevered position was modeled as well. These models allowed for stress maps to be examined and a potential explanation for initial cracking to
be developed. The initial cracking of the electrical access hole occurs in the weld near the
minor axis of the elliptical hole. This initial cracking was due to distortion of the
reinforcing of the electrical access hole. These cracks either propagate through the
reinforcing or join together to cause final failure.

The stress range versus the cycles to failure for the electrical access hole was
plotted to compare the data to known aluminum fatigue details. The data all fell between
categories C and D for aluminum. Further research is needed to verify if a D detail can be
used for designing the electrical access hole in fatigue.
AKNOWLEDGEMENTS

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CHAPTER I
INTRODUCTION

1.1 Problem

Driving at night can be hazardous, and one way of improving the safety of night
time driving is to illuminate the travelled way with overhead lights. In order to have
overhead lights, a structure is required to elevate the lights. This structure is often a pole
made from steel, wood, aluminum, fiberglass or reinforced concrete. Steel and reinforced
concrete can deteriorate over time from corrosion. Wood can rot, and the resin in
fiberglass can degrade. Aluminum does not degrade over time as other materials
mentioned do ("Aluminum" 2010). Aluminum, as well as steel, may be subject to
localized fatigue failures.

Sudden changes in cross section with any structural member results in stress
concentrations. These stress concentrations are potential failure initiation points. Failure
could occur from a single large force applied to the structural member, but more often
occurs from cyclic loading. Minimizing sudden changes in cross section increases fatigue
life; however, there are many times when there is no other economical way of making the
structural member function properly. In the case of light poles, there are several points
where there are sudden changes in cross section. These are at the base, the arm
connections or light connections, and the electrical access hole or handhole.

The mechanical response and fatigue life of the electrical access hole or handhole
is largely unknown. The known data comes largely from field failures and complete full
scale testing or testing of the bases in which the electrical access hole was included. The electrical access hole has yet to be isolated and its fatigue life determined through testing. The lack of fatigue data relating to the electrical access hole was the driving force behind this research.

1.2 Purpose of the Electrical Access Hole

There are two common ways in which to run electrical wires to overhead lights. One method is to run the wire from the top of one light pole to the next with the wire suspended in the air in between the two light poles. While this can be functional, falling objects in a storm could snag the wire. Another method is to bury a conduit between the light poles and run the wire down one light pole into the conduit and then up the next light pole. In many steel and aluminum light poles, the electrical wires run from the conduit into the hollow section of the pole up to the light. The electrical wires running in the pole are service wires, which connect to the main electrical lines running in the conduit. The electrical connection occurs after erection of the light pole. The electrical access hole serves the purpose of allowing access to the electrical wires to complete the electrical connection (Holstein 2016).

1.3 Parts of the Electrical Access Hole

The electrical access holes tested in this research contained reinforcing in the form of a cast aluminum insert welded to the pole. Below is a drawing of the cross section of a pole at the center of the electrical access hole or handhole. The term handhole will refer to the electrical access hole from this point on.
1.4 Previous Work

The University of Akron has conducted extensive research on the fatigue behavior of the bases of aluminum light poles. This research includes base geometry considerations such as through plates and shoebases. An S-N curve for the shoebase design was developed as well as a new fatigue detail classification. The through plate bases have a fatigue detail classification that would be below an E’. Compressive residual stresses exist near the top weld on the shoebase detail. These residual stresses
contribute greatly to the fatigue life of the pole. This research was a continuation of research initiated at Lehigh University (Azzam 2006).

1.5 Objectives of Research Conducted

The main objective of this research was to determine the fatigue detail category of the cast aluminum reinforced handhole currently installed on Hapco light poles with a 25.4 cm (10 in) outside diameter and a 0.635 cm (0.25 in) wall thickness. In order to satisfy changes in AASHTO design manuals requiring fatigue design calculations as well as static design calculations, manufacturers must know the fatigue detail classification of the components they are using in manufacturing their products. Since the “weakest link” governs design, being able to compare the different components used in the making of aluminum light poles allows for improvements to the overall design.

Finding the actual failure mechanism and failure path is the other objective of the research conducted. By determining the failure mechanism and failure path, an understanding of the mechanics leads to improving the design. This also could give a greater understanding of the statistical spread of the failures observed from the poles that are in use.

1.6 Experiments Conducted

There were three different experimental setups used in this research. A four-point beam bending setup put the handhole into pure bending with no shear. This setup was cyclically loaded to determine the fatigue detail category of the handhole. The four-point beam bending setup had poles tested at different stress ranges. A closely spaced three-
point beam bending setup was used to see fatigue cracking in a high shear situation. The three-point beam bending setup had one sample tested. The pole went significantly elliptical during this test. Three static tension experiments were conducted as well. These tests allowed for the placement of strain gages on parts of the inside leg. This was done statically to look at the presence of shear lag in the inside leg of the handhole. After the first tension test, most of the inside leg of the handhole was removed by milling. Another tension test was then conducted on the specimen in order to look at the influence of the inside leg. A tensile specimen with an extruded aluminum reinforced handhole completed the tension tests. The handhole in this tensile specimen is similar to a common reinforcement ring used in steel light poles.

1.7 Finite Element Models Built

Finite element modeling assisted in gaining a greater understanding of the overall mechanical response of the cast handhole reinforcing insert. The data gained from a strain gage only captures average strain in a small region. Finite element modeling generated an overall stress map of the samples tested in the laboratory. The overall stress map allowed for placing the gages in ideal locations. The models showed the localized deformations that were occurring. The localized deflections are important to understanding the overall response observed in the cyclical testing.

Finite element models developed were a cyclical four point bending sample, a tensile specimen with the complete cast handhole, a tensile specimen with an extruded reinforcing ring, and a cantilevered model similar to an actual light pole. The overall mechanical response of the three models with the cast reinforcing was similar.
CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Historically, the handhole detail on light poles has proven to be a potential fatigue failure point, but the overall understanding of the mechanics of the handhole is lacking. The FHWA inspection guidelines note handholes as a point to inspect, but little more is stated (FHWA 2005). A small number of failures around the handhole have been observed in New Jersey, but the literature largely refers to the bases as the detail that has been the target of research investigations (Menzemer 2012). This is in contrast to the Hapco’s experiences in which a majority of fatigue failures in the field have occurred near the handhole (Minor 2017).

Figure 1-2 shows a view of the handhole. The center of the handhole is 18in. above the bottom of the pole on many aluminum light poles. There is a cover that is bolted over the opening this is not shown in the drawing. The clock orientation in Figure 2-1 will be referenced for the locations of fatigue cracks in the handhole assembly.
2.2 General Applicable Mechanics

2.2.1 A Plate with a Circular Transverse Hole in Tension

A flat finite plate under uniaxial tension with a circular hole in its center will have stress concentrations around the hole. These stress concentrations are greatest at points formed by a transverse plane through the center of the hole and the circumference of the hole. The maximum local stress divided by the nominal stress is the stress concentration.
factor. The smaller the circular hole relative to the width of the plate, the greater the stress concentration, with a maximum stress concentration factor of around three. A larger hole will have lower stress concentrations, but the nominal stress at that point will be larger. The global deformation of the plate will be a necking down of the plate centered at the points with the highest stress concentrations. Locally, the circular hole will become an ellipse with the major axis oriented in the direction of the force. The two points with the highest stress concentrations will move toward each other (Hibbler 2011).

2.2.2 A Circular Tube with a Singular Transverse Hole in Tension

Bending a flat plate with a central hole, and connecting its edges forms a circular tube. When this tube is under uniaxial tension, it not only has stress concentrations around the hole, but experiences bending from the eccentricity created by the shifting of the neutral axis near the hole. If the hole is small enough, the bending stresses are negligible; however, as the size of the hole increases, the influence of bending stresses increase. In the case of a large hole, the bending stresses are a greater contributor to the global mechanical response of the circular tube than the stress concentrations because the stress concentrations decrease quickly away from the hole (Pierce 1973).

2.2.3 A Solid Circular Shaft with a Transverse Hole in Bending

A solid circular shaft with a transverse hole in bending oriented so the hole runs from maximum compression to maximum tension has a maximum stress concentration factor of three. The maximum stress concentration factor occurs when the diameter of the hole is small, or essentially zero as compared to the diameter of the shaft. At a ratio of 0.3
of the hole’s diameter to the diameter of the shaft, the stress concentration factor is 1.9. The handhole only cuts through one side of the light pole, but considering an opening of 10.2 cm (4 in) and a pole diameter of 25.4 cm (10 in) results in a ratio of 0.4. This condition is not within the bounds of the solution, but it seems reasonable that the stress concentration factor would be less than 1.9 (Peterson 1953).

2.3 Fatigue in Aluminum

Routine fatigue design involves the use of S-N curves, which have been developed for many common materials and common geometries. There are seven different fatigue detail classifications for aluminum given in the ADM (Aluminum 2010). Each of these detail classifications has its own S-N curve for use in design. The S-N curves for aluminum include a detail for light pole shoebases. In this case, the S-N curve for the shoebases is not parallel to the other S-N curves (Aluminum 2010).

The actual development of an S-N curve depends upon how the stress range is calculated. In order for fatigue to occur there must be a localized plastic region but the global stress state of the structural member will be elastic. In the plotting of stress range versus number of cycles to failure, the stress range expressed could be a global or local stress range. The global stress range is easier to capture or calculate, but it often is only a relative reference point to what is causing fatigue cracking (Maddox 2003).

2.4 Historical Handhole Failures

Cracking or localized failures of handhole details on light poles or similar structures is recorded in a few instances. The Mullica River Bridge had several light
poles on it fail, and at least one of them was cracked in and around the handhole. This occurred on August 28, 2011. Handhole cracking occurred in the throat of the weld between the extruded pole and the cast handhole. On one side of the handhole at the 3:00 or 9:00 position, the crack ran transversely from the weld into the extruded pole. Opposite of this there was a crack in the casting where the two legs meet. This crack was running in the transverse direction and appeared to have been caused by an internal flaw in the cast aluminum (Menzemer 2012).

The NCHRP report 469 on the Fatigue Resistant Design of Cantilevered Signal, Sign, and Light Supports mentions cracks found near handholes a) California in 1995, b) Minnesota in 1999, c) New York, and d) New Mexico. There is not sufficient detail mentioned in Table 2-1 (Dexter 2002). In Iowa, after a high mast light tower failure, another tower was found to have a large transverse cracked running through the bottom of the handhole. This crack was found to be caused by fatigue. In the report by Wiss Janey and Elstner, it was noted that most welds around handholes would have defects that are crack like. Figure 2.2 shows the crack that was found (Koob 2007).
2.5 Inspection of Light Poles and Similar Structures

Light poles and sign supports may be more numerous on roadways than bridges, but these structures cost less and pose lower risk to human life if they fail. Therefore, the management of light poles and sign supports is different from bridges. In the case of overhead sign supports, the structure is typically replaced instead of repaired if signs of fatigue cracking are found. Design requirements for these structures include fatigue calculations in addition to static design calculations (FHWA 2005).

Handholes are a point of interest in the FHWA inspection guidelines. The perimeters of handholes are to be checked in inspections, as the welds connecting the handhole to the pole are a point where cracks may start. The covers over handholes can
be missing or the bolts fastening them on can become stuck. The cover keeps moisture and animals out of the inside of the structure. Removing the handhole is any easy way to check for corrosion or even just moisture on the inside of the tube. In some cases, collected water inside the tube can become frozen and crack the tube. These longitudinal cracks can often be repaired (FHWA 2005). Even in bridges, longitudinal cracks are not much of a concern as compared to transverse cracks (Fisher 1989)

2.6 Previous Work

The New Jersey Department of Transportation had 14 light poles fail on Route 149 near Grassy Sound Bridge in the late 1990’s. The failures were suspected to be caused by vibrations with cracking and failure occurring in a relatively short time span. Six of the light poles that failed had an arm that cantilevered off the top of the pole to hold the light. These cantilevered light poles were attached to the bridge. The other eight light poles had lights at the top of the pole and were located near the bridge. Cracks were on the weld between the base and the pole and around the handholes. Breakaway transformer boxes between the light pole and the foundation broke from fatigue before the light pole.

These failures were the reason research on light poles initiated at Lehigh University’s Advanced Technology for Large Structural Systems Laboratory. While much of the research focused on the natural frequency of the pole and how wind forces could cause vibrations, 12 light poles were tested for fatigue life. Half of the light poles had cantilevered arms and the other half did not. Seven of the samples had cracks around the base at the end of fatigue testing. Some of the cracks observed in fatigue testing
originated at the weld root and ran to the weld throat. Breakaway transformer bases were used in conjunction with some of the fatigue tests. The data points were scattered but a recommendation for a category E fatigue detail was made (Johns 1998).

Due to the small sample size tested at Lehigh University, the University of Akron tested 29 light poles to determine the fatigue behavior of aluminum light pole bases. The light poles included 19 with shoebases and 10 with through plates. The shoebase detail has an S-N curve that is much flatter than the set of common aluminum fatigue details. The shoebase has a constant amplitude fatigue life between 3.5 ksi and 3.0 ksi. The flattening of the slope of the S-N curve is from compressive residual stresses in the extruded pole near the weld toe. These compressive residual stresses come from the welding sequence used on the shoebase. The top of the shoebase is welded first followed by the bottom. As the bottom weld cools, it pulls the tube toward it, and compresses the material above the top weld (Azzam 2006).

The through plate base had less fatigue life than the shoebase, with all of the poles falling below the D detail classification. After a statistical analysis, the through plate could not be classified as an E’ detail. The cracking of the poles with through plate bases was not at the extreme fiber but in line with the bolts. This was because of distortion of the through plate. The stress pattern caused by this distortion was shaped like a butterfly (Azzam 2006).

Lehigh University has also conducted fatigue testing on high mast steel light poles. The poles were tested in a cantilever position with spacers used to prevent the pole from going ellipitical at the load point. The geometry of these poles differs significantly
from aluminum poles, but in the testing conducted, 13 of the specimens had handholes. None of the handholes cracked in the testing (Thompson 2011).

2.7 Similarities to Water Hammer

The geometry of the handhole on a light pole is similar to the geometry of a fluid carrying pipe with another pipe T-ing off it. A pipe under pressure is an oblong pressure vessel, whereas, the light pole is a cantilever beam. This difference would usually cause failure locations and mechanisms to be completely different. In the case of fatigue failures, the pipe and the light pole can exhibit similar failure mechanisms. The pressured pipe can fail in fatigue due to water hammer. This occurs by a weakened section of pipe buckling inward due to low pressures that occur during water hammer. If this buckling occurs repeatedly, an internal crack can propagate longitudinally along the pipe until the remaining thickness of material between the crack tip and the outside of the pipe is too small to withstand the hoop stresses causing a bursting of the pipe (Engineering 2011). Longitudinal cracks formed in the welds around the handholes before failure in a bending manner occurred.
CHAPTER III
EXPERIMENTAL SETUPS AND CORRESPONDING FINITE ELEMENT MODELS

3.1 Introduction

The main focus of this research was the testing of four point bending samples. Twenty four specimens were received from Hapco for the purpose of being tested in cyclical fatigue tests. Each specimen had two handholes, and none of the handholes had a cover. Tensile tests were conducted so that strain gages could be placed in areas on the handhole that were inaccessible in the four point bending tests. These strain gages were used to look at the presence of shear lag in the handhole. The strain gages used were mostly Miro-Measurements 350 ohm gages that were 0.635 cm (0.25 in) long and 0.457 cm (0.18 in) wide. There were also an assortment of 120 ohm gages used.

The Finite Element Models were made to look at the overall response of the handhole to tension and bending. These models were generated by making Solidworks models of the tube and the cast insert. The fillet weld was modeled by creating mating surfaces between the tube and the cast insert. The weld was essentially the meeting point of the two components when they were put together. These Solidworks assemblies were then imported into Abaqus. The Abaqus models were all general static analyses with non-linear geometry. The models were made with a Tet element of the type C3D10. This element is a three dimensional element with 10 nodes. The modulus of elasticity was
taken to be 6895 MPa (10,000 ksi) and Poisson’s ratio was set at 0.3. These models were not used to match stress readings from the laboratory, but to gain an overall stress map of the specimens under load and to find the deflected shape of the specimens.

3.2 Four Point Bending

3.2.1 Experimental Setup

A four point bending setup was built to facilitate the cyclical testing of an aluminum tube with two handholes. The aluminum tube was 25.4 cm (10 in) in diameter with a wall thickness of 0.635 cm (0.25 in). The tube was 3.66 m (144 in) long with the center of the handholes placed 1.37 m (54 in) in from either end. The tube rested on rollers inset 15.2 cm (6 in) from either end. Load was applied to the tube via a spreader beam with rollers that made contact 76.2 cm (30 in) in from either end of the tube. The spreader beam was attached to an MTS 250 kN (55 kips) actuator. Figure 3-1 shows the four point bending setup before any cyclic testing started. The tube was oriented so that the handhole openings were down and in tension during cyclical testing. Fatigue failure of the handhole was determined when the handhole region was cracked to the point that no load could travel through the handhole. Once the first handhole had failed, the failed handhole was reinforced with a moment connection clamp, and the test was continued until the other handhole broke.
The aluminum rollers shown in Figure 3-1 ground on the tube quite severely and were replaced with steel rollers. The steel roller still ground on the tube, but not to the extent that the aluminum rollers did. Specimens 1, 2, and 3 were tested with the aluminum rollers. All subsequent specimens were tested with the steel rollers.

The number of strain gages placed on the four point bending specimens was not the same for all of the specimens tested. Specimen 1 had nine strains gages on it. Eight of these strain gages were placed on the elliptical axes of the handholes on the extruded part of the tube 0.635 cm (0.25 in) away from the weld toe. The ninth strain gage was placed on the opposite side of the tube as one of the gages on the major elliptical axis. Specimen 2 had eight strain gages in the same configuration as Specimen 1 minus the strain gage on
the opposite side of the tube. The strain gages used on Specimens 1 and 2 were 120 ohm strain gages instead of the 350 ohm strain gages.

Specimen 3 had seven strain gages with four of the gages placed on the minor elliptical axis on the extruded part of the tube 0.635 cm (0.25 in) away from the weld toe. This location will be referred to as the typical location. Two strain gages were placed on each end the inside leg of the handhole along the minor elliptical axis; the gage near the outside was a 120 ohm gage. The final strain gage was placed halfway between the two handholes on the extreme fiber. Strain gages were placed on Specimen 4 to try and capture stress variations that occur around the handhole. One of the handholes had two strain gages placed on the minor axis in the typical location. The other 20 strain gages were placed on four transverse planes. The first plane coincided with the minor axis of the handhole with three strain gages on either side of the handhole with first gage 0.635 cm (0.25 in) away from the weld toe and subsequent strain gages 1.91 cm (0.75 in) apart. The next transverse plane was 6.34 cm (2.5 in) away from the first plane. On the second plane the gages were symmetrically placed with the first gage was 0.635 cm (0.25 in) away from the weld toe. The next gage was 2.79 cm (1.1 in) away from the first, and the third gage was 2.54 cm (1 in) away from the second gage. The third transverse plane was 6.34 cm (2.5 in) away from the second transverse plane. One gage was placed on the major axis of the handhole with gages on either side of it at 7.62 cm (3 in) and 12.7 cm (5 in). The fourth transverse plane was 13.0 cm (5.13 in) away from the third transverse plane. One gage was placed on the major axis of the handhole with gages on either side at 12.7 cm (5 in). This configuration is shown in Figure 3.2.
Specimens 5 through 8 had five strain gages with four of the gages placed on the minor axis in the typical location. The fifth strain gage was halfway between the handholes on the extreme fiber. Specimen 9 had eight strain gages placed on it. Five of these strain gages were in the same locations as Specimens 5 through 8. One gage was placed in the transverse direction between the two handholes 22.9 cm (9 in) towards the handhole with the gages 1 and 2. Two strain gages were placed on the outside leg of the handhole 9.53 cm (3.75 in) away from the minor axis in the longitudinal direction. These two gages were centered on the outside leg. Specimen 10 had five strain gages on it in the same configuration as Specimens 5 through 8.

The stress range at which the specimens were cycled was varied from specimen to specimen. The stress range versus the number of cycles to failure could then be graphed to determine a fatigue detail category for the handhole. Table 3.1 shows the stress ranges.
at which each of the specimens were tested at. The handhole with gages 1 and 2 or the
northern handhole was denoted as handhole A with other handhole as handhole B.

Table 3.1 Cyclical Loading Rates on Specimens

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<th>Specimen</th>
<th>Stress Range</th>
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3.2.2 Finite Element Model

A Finite Element Model was built geometrically the same as the four point
bending specimens. The outside surface of the specimen was divided into pieces that
were close to 0.508 cm (0.2 in) by 0.508 cm (0.2 in). Tetrahedrons were then generated
for a mesh. Load was applied to the tube by selecting the outer nodes on transverse
planes where the rollers attached to the spreader beam would be. A total of 158 nodes had
a concentrated load of 0.0445 N (0.00001 kips) applied to them so that 7.03 N (0.00158
kips) was applied to the tube were each of the rollers from the spreader beam would be.
Similarly, the rollers on the pedestals were model by fixing the transverse and lateral
degrees of freedom on the outer nodes on a transverse plane. Four nodes on the neutral
axis at one end were fixed in the longitudinal direction. Concentrated loads of 0.0445 N
(0.00001 kip) were applied to the nodes selected to model the rollers on the spreader beam.

3.3 Tensile Tests

3.3.1 Specimens

The first tensile specimen was cut out of one of the four point bending samples. This specimen was 95.5 cm (37.6 in) long and 21.0 cm (8.25 in) wide with the handhole in the center. The specimen was cut so that on the minor axis of the ellipse there was 3.81 cm (1.5 in) of the extruded tube from the toe of the weld. A distance of 7.62 cm (3 in) from each end of the specimen was flatted to accept the tensile grips.

The first tensile specimen had seven strain gages in a longitudinal orientation installed on it. Gages 1 through 5 were aligned on a plane running transversely through the specimen on the minor axis of the elliptical handhole. Gage 1 was on the narrow face
of the inside leg; this installation is not possible on the four point bending specimen. Gage 2 was on the inside leg with one of its edges near the point made by the intersection of the inside and outside legs. Gage 3 was on the outside leg close to the weld. Gage 4 was on the weld. Gage 5 was on the extrusion near the toe of weld. Longitudinally, Gage 6 was in line with gage 5, at 15.2 cm (6 in) away. Gage 7 was transversely in line with Gage 6, at the center of the specimen.

Figure 3.4 First Tensile Specimen
After the first tensile specimen was tested in tension, the seven strain gages were removed. The inside leg was milled so that at its narrowest it was 1.87 cm (0.735in) and at the thickest 2.86 cm (1.125in). Three strain gages were on placed on the modified tensile specimen. The gages were placed on the same line as the previous gages 1 through 5. Gage 1 was on the extruded part of the tube at 1.02 cm (0.4in) away from the weld toe. Gage 2 was on the outside leg where gage 3 had previously been. Gage 3 was on the inside leg on the milled down surface.

Figure 3.5 First Tensile Specimen after the Inside Leg was Milled Down
A second tensile specimen was built from an aluminum tube 15.2 cm (6 in) in diameter with a 0.476 cm (0.188 in) wall thickness. A 3.81 cm (1.5 in) section of the tube was forged into a slot shape 19.1 cm (7.5 in) long by 6.35 cm (2.5 in) wide. A hole that accepted the forged piece was made in a section of the tube. The forged piece was then welded to the tube. A 13.3 cm (5.25 in) wide section of the tube was cut out with the built handhole in the center. This specimen had an overall length of 102 cm (40 in), and again 7.62 cm (3 in) from each end were flattened to accept the tensile grips.

Five gages were placed on the second tensile specimen in the longitudinal direction. Gage 1 was on the tube 1.71 cm (0.675 in) away from the weld toe aligned with the center of the handhole. Gages 2 and 3 were aligned on a plane that passed through the center of the handhole. Both gages were on the inside face of the handhole near the edges. Gage 2 was toward what would be the outside of a light pole. Gage 3 was near what would be the inside of a light pole. Gages 4 and 5 were on a plane near where a half circle portion and the rectangular section of the slot met. These gages were on the narrow faces of the handhole. Gage 4 was on what would be the outside of a light pole, and gage 5 was on the inside. Gages 1 and 2 were 350 ohm resistors while gages 3, 4, and 5 were 120 ohm resistors.
3.3.2 Finite Element Models

A corresponding finite element model for the first tensile specimen, before being milled, was developed. The handhole and tube thickness were the same as what was used in the experiment. This model was 61 cm (24 in) long with the half of the tube opposite
the handhole removed. The outside surface of the specimen was divided in pieces 0.508 cm (0.2 in) by 0.508 cm (0.2 in), and then tetrahedrons were generated from these pieces. This dimension is smaller than the thickness of the extruded portion, but had to be in order to get a satisfactory mesh. A concentrated load of 445 Newtons (0.1 kips) was placed on all of the nodes on what would be the inside and outside diameter of the tube. These loads were in opposite directions on each end. The stress map where root of the weld would be could be easily looked at in this model.

![Finite Element Model: First Tensile Specimen](image)

A finite element model that was similar to the built tension specimen was developed. The fillet weld that was used to join the two pieces was modeled as a loop with a square cross section. The hole in the tube was modeled slightly larger than the dimensions of the reinforcing piece so that the forces had to travel through the loop that
represented the fillet weld. The thickness of the tube was 0.476 cm (0.1875 in) and the surface of the model was broken in squares with this dimension. Tetrahedrons were then generated to form the three dimensional mesh used in the modeling. All of the nodes on the ends that would be on the inside or outside diameter had a concentrated load of 445 Newtons (0.1 kips) applied to them.

![Finite Element Model: Second Tensile Specimen](image)

3.4 Three Point Bending

The remaining portion of the four point bending specimen that was cut up for the tensile tests was tested in high shear fatigue. This was achieved by placing the tube on closely spaced flat supports and a flat plate was used to apply load to the tube. The center of the handhole was 22.2 cm (8.75 in) away from one of the end supports to maximize the ratio of shear to bending. Styrofoam was placed between the end supports
and the tube to keep the tube from rolling. This set up allowed the tube to become significantly elliptical during loading.

Five stain gages were placed on this specimen. Four of the gages were oriented transverse to the tube, and the remaining gage was oriented longitudinal to the tube. The four transverse oriented gages were placed on the elliptical axes at 0.635 cm (0.25 in) away from the weld toe. The longitudinal oriented gage was placed 1.27 cm (0.5 in) away from the transverse gage closest to the center. Figure 3–5 is a picture of the high shear fatigue set up. This experiment was carried out to gain a reference point by which to bound the possible fatigue failures on actual light poles as actual light poles will experience bending and shear stress during cyclical loading. A finite element model was not developed for this experiment.
3.5 Finite Element Model of a Cantilevered Pole

A finite element model of a cantilevered light pole was built to compare laboratory results against what would be the configuration of handholes on aluminum light poles in service. This model was used to do a mesh convergence study and the results of that study were used to determine the mesh sizes for the other finite element models. This model was 366 cm (144 in) long with the handhole placed 45.7 cm (18 in) above the fixed end. The tube was 25.4 cm (10 in) in diameter with a wall thickness of
0.635 cm (0.25 in). The handhole was the same dimensions as the handhole used the four point bending model and the tension model for the first tensile specimen.

The surface of the cantilevered light pole was divided into squares with a dimension of 1.27 cm (0.5 in) and 0.584 cm (0.23 in) from which tetrahedrons were then generated. The 0.584 cm (0.23 in) was very close to the thickness of the extruded tube at 0.635 cm (0.25 in). The thickness of the tube could not be used because ABAQUS could not generate a satisfactory mesh with that dimension. Concentrated loads were applied to the nodes on the outer and inner diameter of the free end so that the fiber with maximum tension from bending passed through the center of the handhole. Concentrated loads of 0.0445 N (0.0001 kips) were applied to 532 nodes making the total applied load 237 N (0.0532 kips).

Figure 3.10 Cantilevered Pole
CHAPTER IV

ANALYSIS OF EXPERIMENTAL RESULTS AND FINITE ELEMENT MODELS

4.1 Experimental
4.1.1 Crack Path

Of the fifteen handholes that were broken in four point bending by fatigue, there was a similar pattern to the fatigue crack initiation. The initial visual cracking near the handhole occurred through the throat of the fillet weld near the minor axis. Typically, there would be two of the initial cracks, one on either side of the handhole. This initial crack would be oriented in the longitudinal direction. This crack would be present for a significant amount of the later portion of the life of the specimen. The smooth initial crack would become stacked like tension shear cracks as it propagated toward the major axis of the handhole. As the stacked cracks joined together they formed a jagged edge. The stacked cracks appeared to follow the weld puddles, which can be seen in Figure 4.1
Final failure occurred with transverse cracks in the extruded tube, and often with transverse cracks in the cast insert. The transverse cracks in the cast insert did not always propagate completely through the cast insert. When this happened, failure occurred with a different crack in the cast insert or by the initial cracks in the weld joining near the major axis. Figure 4.2 shows cracking in the weld and through the cast insert.
Figure 4.2 Final Fracture of Handhole

The propagation of the cracks can be seen in the strains that were recorded periodically during the cyclical testing. Even the initial cracking caused an increase in strain at the typical location. The initial cracking must influence load carrying capacity, which is contrary to what a longitudinal crack would do. Figure 4.3 shows Micro Strains from the testing of Specimen 10. Around 100,000 cycles the initial cracks in the weld were seen. The strains in gages 1, 2, 4, and 5 all increase above the strains of gage 3 around the same time. Gage 3, which was used to determine the stress range, only decreases slightly until the very end.
The three point bending test ended without the actual failure of the handhole. This was due to the cracking of the tube near the load application point. The handhole did experience cracking in the fillet weld very similar to what occurred in the four point bending. The major difference being that that the crack did not form a stacked pattern as it moved toward the major axis on the weld.

4.1.2 Shear Lag

Specimen 3 that was tested in four point bending had two gages installed on the inside leg to look at the presence of shear lag. These gages had showed that the very inside of the inside leg carries very little force as compared to the other side of the inside leg. Figure 4.4 shows the strain readings from the two gages during the cyclical testing.
The results from Specimen 3 prompted the tensile tests that occurred. The first tensile specimen was only statically tested but the presence of shear in the inside leg could be seen. Not all of the gages returned useful data as it was later determined that gage 3 was most likely centered on a neutral axis. Figure 4.5 shows the gage readings from 0 to 13300 N (3000 lbs.) of force on the tensile specimen.
Figure 4.5 Tensile Test: First Tensile Specimen

Gage 2 has the highest strain readings while Gage 1 is essentially zero; showing that the inside portion of the inside leg does contribute to the structural capability of the handhole. The inside portion of the inside leg often has a hole drilled in it to receive a grounding terminal (Holstein 2017). The shape of the inside leg may have to do with electrical wiring and not structural capability. This most likely makes the results from tensile test on the first sample once the inside leg had been milled down meaningless. The results from that test are in Figure 4.6.
The second tensile specimen was intended to be a comparison to see if shear lag occurred in the geometry typically used for the handhole in steel light poles. Figure 4.7 shows the results from the tensile test on the second tensile specimen.
4.1.3 Stress Variations around the Handhole

Specimen 4 had twenty strain gages around one of the handholes to look at the variation in strain. The strains were normalized against the strain from gage 19 because it was used to determine the stress range of the cyclical test. Figure 4.8 show normalized strains during static testing.
Figure 4.8 Normalized Strains under Static Load

The highest strains were the second row closest to the handhole. There is the typical butterfly distribution formed by stress concentrations around a circular hole. The cast insert takes much of the load as the outer gages in the first row have about half the strain of the other outer gages. Figure 4.9 shows the normalized strains just before visible cracking occurred.
4.1.4 Fatigue Detail Classification

Fifteen handholes were broken from the testing of 10 of the four point bending specimens. Five of handholes were not broken due to an inability to place the moment transfer over the first broken handhole. The data from the four point bending tests are contained in Table 4.1.
Table 4.1 Results of Four Point Bending Tests

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Figure 4.10 shows the plotting of stress range versus cycles to failure for the fifteen handholes that broke. The data has a power trend curve of \( f(x) = 1940x^{-0.295} \). The data all lies above the D detail curve and beneath the C detail curve; therefore, the handhole appears to be classifiable as a D detail.
4.2 Finite Element Models

4.2.1 Mesh Convergence

With any finite element model, the proper mesh size must first be determined in order for any analysis to be accurate. The proper mesh size is determined by finding mesh convergence between the similar models with only the mesh size varying. Mesh convergence was determined by comparing the deflection of the cantilever model. Figure 4.11 shows the node highlighted in red that was used for comparing displacement.
The displacement of the node with mesh sized at (0.5 in) on the surface was 0.1538 cm (0.06057 in). The displacement of the node with the mesh sized at (0.23 in) on the surface was 0.1542 cm (0.06072 in). The variation in the displacement of the node between the meshes was 0.25 percent. This was satisfactory and the thickness of the tube was used as the benchmark for creating meshes for all of the other models.

4.2.2 Longitudinal Stress Maps

Failure in a laterally supported beam occurs because of longitudinal stresses in the beam exceeding a threshold. This makes longitudinal stresses the primary indicator of where fatigue cracks will initiate. This was not the case in this research. Longitudinal stresses caused final failure of the specimens, but initial cracking was in the longitudinal direction. Figure 4.12 shows the longitudinal stresses from the four point bending model.
Figure 4.12 Longitudinal Stress: Four Point Bending

The final failure of the cast insert typically occurred along a transverse plane that was in the area of the stress concentrations at either end of the cast insert. The failure plane of the cast insert does line up with the stress concentrations, but the cracking through the cast insert always occurred after longitudinal cracks formed in the weld.

4.2.3 Transverse Stress Maps

The primary stresses in the transverse direction of the tube proved to be very useful in understanding the behavior of the handhole under tension. The primary stresses in the transverse direction would usually be of little importance with little changing in stress from one point to another; however, Figure 4.13 shows a stress concentration point centered on the weld holding the cast reinforcing piece to the extruded tube.
Figure 4.13 Transverse Stress: Four Point Bending

The stress concentration is actually compression even though the primary stress in the longitudinal direction is tension. This phenomenon occurred in the cantilevered model as well as the model for the first tensile specimen. Figure 4.14 shows the cantilevered model.
In the finite element model for the second tensile specimen, the stress concentration was diminished. The stress concentration appeared greatest where the half circle jointed the straight portion of the slot. Figure 4.15 shows the stress concentration on the second tensile specimen.
While the finite element models show a stress concentration in the transverse direction on the outside of the pole that is in compression, this fact does little to explain the cracks that were observed in the lab. As the tension tests allowed for gages to be placed in inaccessible areas, the finite element models of the tension tests allowed for stress maps to be viewed of internal areas. The root of the weld cannot be observed in the four point bending and cantilevered models. The root or what would be very close to the root of the weld can be observed in the tension models. Figure 4.16 shows the inside equivalent of what has been shown in previous figures.
The stress concentration seen from the inside is now in tension. This indicates that the weld is undergoing bending from the root to the throat of the weld. This bending is occurring about a longitudinal axis. This bending is coming from the displacement of the cast insert from the applied tensile forces. As discussed in the literature, a circular hole in a plate will become an ellipse when under tension. The opening in the handhole is already an ellipse, but the dimension of the opening in the minor axis will decrease as the major increases. The cast insert will undergo a similar deformation. The fillet weld on the outside leg is only restraint to the cast insert. As this deformation occurs the cast insert begins to distort by the inside and outside legs trying to rotate together. The axis of rotation is in the longitudinal direction, and goes through the weld. Figure 4.17 shows this rotation from exaggerated displacements.
Figure 4.17 Exaggerated Displacements
5.1 Conclusions

The initial fatigue cracking of the handhole occurs due to distorting of the cross section around the handhole. This distortion occurs because of the severe geometric shape of the cast insert. Because the initial cracking is caused by geometry, the effects of material type and material condition are secondary concerns. Welding causes residual stresses; however, the finite element models did not account for this. The finite element models showed the possibility of the same initial cracking as what was observed in the laboratory.

The transition from the initial cracks to the ultimate failure is not well understood. The initial cracks cause an increase in stain in the tube on the minor axis. This indicates that the initial separation of the cast insert from the tube causes a decrease in load carrying capacity. This decrease must come from an out of plane movement by the handhole that cannot occur as long as the weld is intact.

Pictures of field failures of the handhole detail on aluminum lightpoles from Hapco are similar to the failures observed in the laboratory. Actual light poles are in a cantilevered position not under constant moment so the failures would not be expected to be the same. Figure 5.1 shows a light pole failure from fatigue through the handhole.
A fatigue detail classification of a D detail would be recommended by the results of this research. This is based on only fifteen handholes that were broken under only bending forces. Further research is needed to confirm if a handholes can be designed in fatigue using the D detail for aluminum.

5.2 Future Research

This research involved the testing of one handhole type and one tube size. The tube was 25.4 cm (10 in) in diameter with a wall thickness of 0.635 cm (0.25 in). The handhole was 10.2 cm (4 in) by 15.2 cm (6 in). Other tube sizes and handhole configurations are used in light poles; theses other geometric configurations may have a better fatigue life than the configuration tested.
Actual light poles are in a cantilever configuration with bending and shear being induced by wind loading. The effects of shear on the handhole were not fully investigated in this research. Handholes should be tested in the configuration that they will be used in the field. This will verify if the proposed fatigue detail classification is correct or not.

Material properties were not varied in this research; the effect of welding and the residual stresses caused was not investigated. Depending on the fabricator’s procedures, the material conditions from the welding could affect the fatigue detail classification. There is little research on the handhole detail in light poles, and any further research would help in the understanding of the fatigue behavior of the handhole.
REFERENCES


FHWA NHI: Vol. 05-036. Guidelines for the installation, inspection, maintenance and repair of structural supports for highway signs, luminaires, and traffic signals. (2005, March). FHWA.


Koob, M. J. (2017, March). Use of Image from Bridge Structures Article [E-mail].


Minor, R. (2017, January 17). RE: Fatigue failures - base vs. hand-holes [E-mail].


