Discussion of Tubular Steel Monopole Base Connections:

The Base Weld Toe Crack Phenomenon: Crack Identification and Proposed Severity Classification System

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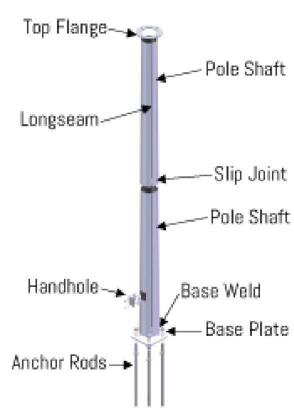
Tubular steel monopoles (poles) are popular support structures in many industries today and have been utilized as support structures in the communications, sports lighting, utility, and transportation industries for many decades. Combining a long history of reliable performance, competitive pricing, and ease of use and installation, steel poles are the preferred structure for numerous aerial support requirements. The use of poles in the communications industry has exploded in the last twenty years due to ever-increasing demand for voice and data usage. However, in the last decade, there have been numerous failures of steel poles across the country in various industries that are attributed to unmitigated cracks in welds at the pole to base plate connection. The property damage in some cases has been significant; and at the very least there is service interruption and repair/replacement costs associated with subsequent loss of the structure. It's reasonable to assert that these failures could have been prevented if timely periodic inspection and maintenance had been performed on these structures. As with America's other aging infrastructure, the cost of ignoring this issue can be significant to public safety, welfare, and your assets. The purpose of this article is to raise awareness of this issue and provide guidance to safely maintain and prolong the service life and reliability of your monopole assets. This paper presents a proposed monopole base crack classification system which is intended to standardize the way the industry deals with inspection, repair, and maintenance of pole base connections.

STEEL POLES

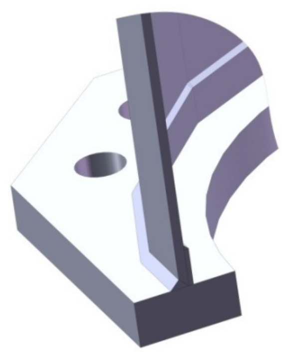
An anchor-based pole has a welded base plate that connects the structure via the anchor rods to the foundation. The base connection is facilitated by shop-welding the steel base plate to the bottom of the pole shaft during fabrication at the original manufacturer's facility. The weld between the base plate and the pole shaft is the only structural connection between those members, it is non-redundant, and therefore the structural adequacy and integrity of this welded connection is crucial to the performance of the structure.



An unmitigated failure, if one was to occur at this joint, will in almost all cases be catastrophic resulting in the collapse of the pole.

The connection detail of the pole shaft to the base plate can vary depending on the type of pole and/or the manufacturer. Typical pole base connection weld details include complete joint penetration groove weld (CJP) and socket style (double fillet weld) connections as shown in the figures below. The CJP connection base plate is butted against the pole shaft and consists of a circumferential single-bevel groove weld with 100% complete weld penetration (CJP) and a reinforcing fillet weld. In other words, the connection zone is all weld material. This connection style is very popular (especially for polygonal poles), a cost economical method of fabrication, and traditionally the base connection of choice for most major pole manufacturers. The socket connection base plate sleeves over the pole shaft and is welded with double fillet welds above and below the sleeved base plate. This connection is also popular due to the fact that the welds are simple fillet welds and a non-destructive examination (NDE) ultrasonic test is not performed on this joint post-fabrication reducing quality assurance costs. The socket connection is easier to fabricate for a round pole than for a polygonal pole. While other joints may be possible (including shop welded base plate stiffeners), the majority of anchor-based poles manufactured fall into one of these two base joint categories.

Typical Communications Monopole Base Connection



Complete Penetration Joint (CJP)

Socket Joint

FAILURES

Pole collapses, while traditionally a very infrequent occurrence, have made news in recent years due to structure failures in both the communication and sports lighting industries. In the sports lighting industry, the first ever recall on poles was issued by the Consumer Product Safety Commission in 2010. With these structures' proximity to areas where people live, work and gather, there is a significant potential for loss of property damage, injury and possibly even loss of life.

Almost all recent pole failures have possessed one similar characteristic: unmitigated and latent toe cracks in the pole shaft immediately above the base plate weld that propagated over time to an extent that caused this connection to fail and the structure to collapse. In recent years, many owners have implemented inspection programs to identify base defects that can be detrimental to the long-term performance and reliability of their pole structures. Toe cracks can be identified during these preventative inspections if the inspector is qualified, experienced, and knows what to look for. The key to maintaining the reliability of your assets is to routinely inspect and maintain them; if crack indications are discovered, then a properly engineered repair can be designed and installed. It is important to note that cracks can develop over time since the structure is constantly exposed to dynamic environmental (wind, fatigue, etc.) influences and increasing loading conditions due to industry demand. Routine inspection and maintenance is the only sure way to reliably extend the service life of your structures and protect your assets.

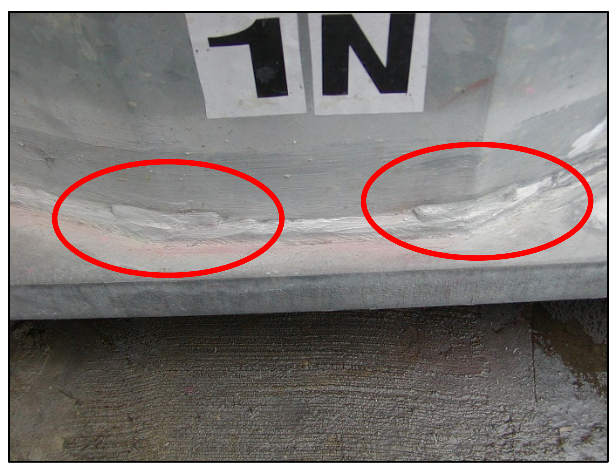
ANATOMY OF A WELD CRACK

According to the American Welding Society (AWS), a defect is a discontinuity which exceeds the permissible limit of a code (AWS A3.0). A crack is a fracture type discontinuity characterized by a sharp tip and high ratio of length and width to opening displacement (AWS A3.0). Cracking occurs in a weld and base metal when the localized stresses at the connection exceed the ultimate strength of the material. Cracking is often associated with stress amplifications near discontinuities in welds and base metal, or near mechanical notches associated with the weldment design. Left in place without repair (unmitigated), cracks may propagate over time and continued loading and can be very detrimental to structural integrity. In addition, cracks greatly reduce the fatigue strength of a member. It is important to note that the AWS Structural Welding Code D1.1 does not allow a crack regardless of size or location to be left in a weldment after inspection per Part 1 of Table 6.1, regardless of size or location (AWS D1.1).

A "toe crack" is defined as a crack in the base metal at the toe of a weld. Toe cracks are generally cold cracks that initiate approximately normal to the base material surface and then propagate from the toe of the weld where residual stresses are higher. These cracks are generally the result of thermal shrinkage strains acting on a weld heat-affected zone that has been embrittled. Toe cracks sometimes occur when the base metal cannot accommodate the shrinkage strains that are imposed by welding. The crack can occur immediately after the hot-dip galvanizing process or a period of time after galvanizing. Toe cracks have not typically been observed in weathering steel or painted poles (not hot-dip galvanized). Typically toe cracks are identified at the upper toe of the base plate weld in the pole base section shaft material.

The phenomenon of toe cracking is not new and has been observed within the pole industry since the 1970's. ANSI/NEMA TT 1 "*Tapered Tubular Steel Structures*" (1983) in Section 10.5 states that *"Shaft to base plate welds shall be inspected by the ultrasonic method for evidence of cracking in the shaft or base plate heat affected zone."* The American Society of Civil Engineers (ASCE) Manual 72, "*Design of Steel Transmission Pole Structures,*" 2nd edition (1990) states in Section 3.5.3.3 Special Design Considerations *"Toe cracking of weldments: Toe cracks, around T-joint welds, undetectable prior to galvanizing have been detected after galvanizing. The formation of these cracks appears to be influenced by several factors in the fabrication process. Requirements for post-galvanizing inspection should be considered."* Most pole manufacturers inspect for toe cracks after the galvanizing process as a normal part of their quality assurance program. In instances where preventative field inspections have been performed on the base plate weld connection while in service, cracks have been found in the pole shaft at the upper toe above the base plate weld. This has occurred on multi-sided (polygonal) and round poles in both complete joint penetration (CJP) groove weld and socket base plate connections. Toe cracks in polygonal poles typically first occur near the vertices (bend-lines or "points" of the multi-sided shaft) since this area generally has a higher stress concentration.

Manufacturer Toe Crack Repairs Visible in the Field



Manufacturer Repair or Reinforcement of Upper Toe of Base Weld Observed in Field

ROOT CAUSES

Toe cracks have been a recognized issue in the pole industry for many years with numerous investigations and discussions on this subject. While all the contributing issues and their interactions are still not fully understood, discussions regarding toe crack root causes continue and the current consensus is that this phenomenon generally involves an interaction of several of the following components:

1. Design: Issues can arise when the base plate design results in an under-sized (i.e. too thin), relatively flexible, base plate which creates increased joint flexibility. The relationship between base plate weight (a function of plate thickness) and base shaft section weight (a function of shaft thickness) is also a factor which can create unbalanced thermal stresses during the galvanizing process. Issues can also arise when the base plate design is very thick. Contrary to engineering judgement, bigger (thicker) base plates are not always better when it comes to the occurrence of toe cracks. The larger the difference between the base section shaft thickness and the base plate thickness, the more probable is the occurrence of toe cracking due to the thermal stresses induced during galvanizing of the assembled section. During the galvanizing process, the larger base plate requires more time to heat during immersion in the liquid zinc and more time to cool after it is removed; whereas the base shaft section heats up and cools relatively quickly. The effect of this unbalanced thermal expansion and contraction is that the base plate restrains the pole shaft and induces stress concentrations in the heat-affected zone at the upper toe of the weld in the relatively thin pole shaft, and this is where the cracking first occurs. At this time there is no universal consensus among design engineers as to what defines a base plate as ‘too thin’ or ‘too thick’. There have been recent efforts in the ASCE 48 Standard Committee (“Design of Steel Transmission Pole Structures”) and the TIA-TR14 Committee (TIA-222-G Standard Addendum 3) to develop a proposed method for base plate design using a yield-line approach. However, regardless of the design method used, it does not appear feasible that a welded base plate connection can be designed to be “crack-proof” or “fatigue-proof”. There are too many other factors other than design alone that can influence crack development and fatigue damage.
2. Materials: Includes quality of material being joined, weld electrodes, high yield/tensile base material strengths, high carbon equivalents (CE), and other metallurgical properties.
3. Fabrication: The manufacturing (cold bending) of a polygonal section: polygonal tubular pole sections are fabricated by cold press-forming high-strength steel plate using a press brake. Embrittling of the steel can occur at the bend points due to the cold working of the material (i.e. strain hardening) resulting in high residual stresses.

4. Welding: Poor welding quality and process, lack of proper pre-heat during welding fabrication, poor weld profile, and improper and/or inconsistent heat input during welding process.

5. Quality: Poor manufacturing quality control; quality checks at the original manufacturer after fabrication and galvanizing overlooked or incorrectly performed.
6. Galvanizing: (Refer to the discussion of unbalanced thermal stresses in the Design item above.) Hot-dip galvanization is the process of coating steel with a layer of zinc by immersing the metal in a bath of molten zinc at a temperature around 840 °F (449 °C). Thermal expansion, hydrogen embrittlement, and the thermal stress differentials due to the large differences in thicknesses between the base section pole wall and the base plate all combine to create the potential for crack formation.
7. Installation: Loose foundation anchor nuts and/or leveling nuts after installation or improper grouting of the base plate causing unanticipated stress increases in the weld joint.

While any single item in the list above can be detrimental to the structure, a combination of two or more of any of the above items can facilitate even more rapid crack development and potentially lead to failure of the base weld connection. This is why it is imperative for the owner to have a program of routine inspection and maintenance performed by qualified engineers.

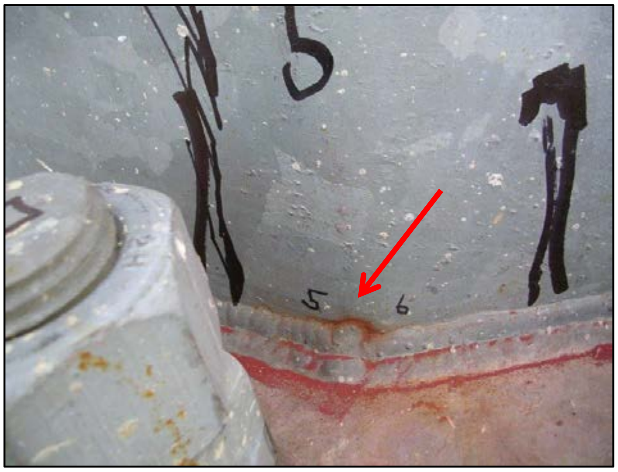
FIELD OBSERVATIONS

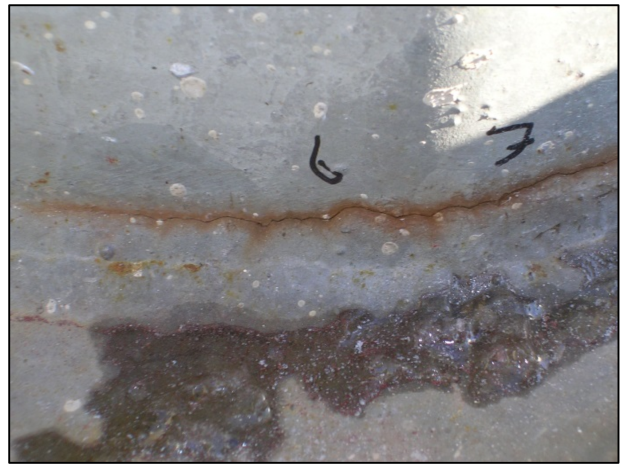
Some pole owners have already recognized this issue and have been conducting routine inspections of their pole bases. Base weld toe cracks have been observed in the field with regularity.

Findings range as follows:

1. In the most severe cases, visible with the naked eye 'wandering' along the upper toe of the weld on the press bend line between two flats on a multi-sided pole (see photos below)
2. Identified with magnetic particle (MT) testing at surface or near-surface, but not visible with naked eye
3. Identified with ultrasonic testing (UT) but not identified with magnetic particle (MT) testing or visible with naked eye
4. Ranging from one location only to each bend line of the pole base section
5. Varying from fractions of an inch to multiple inches in length
6. Depths ranging from thousands of an inch to clear through the base wall thickness (see photo below)
7. Significant bleeding rust observed at the crack at the upper toe of the weld can indicate the crack is completely through the pole shaft thickness

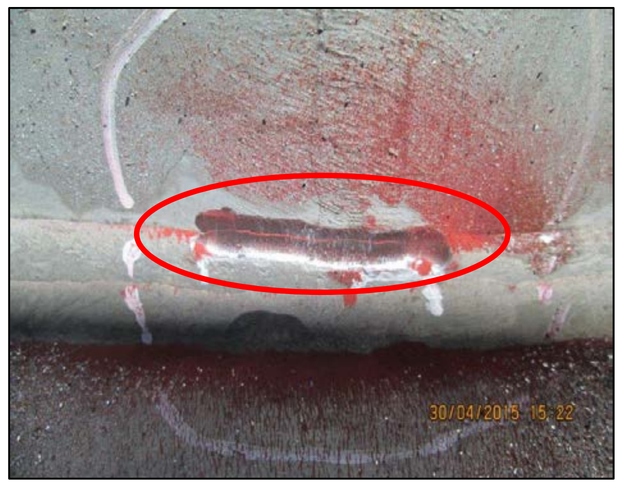
A weld repair of the base connection, as designed by a qualified engineer, is possible in many instances when performed by a qualified welder following an approved welding procedure. However, the timing of the repair based on the severity of the cracks has been a source of debate and confusion for owners and engineers.





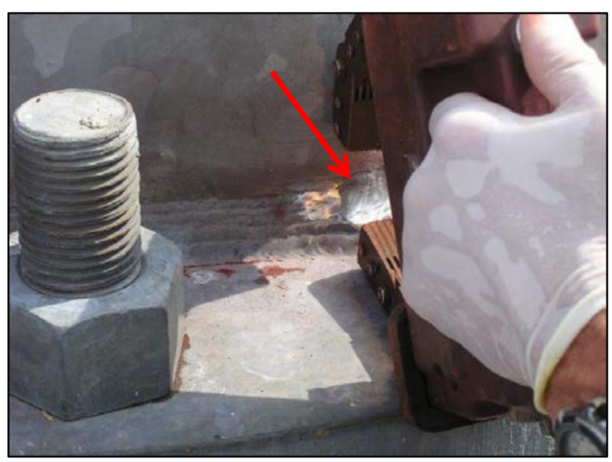
Toe Cracks at Upper Toe of Weld in Pole Shaft at Polygonal Bend Line (Visible Rust)

Minor Toe Crack Visible via MT Powder after Light Grinding



Toe Crack Still Visible via MT Exam after Grinding

Socket Style Pole Base Through-Wall Toe Cracking Viewed From the Inside of the Pole (Visible Rust)



MT Exam Showing Indication (Crack) at Upper Toe

PROPOSED CRACK CLASSIFICATION SYSTEM

The overriding question with toe crack repairs is the timetable required to implement a repair balanced against the extent of the damage to the structure base connection and corresponding reduction in structural capacity. The owners and their design engineers have numerous questions to address: What is the extent of the damage? How urgent is the condition? How quickly must a repair be conducted? Do I need to temporarily support the structure? In response to industry need to classify the severity of the crack(s) in this critical connection and the allowable timeframe to implement the required repairs, a proposed crack classification system has been developed. Based on crack severity (length and depth), the system provides a corresponding recommended repair time frame category in Table 1 below. In addition, category influenced by the age of the pole is considered.

The crack attributes of concern are the depth percentage of the toe crack into the base shaft material versus the thickness of the pole shaft and the length of the crack(s) versus the pole base circumference percentage as detailed in Table 2. The depth of the crack is estimated during the field inspection via ultrasonic testing (UT), a non-destructive weld examination technique. The length of the crack is a cumulative total of all the crack lengths identified around the circumference at the base. Classification categories range from 0 with no cracking to 4, the most severe condition. Repair time frames range from immediate repairs required to sixty (60) days.

Table 3 further corresponds crack depth and length versus the pole age if known to a corresponding repair classification. This is to alert the owner and engineer that extensive cracks in a newer structure can be very detrimental and may be indicative of more serious issues such as fatigue or an under-design situation. Table 3 may default a structure into a higher classification category requiring a reduced repair schedule. For example purposes, classification calculations are included below.

EXAMPLE NO. 1

Given Parameters:

- ✓ Nine (9) total toe cracks identified via NDE techniques
- ✓ Circumference of pole base shaft at weld C_s= 96.0”
- ✓ Pole base shaft thickness t = 0.38”
- ✓ Crack lengths = 1.00”, 1.00”, 1.50”, 0.75”, 4.00”, 6.25”, 3.13”, 9.75”, 2.50”
- ✓ Depth of cracks d_c = 0.13”, 0.13”, 0.06”, 0.13”, 0.16”, **0.18”**, 0.06”, 0.06”, **0.18”**
- ✓ Pole age six (6) years

Calculations:

- ➢ Total crack length L_c = 29.9”
- ➢ Total crack length L_c vs. pole base circumference C_s = 29.90” / 96.0” = 31%
- ➢ Maximum crack depth d_c vs base shaft thickness t = 0.18” / 0.38” = 47%

Resulting Classification Category:

1. Total length of all cracks is between 1/4 and 1/2 circ. (C_S) of shaft: $\frac{1}{4} C_S \leq L_c \leq \frac{1}{2} C_S$
2. Maximum depth of most cracks is less than 1/2 the shaft thickness: $d_c < \frac{1}{2} t$ (most)
3. No cracks have a depth greater than three-quarters the shaft thickness: $d_c < \frac{3}{4} t$ (all)

The resulting classification is CATEGORY 2; moderate toe crack indications identified, cracks are only partial depth through pole base shaft thickness. However, the pole age is six (6) years. For a pole age of 5 to 10 years, Table 3 recommends the engineer consider a more stringent classification **CATEGORY 3**.

Corrective actions**:** Remove cracks via grinding and repair welds and install stiffeners as specified by the engineer

Repair schedule: Complete all repairs within fourteen (14) days

EXAMPLE NO. 2

Given Parameters:

- ✓ Eighteen (18) total toe cracks identified via NDE techniques
- ✓ Circumference of pole base shaft at weld C_s= 150.0”
- ✓ Pole base shaft thickness t = 0.50”
- ✓ Crack lengths = 4.50”, 3.25”, 1.50”, 5.75”, 4.00”, 4.25”, 4.13”, 6.25”, 3.50”, 4.00”, 3.00”, 4.50”, 5.75”, 4.00”, 5.25”, 4.13”, 6.75”, 8.50”
- ✓ Depth of cracks d_c = 0.13”, 0.13”, 0.05”, 0.38”, 0.38”, 0.18”, 0.05”, **0.44”**, 0.18”, 0.13”, 0.13”, 0.38”, **0.44”**, 0.18”, 0.38”, 0.05”, 0.25”, 0.38”
- ✓ Pole age eleven (11) years

Calculations:

- ➢ Total crack length L_c = 83.00”
- ➢ Total crack length L_c vs. pole base circumference C_s = 83.0” / 150.0” = 55%
- ➢ Maximum crack depth d_c vs base shaft thickness t = 0.44” / 0.50” = 88%

Resulting Classification Category:

1. Total length of all cracks exceeds half the circumference (C_S) of shaft: $L_c > ½ C_S$
2. Maximum depth of most cracks equals or exceeds 3/4 the shaft thickness: $d_c \geq ¾ t$
3. Pole age eleven (11) years

CATEGORY 4 - Severe toe crack indications identified; cracks are mostly full depth through pole base shaft thickness

Corrective actions: Immediately do all of the following: stabilize the pole until repairs are completed, remove cracks via grinding and/or drill holes at ends to prevent further crack propagation, and repair welds and install base plate stiffeners as specified by the engineer

Repair schedule: Immediately stabilize the pole structure and begin repairs

CONCLUSION

The formation of toe cracks at the base connection of tubular steel poles has been an industry challenge for many years; and it continues to be a challenge. There are many contributing factors to this issue. Field inspections have shown the importance of understanding and reacting appropriately regarding this issue. Visual and NDE inspection techniques are critical and should be regularly scheduled. It is imperative that inspections are carried out by qualified personnel with specific pole experience, CWI credentials, and non-destructive ASNT credentials. Left unresolved, propagating toe cracks can cause eventual failure of the base connection and lead to the potential collapse of the structure. If identified via timely inspection, these defects can be resolved via weld repairs which restore the original integrity of the structure. Timetable for the required repairs is based on the severity of the weld cracking and age of the structure. This paper presents a proposed crack classification system which is intended to standardize the way the industry deals with inspection, repair, and maintenance of pole base connections.

It is important to note that cracks can develop over time since the structure is constantly exposed to dynamic environmental (wind, fatigue, etc.) influences and the ever increasing loading requirements of these structures. Routine inspection and maintenance is the only sure way to reliably protect your assets and extend the service life of your structures.

Table 1: Base Plate Weld Toe Crack Classification

Classification Category	Description of Weld Toe Crack Category
0	No toe crack indications identified No cracks identified during a complete CWI inspection using Visual and NDE techniques (typically MT & UT); no corrective action required
1	Small toe crack indications identified Cracks are only partial depth through shaft thickness. Crack Length: Total length of all cracks is less than one quarter circumference (C_S) of shaft: $L_c < \frac{1}{4} C_S$ Crack Depth: Maximum depth of all cracks is less than half the shaft thickness: $d_c < \frac{1}{2} t$ *(all)* Corrective Actions: a. Remove cracks via grinding b. Repair welds and install stiffeners as specified by the engineer *Repair Schedule:* *Complete all repairs within sixty (60) days*
2	Moderate toe crack indications identified Cracks are only partial depth through shaft thickness. Crack Length: Total length of all cracks is between ¼ and ½ circumference (C_S) of shaft: $\frac{1}{4} C_S \leq L_c \leq \frac{1}{2} C_S$ Crack Depth: Maximum depth of most cracks is less than half the shaft thickness: $d_c < \frac{1}{2} t$ *(most)* No cracks have a depth greater than three-quarters the shaft thickness: $d_c < \frac{3}{4} t$ *(all)* Corrective Actions: a. Remove cracks via grinding b. Repair welds and install stiffeners as specified by the engineer *Repair Schedule:* *Complete all repairs within thirty (30) days*
3	Extensive toe crack indications identified Cracks are mostly partial depth with some full depth through shaft thickness. Crack Length: Total length of all cracks is between ¼ and ½ circumference (C_S) of shaft: $\frac{1}{4} C_S \leq L_c \leq \frac{1}{2} C_S$ Crack Depth: Maximum depth of most cracks is less than three-quarters the shaft thickness: $d_c < \frac{3}{4} t$ *(most)* Few cracks have a depth greater than three-quarters the shaft thickness: $d_c \geq \frac{3}{4} t$ *(few)* Corrective Actions: a. Remove cracks via grinding and/or drill holes at ends to prevent further crack propagation b. Repair welds and install stiffeners as specified by the engineer *Repair Schedule:* *Complete all repairs within fourteen (14) days*
4	Severe toe crack indications identified Cracks are mostly full depth through shaft thickness. Crack Length: Total length of all cracks exceeds half the circumference (C_S) of shaft: $L_c > \frac{1}{2} C_S$ Crack Depth: Maximum depth of most cracks equals or exceeds three-quarters the shaft thickness: $d_c \geq \frac{3}{4} t$ Corrective Actions: a. Immediately stabilize the pole until repairs are completed b. Immediately remove cracks and/or drill holes at ends to prevent further crack propagation c. Immediately begin to repair welds and install stiffeners as specified by the engineer *Repair Schedule:* *Immediately stabilize the pole and begin repairs*

Table 1 Definitions:

L_c = Total length of all weld cracks measured around circumference $\sum (L_1+L_2+L_3…)$

d_c = Maximum measured depth of crack into the shaft thickness

D_F = Diameter of pole shaft across flats

t = Thickness of pole shaft

π = pi 3.14159

C_S = Circumference of pole shaft: $(\pi)(D_F)$ (approximate)

CWI = Certified Welding Inspector, credentialed per American Welding Society (AWS)

Visual = Visual weld inspection per AWS D1.1

NDE = Nondestructive examination; the act of determining the suitability of a material for its intended purpose using techniques not affecting its serviceability

MT = Magnetic particle NDE weld inspection (surface/near surface) per AWS D1.1

UT = Ultrasonic NDE weld inspection (volumetric) per AWS D1.1 or procedure

Crack = A fracture-type discontinuity characterized by a sharp tip and high ratio of length and width to opening displacement

Toe Crack = A defect observed at the upper weld toe

Table 2: Weld Toe Crack Classification Based on Crack Depth and Length Criteria

	Maximum Depth of Measured Weld Crack			
Total Length of Cracks	$d_c < \frac{1}{4}$ t	$d_c < \frac{1}{2}$ t	$d_c < \frac{3}{4}$ t	$d_c \geq \frac{3}{4}$ t
$L_c < \frac{1}{4} C_S$	1	1	2	3
$\frac{1}{4} C_S \leq L_c \leq \frac{1}{2} C_S$	1	2	3	4
$L_c > \frac{1}{2} C_S$	2	3	4	4

Table 3: Weld Toe Crack Classification
Based on Crack Depth and Length Criteria vs. Pole Age

Age of Pole In Years	Maximum Depths and Lengths of Measured Weld Cracks						
	$L_c < \frac{1}{4} C_S$		$\frac{1}{4} C_S \leq L_c \leq \frac{1}{2} C_S$		$L_c > \frac{1}{2} C_S$		*Total Length (L_C)*
	$d_c < \frac{1}{2}t$	$d_c \geq \frac{1}{2}t$	$d_c < \frac{1}{2}t$	$d_c \geq \frac{1}{2}t$	$d_c < \frac{1}{2}t$	$d_c \geq \frac{1}{2}t$	*Crack Depth (d_C)*
< 5	2	3	3	4	3	4	
5 to 10	1	2	3	4	3	4	
> 10	1	2	2	3	3	4	

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