Fatigue Testing and Retrofit Details of High-Mast Lighting Towers

RYAN J. SHERMAN, MATTHEW H. HEBDON and ROBERT J. CONNOR

ABSTRACT

Fatigue cracking has been the cause of a number of high-mast lighting tower (HMLT) failures throughout the United States. In almost every case, forensic evaluations have shown cracking initiates and propagates due to wind-induced fatigue at mainly the base plate–to–tube wall connection detail or the hand-hole weld detail. Subsequent inspections of HMLT inventories have revealed a number of additional cases of fatigue cracking in various stages. Simply replacing the towers is not an economically feasible alternative because thousands of HMLTs are in use along major highways across the United States. As a result, strategies to retrofit existing HMLTs are needed. Results from laboratory testing performed on two HMLT retrofit configurations are presented. Both retrofits provided an increase in fatigue life compared with the as-built HMLTs. The retrofit strategies are employed without removing the pole from the foundation using simple bolting techniques and moderately skilled labor, providing cost savings for owners and increasing safety for the motoring public.

KEY WORDS: high-mast lighting tower (HLMT), fatigue, retrofit, sign structure.

BACKGROUND

Two high-mast lighting towers (HMLTs) near Rapid City, South Dakota, collapsed within five months of each other (November 2005 and April 2006). Both towers were identical hexadecagonal (16-sided), 150-ft-tall galvanized structures. Each pole had a base plate thickness of 1.75 in., tube wall thickness of 0.375 in., base diameter of 29 in., eight anchor rods and a complete-joint-penetration (CJP) weld with backing ring connecting the base plate to the tube wall. Failure in each case occurred at the base plate–to–tube wall connection detail. A forensic evaluation of both poles confirmed the cause of failure was wind-induced fatigue (Sherman et al., 2011). Fatigue cracks of various lengths, including those resulting in total collapse, have been observed in HMLTs around the United States (Connor et al., 2011). The two failures in South Dakota prompted a statewide inspection effort of approximately 140 towers. Cracking was discovered in both welded through-socket and full-penetration weld connection types: 14 instances and 3 instances, respectively. This resulted in 11 additional towers being removed from service. Sketches of these connection details can be found in Figure 1.

Fatigue of HMLTs typically has been a direct result of wind-induced vibration. HMLTs are flexible structures and can, therefore, experience rapid accumulation of damaging fatigue cycles. It is well established that there are two types of wind phenomenon that must be considered during the fatigue design of HMLTs: natural wind gusts and vortex shedding (AASHTO, 2013). Natural wind gusts cause the pole to move parallel to the direction of wind flow, while vortex shedding is a complex aero-elastic phenomenon. When wind flows past the pole at a steady rate, vortices are formed that create a wake. The force of the wake drives the pole back and forth perpendicular to the direction of the wind. When the pole is moving transverse to the direction of the wind flow, it is referred to as vortex shedding, which can produce a large number of stress cycles in a short period of time (Kaczinski et al., 1998; Ahern and Pucket, 2010).

From a survey conducted during a recent National Cooperative Highway Research Program (NCHRP) study (Connor et al., 2011) more than 10,000 HMLTs have been installed across the country. As such, robust, cost-effective retrofit strategies are needed because it is not economically feasible to replace all poles susceptible to fatigue cracking. One concept, referred to as "jacketing," has been developed. Retrofit jackets installed at the base plate and lowest portion of the pole shield the details commonly susceptible to fatigue crack growth: the base plate–to–tube weld connection detail and the hand-hole detail (Koob, 2007; Roy et al., 2011; Callahan and Connor, 2011). Comprised of multiple pieces, the jackets can be installed without removing the HMLT from service. The jacketing concept has been successfully installed

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in Iowa and Texas on four different pole types (Koob, 2007). Field monitoring and laboratory fatigue testing were conducted on one Iowa HMLT to confirm the performance of the jacket retrofit (Connor and Hodgson, 2006; Phares et al., 2007; Callahan and Connor, 2011).

Details used on HMLTs in South Dakota required a retrofit jacket with different geometry than previously tested during research performed by Callahan and Connor (2011) to be fabricated; hence, there was concern the data obtained during that study were not directly applicable. Therefore, laboratory fatigue testing was conducted on jacket retrofits designed for typical South Dakota HMLT details. The research confirmed the jacket retrofit concept was an effective method for extending the life of HMLTs with and without existing fatigue cracks. This paper reports on the results of the experimental program, fit-up issues and general commentary on performance and detailing. The objective of this study was not to investigate causes of cracking (i.e., vortex shedding versus natural wind) or perform finite element analysis, but to focus on the development and testing of a robust retrofit strategy.

TEST SPECIMENS

General

Laboratory fatigue testing was conducted on three types of specimens: as-built specimens, tall-jacket retrofit specimens and short-jacket retrofit specimens. The first phase (as-built specimens) consisted of testing two HMLT base sections similar to in-service South Dakota HMLTs that experienced fatigue crack growth. The second phase (tall-jacket retrofit specimens) consisted of three specimens using a jacket retrofit approximately 60 in. tall fastened to a pre-cracked, as-built specimen. The third phase (short-jacket retrofit specimens) consisted of three specimens using a jacket retrofit approximately 30 in. tall fastened to a pre-cracked, as-built specimen.

The as-built specimens had a through-socket fillet-welded base connection detail typical of the majority of the in-service inventory in South Dakota where cracking had been observed. Socket-type connections are constructed by extending the tube base through a hole in the base plate and fillet welding around the perimeter at both the top and bottom of the base plate. In each jacket retrofit test, the base connection of the as-built pole was nearly completely severed (approximately 90%) with a cutting wheel to ensure the entire load was carried by the retrofit. This was conservative because an in-service structure would collapse if the base plate to tube weld were cracked to such a degree.

As-Built Test Specimens

Only the base section of the pole was tested as the location of fatigue-sensitive details, located within the bottom 72 in. of the HMLT, was tested. Two as-built specimens were tested to establish their baseline fatigue performance. No additional specimens were deemed necessary because the fatigue resistance of the as-built pole with the socket connection was known to be poor, typically worse than Category E′ (Rios, 2007; Roy et al., 2011). The as-built specimens were then used as a "fixture" for the jacket retrofit testing.

The as-built specimens were fabricated using a 35-ft-tall, 16-sided HMLT made of galvanized steel. The tube

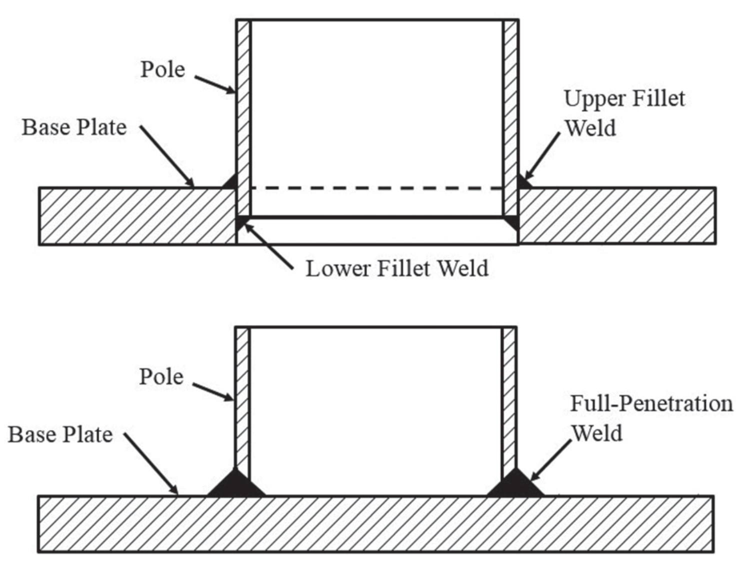

Fig. 1. Typical HMLT base connection details: welded-through socket (top) and full-penetration weld (bottom).

section base diameter was 25.89 in. and tapered at a rate of 0.14 in./ft. The tube wall thickness was 0.19 in., base plate thickness was 1.5 in. and ten 1.5-in. anchor rods secured the base plate to the foundation. A welded through-socket connection detail was used for the base plate-to-tube wall connection, and a doubler plate was used for the hand-hole detail. Strain gage locations for the as-built specimens can be seen schematically in Figure 2, and a photograph can be seen in Figure 3.

Tall-Jacket Retrofit Specimens

The tall-jacket geometry was similar to that used during a previous testing program sponsored by the Iowa Department of Transportation (DOT) (Callahan and Connor, 2011). Three identical tall-jacket retrofit specimens were tested to evaluate their fatigue performance on the same as-built specimen.

The tall-jacket retrofit specimen was comprised of two "half-jacket" base sections connected with splice plates. Both half-jacket sections were 60 in. tall and made of galvanized steel. One hundred fifty ⅞-in. A325 tension-controlled galvanized bolts were used to secure the new 0.5-in.-thick jacket tube wall to the existing tube wall of the pole. All holes were drilled through the existing tube wall using the retrofit jacket as a template. The holes were 1⁄16 in. over the fastener size. This number of fasteners was used to meet the American Association of State Highway and Transportation Officials (AASHTO) maximum fastener spacing and edge distance requirements and subsequently was well beyond the capacity required for strength considerations to ensure the as-built pole and jacket retrofit acted as one.

The new 1.5-in.-thick jacket base plate was attached to the original base plate with the ten existing anchor rods in addition to twelve 1.0-in. galvanized heavy hex A325 bolts. The A325 bolts connected the two base plates only, and had no connection to the concrete footing. In addition to the half jackets and splice plates, the tall-jacket retrofit also included four fill plates. Fill plates were required to ensure proper bolt tightening at the locations covered by the jacket directly above and below the hand-hole doubler plate. Figure 4 shows the strain gage locations used for the tall-jacket retrofit. A photograph of one of the tall-jacket halves can be found in Figure 5.

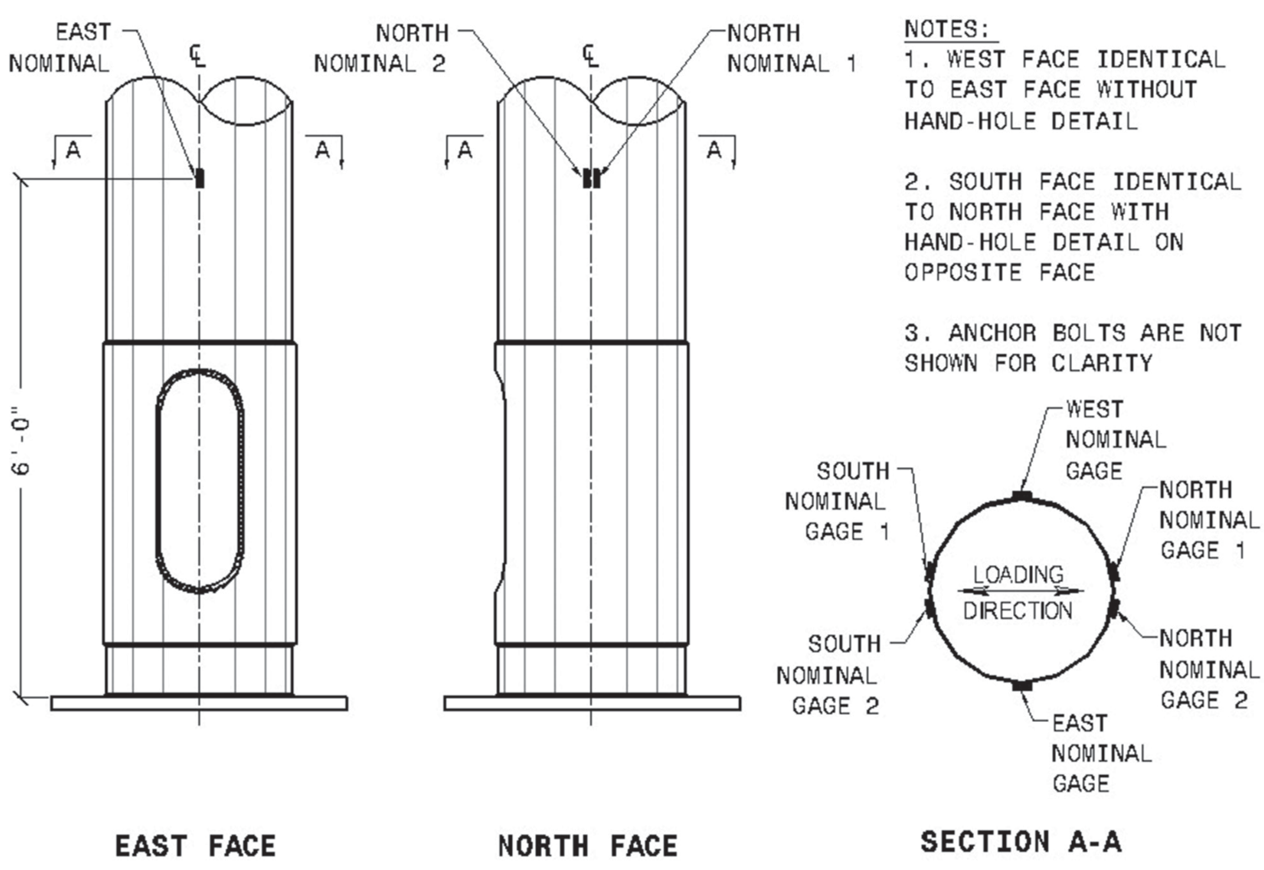

Fig. 2. Strain gage layout for as-built specimen.

Fig. 3. Base section of as-built test specimen (note doubler plate around hand-hole detail).

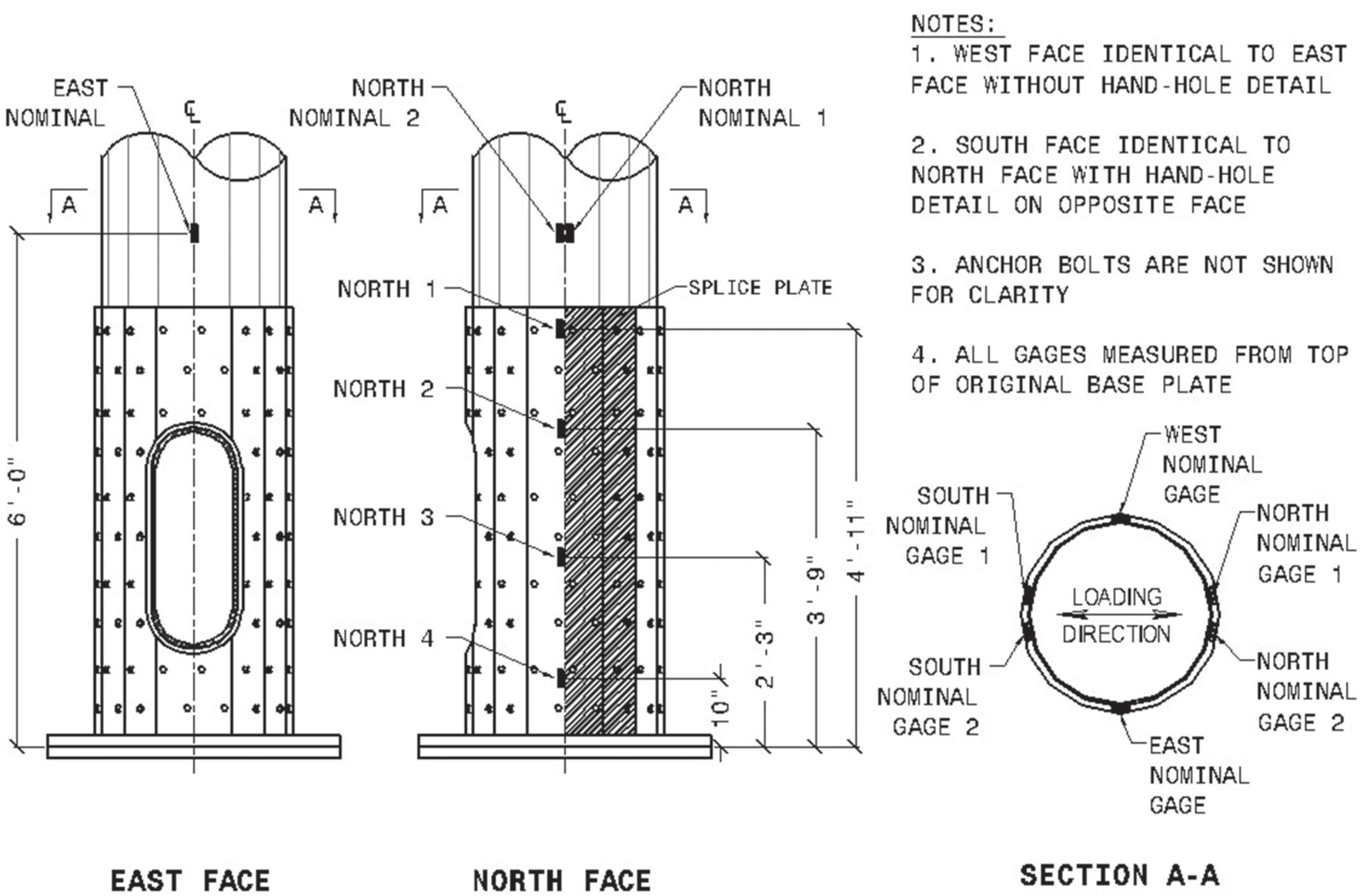

Fig. 4. Dimensions and strain gage layout of tall-jacket specimen.

Short-Jacket Retrofit Specimens

Although the tall retrofit proved to be effective, a second retrofit configuration was developed to reduce the installation challenges that had previously been observed in the field. After evaluating several alternatives, the decision was made to divide the jacket into quarters. Additionally, cracking had not been observed around the hand-hole during field inspections with the doubler plate hand-hole detail. Thus, field performance indicated the jacket did not need to extend above the hand-hole; therefore, the jacket was designed to extend approximately half the height of the tall-jacket retrofit. Reducing the height of the short-jacket retrofit lowered the fabrication cost and aided in quicker and easier installation.

Each short-jacket quarter was 31 in. tall, including the 1.5-in.-thick base plate. The short jacket had the same 0.5-in.-thick tube wall connected to a 1.5-in.-thick base plate with a CJP weld. The weld was inspected using ultrasonic testing during fabrication. Due to the reduction in height, only ninety-eight ⅞-in. A325 tension controlled bolts were required to secure the jacket tube wall to the existing tube wall of the pole. The ten existing anchor rods were used in addition to eighteen 1.0-in. galvanized heavy-hex A325 bolts to connect the new and existing base plates. Strain gage locations for the short jacket are shown in Figure 6. Photographs of the short-jacket retrofit can be found in Figure 7.

The primary differences between the tall and short jackets were height and number of components. Additionally, the short-jacket retrofit incorporated other modifications to resolve some fit-up issues encountered during the tall-jacket installation. Whereas the tall retrofit utilized splice plates between the tube walls of the two jacket halves, the short design eliminated these plates by considering the original as-built tube wall as a splice plate. Both fill plates were subsequently omitted from the short-jacket retrofit. The upper fill plate was no longer required because the top of the short jacket did not extend beyond the doubler plate of the hand-hole. The lower fill plate was omitted because the lowest row of bolts was relocated up to the doubler plate section. Collectively, these design improvements minimized problems experienced during the installation of the tall-jacket retrofit and reduced the total fabrication and installation costs.

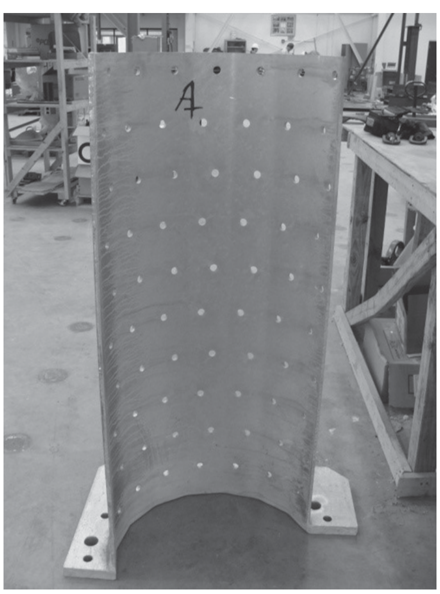

Fig. 5. Typical tall-jacket retrofit.

Fabrication and Fit-Up Issues

Additional fabrication and fit-up issues were encountered during the installation of the jacket retrofits. A fabrication error resulted in poor alignment between the breaks in the pole and those in the jacket. It was believed to be a result of a combination of inaccurate field measurements and radial misalignment (see Figure 8 for resulting retrofit fit-up). This fabrication issue was only present in the short-jacket retrofit.

A tolerance issue was observed at the base plate–to–tube wall connection. The angle between the jacket base plate and jacket tube wall differed from the angle of the original pole. Due to the differing angles, full contact between all components was not achieved, resulting in an "oil canning" effect observed during the fatigue testing.

In addition, the internal winch plate on the as-built tube wall conflicted with bolt holes in both the tall and the short-jacket retrofits. The box in Figure 9 highlights the location of the conflict on the short-jacket retrofit. The decision was made to omit a number of fasteners to represent a worst-case field-installed condition.

Given the fabrication and fit-up issues encountered during the testing of the retrofits, the fatigue life results presented herein characterize a conservative representation for similar jacket retrofits. If these issues were improved a longer fatigue life would be expected.

EXPERIMENTAL TESTING

Experimental Test Setup—General

The HMLTs were tested in the vertical position. A reinforced concrete foundation, post-tensioned to the laboratory reaction floor, encased the full-size anchor rods supporting the HMLT. The anchor rod nuts were fastened to the base plate using the turn-of-the-nut tightening procedure and a hydraulic wrench (Dexter and Ricker, 2002). Cyclic loading was applied through an 11-kip MTS servo-controlled hydraulic actuator connected between the top of the HMLT and the laboratory reaction wall (see Figure 10). To simulate worst-case stress conditions for the weld termination of the jacket, the load was applied perpendicular to the hand-hole location (from south to north). The hand-hole detail was located at the center of a jacket section. During the Iowa retrofit testing, it was found that locating the jacket splice through the hand-hole resulted in poor fatigue performance (Callahan and Connor, 2011).

Strain gages were installed to measure the nominal stress range in the as-built pole as well as to measure load transfer to the jackets. Due to the flexibility of the specimens, the MTS servo-controller was programmed using displacement control. The displacement range was manually adjusted throughout the test to maintain the desired nominal stress range as the specimen cracked. Static tests were conducted periodically during fatigue loading to monitor the stiffness of the pole. The fatigue test was considered complete upon a 10% drop in stiffness relative to the initial conditions or after substantial cracking: total crack length of approximately 20 in. Similar approaches were used on tests of flexible ancillary structures (Koenigs et al., 2003; Callahan and Connor, 2011). Magnetic-particle and liquid-dye-penetrant nondestructive testing were used to verify the crack lengths at the completion of each fatigue test.

Specimens were cycled at a constant amplitude stress range of 8 ksi measured with strain gages at a nominal location on the tube portion of the specimen. Maximum stresses were measured at the strain gages located on the north and south faces of the HMLT, in line with the actuator. Based on previous research, the 8-ksi stress range was found to be representative in terms of upper bound in-situ nominal stress range in poles of similar cross-section while minimizing test duration (Rios, 2007; Callahan and Connor, 2011). Additionally, field monitoring of HMLTs described in NCHRP Report 718 found 8 ksi to be an upper bound effective stress range (Connor et al., 2011). Nominal stresses were measured to avoid stress concentrations around the base plate–to–tube wall connection and to avoid any other jacket effects. The nominal stresses were extrapolated to the base using basic mechanics. Nominal stresses were selected to compare the relative fatigue resistance of the as-built pole with both jacket types. Strain gages were installed on the

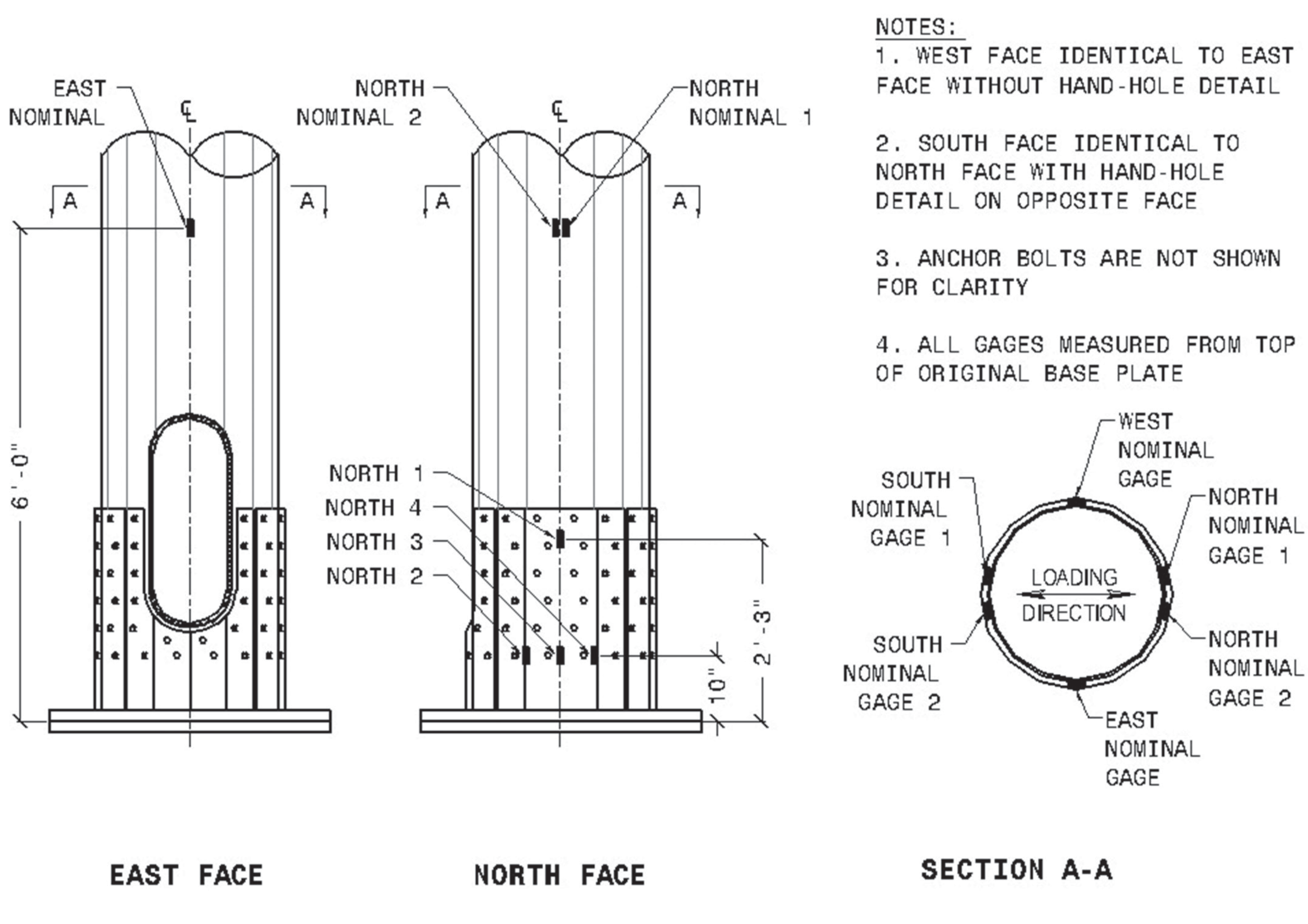

Fig. 6. Dimensions and strain gage layout of short-jacket specimen.

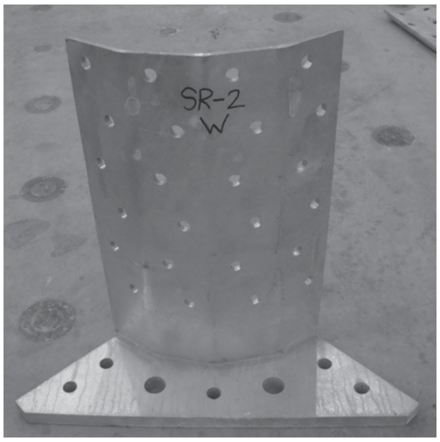

Fig. 7. Typical short-jacket retrofit.

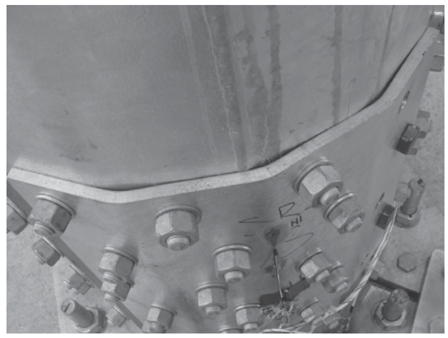

Fig. 8. Short-jacket retrofit misalignment.

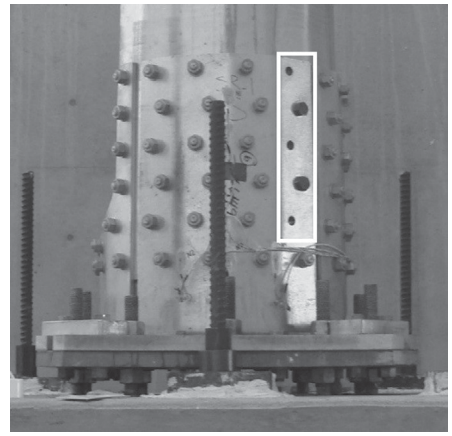

Fig. 9. Short-jacket retrofit with bolts removed at winch plate conflict.

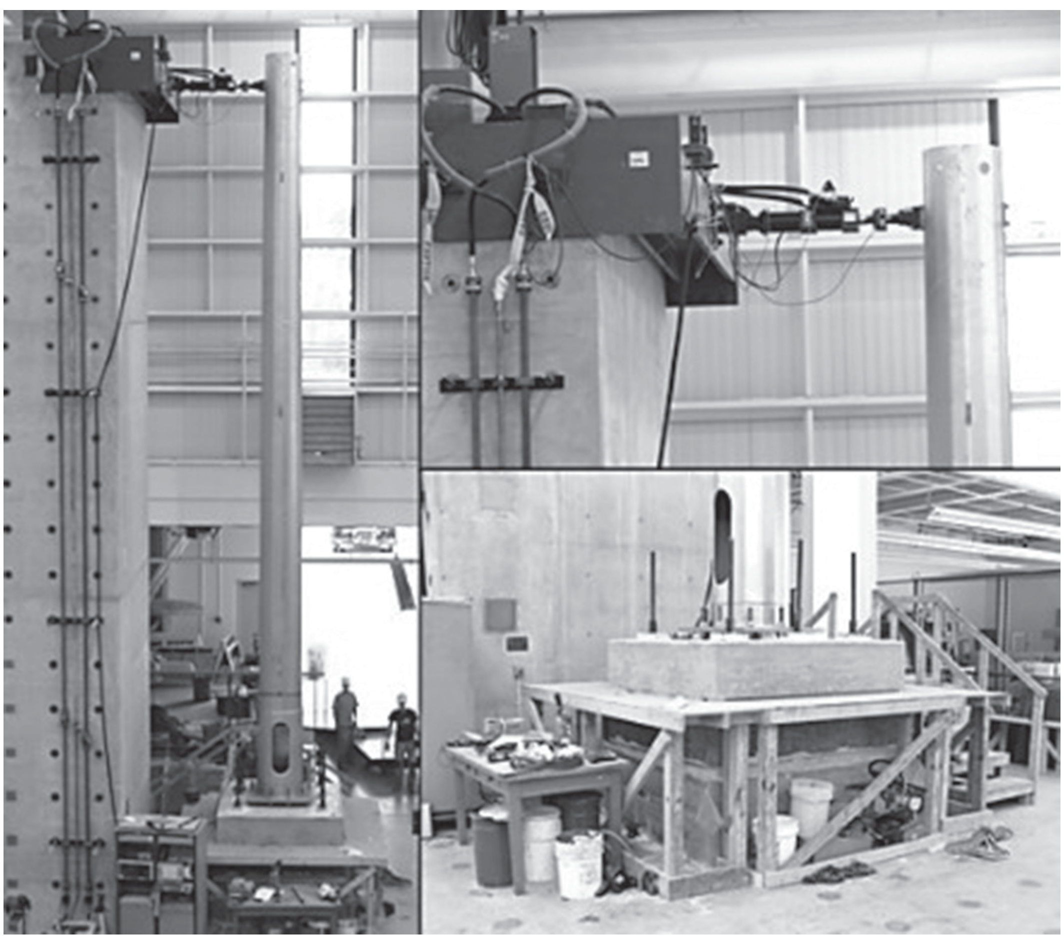

Fig. 10. As-built specimen test set-up (similar for all other specimens).

Table 1: Jacket Retrofit Performance Summary					
		Cycle Count		Final Crack Length (in.)	
Specimen	Projected* SR (ksi)	Crack First Observed	Final	North Face	South Face
AB_1	9.1	162,000	162,000	1.0	14.0
AB_2	9.1	25,800	260,000	21.5	17.0
TR_1	2.9	1,856,260	6,234,949	21.0	No crack
TR_2	2.9	—	10,045,448	No crack	No crack
TR_3	2.9	931,234	2,886,760	19.5	No crack
SR_1	2.9	309,008	1,145,540	17.0	2.0
SR_2	2.9	770,422	2,323,369	16.5	5.0
SR_3	2.9	1,498,373	5,037,731	11.8	7.9

* Nominal stress range in as-built pole 72 in. above base was 8 ksi for all specimens.

jacket to establish the stress transfer distribution from the pole to the jacket. Though details of these measurements are not discussed herein, the data confirmed the jacket was fully engaged and no slip occurred between the jacket and as-built pole.

As-Built Specimen Results

At the 8-ksi constant stress range, the two as-built specimens lasted 162,000 cycles and 260,000 cycles (Specimens AB_1 and AB_2, respectively) before reaching failure (see Table 1). The resulting fatigue life was worse than category E′ and was comparable with previous research on HMLT through-socket connection details (Rios, 2007; Roy et al., 2011). Fatigue cracks formed at the points of maximum stress at the base plate-to-tube wall connection. Specimen AB_1 had cracks of 14 in. (see Figure 11) on the south and 3.5 in. on the north. Specimen AB_2 had cracks of 21.5 in. and 17 in. (south and north, respectively). All cracks initiated from the base plate to tube wall weld at the upper weld toe. Both tests were stopped due to the size of the fatigue cracks.

Tall-Jacket Retrofit Specimen Results

Three tall-jacket retrofit specimens were tested to establish their fatigue resistance. The addition of the tall-jacket retrofit resulted in a substantial increase in fatigue life of the as-built pole. At a stress range of 8 ksi in the as-built pole, specimen TR_1 had a fatigue life of 6,235,000 cycles, specimen TR_2 had a fatigue life of 10,045,000 cycles and specimen TR_3 had a fatigue life of 2,887,000 cycles

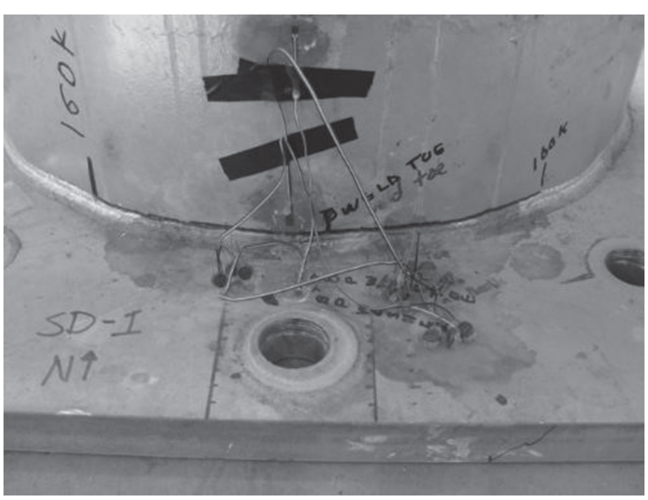

Fig. 11. Cracking on south face of AB_1.

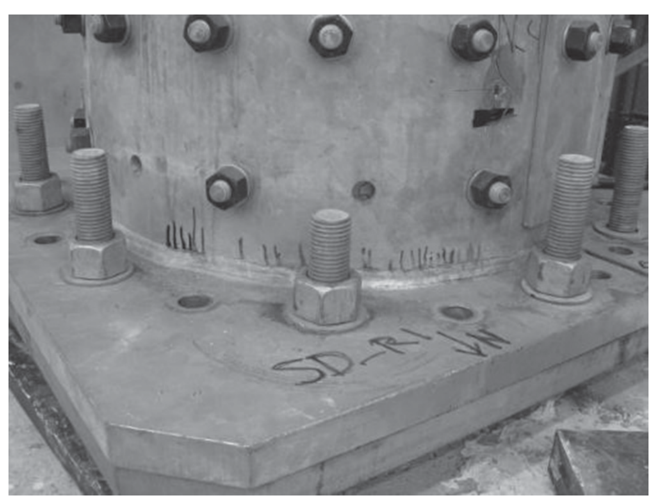

Fig. 12. Specimen TR_1: north crack at upper weld toe after inspection with dye penetrant.

(see Table 1). In two specimens (TR_1 and TR_3), cracks formed at the tube-to-base plate connection in the upper weld toe at the point of maximum stress. Specimen TR_2 was considered a runout for this test after cycling more than 10,000,000 cycles. The other two specimens had fatigue cracks that initiated in the weld toe at the points of maximum stress. Figure 12 shows the completed TR_1 specimen with fatigue cracks after using dye penetrant to verify crack length. The final crack length for specimen TR_1 was 21 in., while TR_3 had a crack measuring 19.5 in. All tests were stopped due to the crack length.

Short-Jacket Retrofit Specimen Results

Strain gages were placed in similar locations as the tall jacket in order to compare behavior. The stress range was maintained in the as-built pole at 8 ksi for the short jackets. Specimen SR_1 had a fatigue life of 1,146,000 cycles, specimen SR_2 had a fatigue life of 2,323,000 cycles and specimen SR_3 had a fatigue life of 5,037,731 cycles before reaching failure (see Table 1). Fatigue cracks initiated at the points of maximum stress and generally had consistent crack growth. Cracks initiated at the upper weld toe of the base plate-to-tube wall connection and grew circumferentially. Each of the three specimens formed cracks at both sides of the jacket (where stresses were highest). Crack lengths varied from 2.0 in. to 17.0 in. (see Figure 13 for cracks on specimen SR_1). Once again, all tests were stopped due to crack length.

DISCUSSION

Results from the fatigue testing are summarized in Table 1. The nominal constant amplitude stress range measured in the tube wall, 8 ksi, versus the number of cycles to failure for each specimen was plotted on an *S-N* curve (see Figure 14), showing the increase in life for the jacket retrofits compared to the as-built pole specimens. This fatigue curve was indicative of the performance for in-service conditions because, for an in-service HMLT, the nominal stress-range due to loading does not change (i.e., wind or loading did not increase because a retrofit was installed). By comparing the *best* performing as-built pole specimen to the *worst* retrofit specimen (AB_2 to SR_1), an increase in life of greater than 440% was achieved.

Two potential reasons for the observed increase in fatigue performance were evaluated: (1) an improvement in category of the fatigue detail and (2) a decrease in the stress range at the controlling fatigue detail. The test data were examined to determine the primary factors for the increased fatigue life of the retrofits.

The nominal stress range for each test was projected to the base of the pole using basic mechanics of materials. Using the nominal stress was desired for comparison to eliminate any local stress concentration effects, base plate flexibility effects and local effects due to the jacket. Strain gage measurements were used to verify the calculated stresses and were representative of the behavior of the pole. In doing so, it was found that the vertical stress near the base appeared to be resisted by a section modulus that included the thickness of the original tube wall and retrofit jacket. As expected, the reinforcing plate around the hand-hole did not significantly contribute to the section modulus because it did not extend to the base of the pole (see Figures 2 and 3). The original tube wall was generally observed to act in conjunction with the jacket near the base, even though there was a gap between these two plates at the very bottom. However, at the very

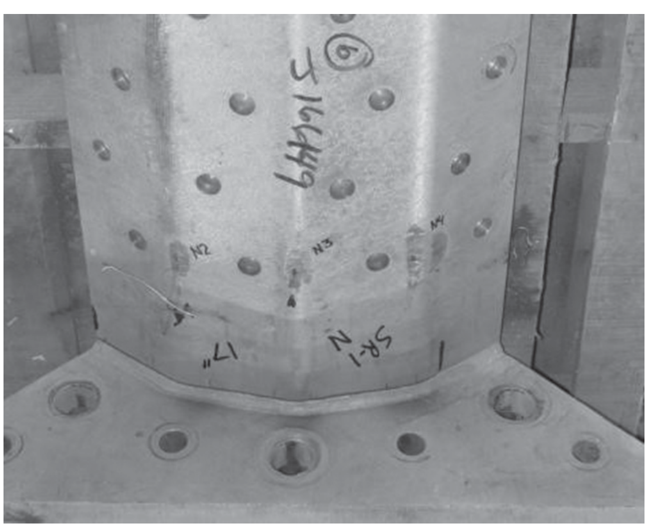

Fig. 13. Specimen SR_1: north crack at upper weld toe after inspection with dye penetrant.

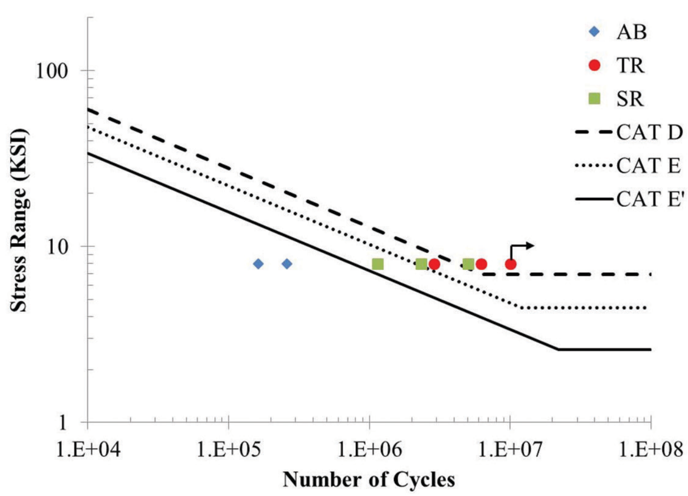

Fig. 14. Fatigue test data (nominal stress-range) plotted with AASHTO fatigue curves.

bottom of the retrofit jacket, adjacent to the weld, only the retrofit jacket was available to carry the moment due to the severed as-built pole to base connection. As a result, only cross-section of the retrofit jacket was used to calculate the stress range at this location. Using these revised stresses and the projected stresses from the as-built pole, the data were plotted again as shown in Figure 15.

Plotting the adjusted data indicated that the increase in fatigue life was primarily due to the decrease in stress range at the controlling fatigue detail and not due to a significant improvement in detail category. The sloped line through the fatigue data points in the *S-N* curve of Figure 15 suggested the behavior of the tall-jacket retrofit was approximately the same as the as-built pole. In fact, the fatigue behavior of the short-jacket retrofit appeared to be slightly worse than that of the as-built structure. The lower fatigue life was not surprising because the short jacket was observed to be more flexible. This added flexibility produced out-of-plane bending stresses near the base plate weld, which are not accounted for by the basic nominal stress range calculations. Thus, a lower fatigue life is observed. Figure 15 shows that the fatigue life of the short jackets was lower than both the as-built specimens and the tall jackets. Thus, the increase in life realized by adding the retrofit jacket was due to the drop in the effective stress range and not an improvement in fatigue category associated with the CJP weld.

Interpretation of Results

The lower fatigue performance of TR_3, compared with TR_1 and TR_2, is attributed to poor fit-up resulting in cyclic distortion between the original base plate and the base plate of the jacket. This was visually observed during testing. The distortion resulted in increased local stress ranges at the base plate weld of the jacket. Similar observations were made during the HMLT retrofit testing conducted for Iowa (Callahan and Connor, 2011).

The stress range applied in the laboratory was greater than the typical in-service effective stress ranges measured in the field on poles of similar cross-section. For example, the average nominal effective stress range in a nearly identical as-built pole located in Rapid City, South Dakota, was approximately 1.0 ksi (Connor et al., 2011). Further, based on field measurements of the Rapid City pole, an average of approximately 12,000 cycles were accumulated per day over an interval of about 590 days. Assuming all cycles less than 0.5 ksi were truncated (due to insignificance), a life estimate of an in-service retrofit jacket was made using the data collected from the in-service measurements in conjunction with the laboratory fatigue test data presented herein.

This estimate was made using several conservative, but reasonable assumptions:

1. The number of cycles per day (12,000) is reasonable based on the field measurements made at 11 other locations across the country as reported in NCHRP Report 718 (Connor et al., 2011).

2. If the laboratory pole was placed under identical loading conditions as the field-tested pole (Rapid City, South Dakota, as reported in NCHRP Report 718), the ratio of the section modulus of the field tested pole (S_{x_Field}) and laboratory pole (S_{x_Lab}), calculated to be approximately 2, should be applied to the field-measured effective stress range (S_{ref_Field}) to obtain the effective stress range of the laboratory pole and/or jacket (S_{ref_Lab}) in field-like conditions.

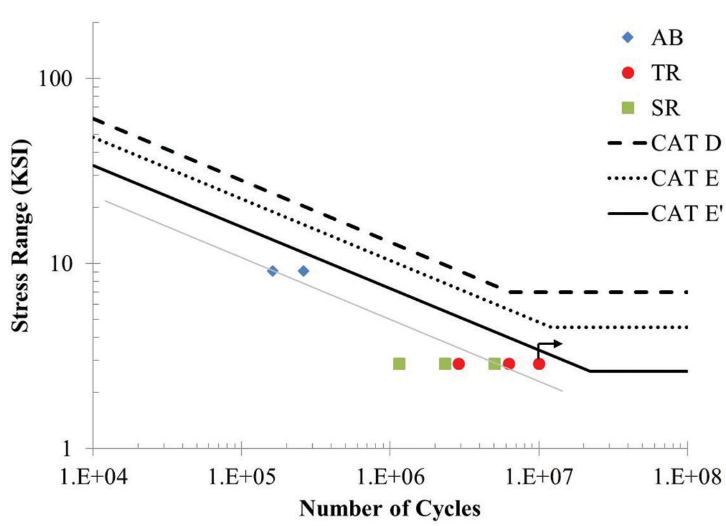

Fig. 15. Fatigue test data (nominal stress-range projected to base) plotted with AASHTO fatigue curves.

$$\left(S_{ref\_Lab}\right)\left(S_{x\_Lab}\right)=\left(S_{ref\_Field}\right)\left(S_{x\_Field}\right)$$

$$S_{ref\_Lab}=S_{ref\_Field}\left(\frac{S_{x\_Field}}{S_{x\_Lab}}\right)$$

$$=1\text{ ksi }(2)$$

$$=2\text{ ksi}$$

3. The number of cycles to failure follows the normal AASHTO *S-N* curve relation:

   $N=A/S_{ref}^{3}$

   where *A* is the detail constant

4. Although S_{ref} is less than the fatigue limit, the fatigue limit is exceeded in the variable amplitude stress range spectrum more than 1 in 10,000 times (i.e., all cycles contribute to damage).

Based on these assumptions the estimated number of cycles to failure, assuming the *poorest* performing of the six tested jackets was installed in the field with a completely severed base connection (an extreme, worst-case condition), was calculated as:

$$A=\left(N_{Field}\right)\left(S_{ref\_Field}\right)^{3}$$

$$=\left(N_{Lab}\right)\left(S_{ref\_Lab}\right)^{3}$$

$$N_{Field}=\frac{(1{,}145{,}540\text{ cycles})(8\text{ ksi})^{3}}{(2\text{ ksi})^{3}}$$

$$=7.3\times10^{7}\text{ cycles}$$

Converting cycles into years (assuming 12,000 cycles/day) yields:

$$\frac{7.3\times10^{7}\text{ cycles}}{\left(12{,}000\ \frac{\text{cycles}}{\text{day}}\right)\left(365\ \frac{\text{days}}{\text{year}}\right)}=16.7\text{ years}$$

Next, using the best performing as-built pole (i.e., no jacket) tested in the laboratory, the life of that same pole installed in the field can be estimated as follows:

$$N_{Field}=\frac{(260{,}000\text{ cycles})(8\text{ ksi})^{3}}{(2\text{ ksi})^{3}}$$

$$=1.7\times10^{7}\text{ cycles}$$

$$\frac{1.7\times10^{7}\text{ cycles}}{\left(12{,}000\ \frac{\text{cycles}}{\text{day}}\right)\left(365\ \frac{\text{days}}{\text{year}}\right)}=3.8\text{ years}$$

The preceding example indicates a life increase from 3.8 years to 16.7 years, or 440%. This approach was applied to all jacket retrofit specimens tested. Life increases ranged from the earlier reported 440% to greater than 3,800% for the run-out specimen, with an average life increase of 1,770%. During the fatigue testing, the jackets resisted the entire bending moment because the tube walls were completely severed. Thus, these calculations were a conservative assessment of the increase in fatigue life for a retrofitted HMLT.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the research, the following conclusions and recommendations are made:

- The fatigue performance of the fillet-welded socket base connection is poor.
- Fabrication quality has a large impact on performance; therefore, onsite measurements of the pole to be retrofit are recommended to improve fit-up. Further, an ultrasonic testing (UT) examination should be performed on the base plate–to–tube wall connection detail.
- Installation and fit-up challenges associated with the tall-jacket retrofit concept are much greater than those associated with the short-jacket retrofit concept as tested herein. It is expected that dividing the tall jacket into quarters—though not explicitly tested as part of this research—will improve installation fit-up with little to no impact on fatigue performance (based on the results of the short-jacket retrofit).
- Both jacket retrofit concepts have been shown to provide an effective repair/retrofit solution for existing in-service HMLTs in extending their functional life more than 400%.

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