Monopole Base Weld Toe Cracks and Why They May Collapse Your Tower

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Crack identification and a proposed severity classification system hold promise for helping owners maintain their towers in the face of aging and wear that can lead to cracks that threaten structural integrity.

Tubular steel monopoles (poles) are popular support structures in many industries (see Figure 1). They have seen use 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, users prefer steel poles for numerous aerial support requirements. Telecommunications pole use exploded during the past 20 years with an ever-increasing demand for voice and data service. In the last decade, numerous steel poles deployed in various industries failed because of unmitigated cracks in welds at the pole-to-base plate connection. The failures caused significant property damage in some cases and, at the least, service interruption and pole repair or replacement cost. Timely periodic inspection and maintenance could have prevented the pole failures. Ignoring cracks in welds places public safety and welfare at risk along with your assets. The following information provides guidance to safely maintain and prolong monopole service life and reliability. It presents a proposed monopole base crack classification system intended to standardize inspection, repair and maintenance of pole base connections.

Figure 1. Tubular steel monopoles are popular support structures in many industries. They have seen use as support structures in the communications, sports lighting, utility and transportation industries for many decades.

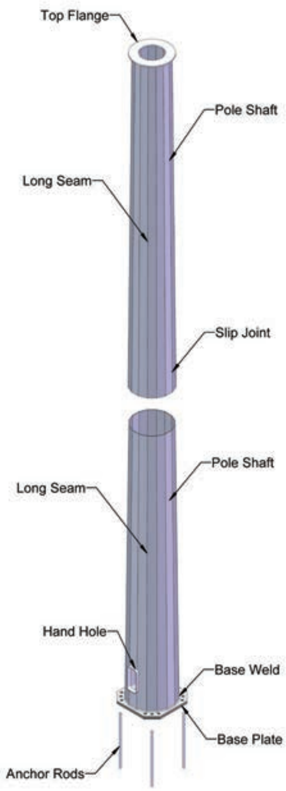

Figure 2. An unmitigated failure of the welded connection between the base plate and the pole shaft almost always causes a pole to collapse.

Figure 3. Typical pole base connection weld details include complete joint penetration (CJP) groove weld and socket-style (double-fillet weld) connections.

Figure 4. Although poles collapse infrequently, when they do, it often makes the news.

Steel Poles

An anchor-based pole has a welded base plate that connects the structure via the anchor rods to the foundation (see Figure 2). 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 nonredundant, and therefore the structural adequacy and integrity of this welded connection is crucial to the structure. If an unmitigated failure were to occur at this joint, in almost all cases the pole would collapse.

The connection detail of the pole shaft to the base plate can vary depending on the type of pole or the manufacturer. Typical pole base connection weld details include complete joint penetration (CJP) groove weld and socket-style (double-fillet weld) connections (see Figure 3). The CJP connection base plate butts against the pole shaft and consists of a circumferential single-bevel groove weld with 100 percent complete weld penetration and a reinforcing fillet weld. In other words, the connection zone is all weld material. This connection style is especially popular for polygonal poles. The fabrication method is economical. It's the base connection most major pole manufacturers choose.

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 because the welds are simple fillet welds, and a nondestructive examination (NDE) ultrasonic test is not performed on this joint post-fabrication, which reduces the quality assurance cost. The socket connection is easier to fabricate for a round pole than for a polygonal pole. Although it may be possible to use other joints (including shop-welded base plate stiffeners), the majority of anchor-based poles manufactured fall into one of these two base joint categories.

Failures

Pole collapses, although they generally occur quite infrequently, have made news in recent years because of structure failures in both the communications and the sports lighting industries (see Figure 4). In the sports lighting industry, the first-ever recall of poles was issued by the U.S. Consumer Product Safety Commission in 2010. The proximity of these structures to areas where people live, work and gather raises a significant potential for property damage, injury and possibly even loss of life.

Almost all recent pole failures have 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

Figure 5. Toe cracks in polygonal poles typically first occur near the vertices (bend-lines or points of the multisided shaft) because this area generally has a higher stress concentration.

identified during these preventive inspections if the inspector is qualified and experienced enough to know what to look for. The key to ensuring 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. Cracks can develop over time because the structure is constantly exposed to dynamic environmental influences such as wind, fatigue and increased loading. Routine inspection and maintenance are the only sure ways 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 that exceeds the permissible limit of a code (AWS 3.0). A crack is a fracture type of discontinuity characterized by a sharp tip and a high ratio of length and width to opening displacement, according to 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 highly detrimental to structural integrity. In addition, cracks greatly reduce the fatigue strength of a member. The AWS Structural Welding Code D1.1 does not allow a crack 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 later. 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 1970s. ANSI/NEMA TT 1 "Tapered Tubular Steel Structures" (1983) in Section 10.5 states, "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,* second 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 preventive 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 groove weld and socket base plate connections. Toe cracks in polygonal poles typically first occur near the vertices (bend-lines or points of the multisided shaft) because this area generally has a higher stress concentration (see Figure 5).

Root Causes

Toe cracks have been a recognized issue in the pole industry for many years, and numerous investigations and discussions have been conducted about them. Although not all of the contributing factors and their interactions are fully understood, discussions regarding toe crack root causes continue, and the consensus is that this phenomenon generally involves an interaction of several of the following components.

Design. Problems can arise when the base plate design results in an undersized (too thin), relatively flexible base plate that 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) also is a factor that can create unbalanced thermal stresses during the galvanizing process. Problems can also arise when the base plate design is very thick. Contrary to engineering judgment, 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 toe cracking would occur because of the thermal stresses induced while galvanizing the assembled section. In the galvanizing process, the larger base plate requires more time to heat during immersion in 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. There is no consensus among design engineers as to what defines a base plate as too thin or too thick. The ASCE 48 Standard Committee (Design of Steel Transmission Pole Structures) and the TIA-TR14 Committee (TIA-222-G Standard Addendum 3) have tried 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.

Materials. The consideration of materials includes the quality of material being joined, weld electrodes, high yield/tensile base material strengths, high carbon equivalents (CEs) and other metallurgical properties.

Figure 6. In the manufacturing (cold bending) of a polygonal section, tubular pole sections are fabricated by press-forming high-strength steel plate using a press brake.

Fabrication. In the manufacturing (cold bending) of a polygonal section, tubular pole sections are fabricated by cold press-forming, high-strength steel plate using a press brake (see Figure 6). Embrittling of the steel can occur at the bend points because of the cold working of the material (i.e., strain hardening) resulting in high residual stresses.

Welding. Factors that may result in poor welding quality and process include a lack of proper pre-heat during welding fabrication, a poor weld profile or improper or inconsistent heat input during the welding process.

Quality. Poor manufacturing quality control or quality checks at the original manufacturer after fabrication and galvanizing that are overlooked or incorrectly performed can influence crack development and fatigue damage.

Galvanizing. Hot-dip galvanization coats steel with a layer of zinc by immersing the metal in a bath of molten zinc at a temperature around 840 degrees Fahrenheit (449 degrees Celsius). Thermal expansion, hydrogen embrittlement and the thermal stress

Table 1: Base Plate Weld Toe Crack Classification

Classification Category	Description of Weld Toe Crack Category
0	**No toe crack indications indentified** 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: $L_C < ¼\ C_S$ **Crack depth:** Maximum depth of all cracks is less than half the shaft thickness: $d_C < ½\ t$ (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: $¼\ C_S \leq L_C \leq ½\ C_S$ **Crack depth:** Maximum depth of most cracks is less than half the shaft thickness: $d_C < ½\ t$ (most) No cracks have a depth greater than three-quarters the shaft thickness: $d_C < ¾\ t$ (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: $¼\ C_S \leq L_C \leq ½\ C_S$ **Crack depth:** Maximum depth of most cracks is less than three-quarters the shaft thickness: $d_C < ¾\ t$ (most) Few cracks have a depth greater than three-quarters the shaft thickness: $d_C \geq ¾\ t$ (few) **Corrective actions:** a. Remove cracks via grinding and/or drill 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: $L_C > ½\ C_S$ **Crack depth:** Maximum depth of most cracks equals or exceeds three-quarters the shaft thickness $d_C \geq 3/4t$ **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***

differentials caused by the large differences in thicknesses between the base section pole wall and the base plate all combine to create the potential for crack formation.

Installation. Loose foundation anchor nuts or leveling nuts after installation or improper grouting of the base plate cause unanticipated stress increases in the weld joint.

Although any single item mentioned can be detrimental to the structure, a combination of two or more of them 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

Table 1: Definitions

Lc	= Total length of all weld cracks measured around circumference $\sum (L_1+L_2+L_3\ldots)$
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
Cs	= 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

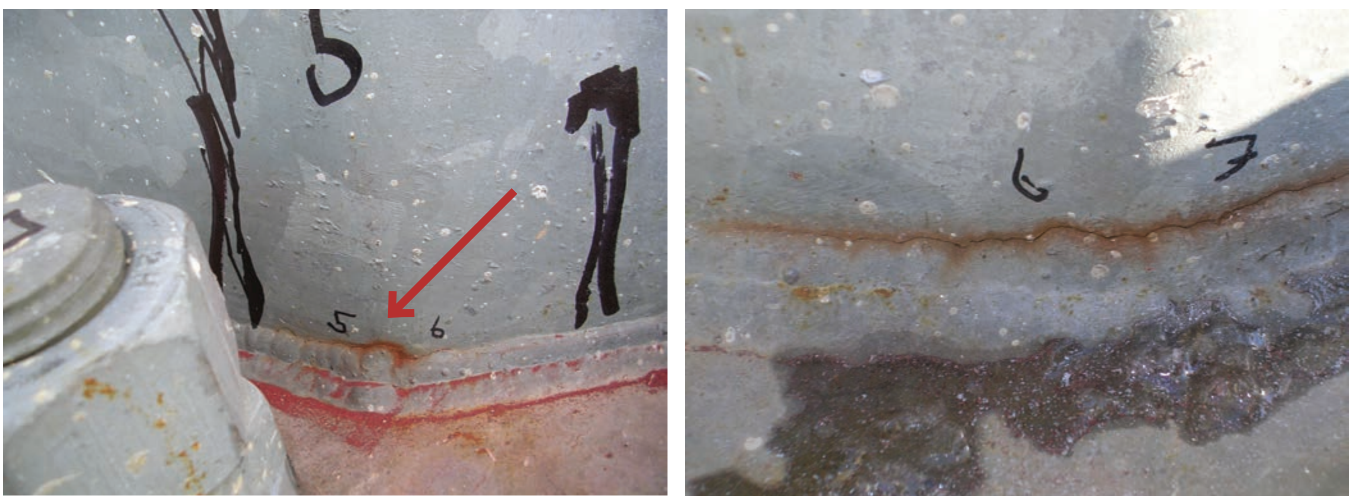

Figure 7. Toe cracks at upper toe of weld in pole shaft at polygonal bend line (visible rust).

Figure 8. A minor toe crack is visible via MT powder after light grinding.

Figure 9. A toe crack is still visible via MT exam after grinding.

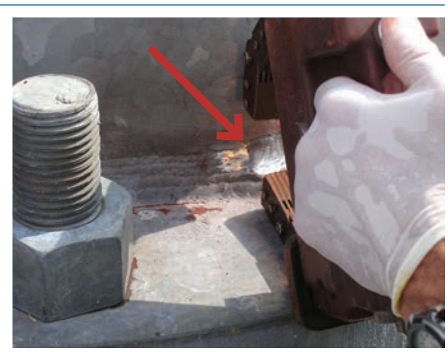

Figure 10. An MT exam showing indication (crack) at upper toe.

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

Total Length of Cracks	Maximum Depth of Measured Weld Crack			
	$d_C < ¼\,t$	$d_C < ½\,t$	$d_C < ¾\,t$	$d_C \geq ¾\,t$
$L_C < ¼\,C_S$	1	1	2	3
$¼\,C_S \leq L_C \leq ½\,C_S$	1	2	3	4
$L_C > ½\,C_S$	2	3	4	4

Figure 11. Socket-style pole base through-wall toe cracking viewed from the inside of the pole (visible rust).

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, "wandering" along the upper toe of the weld on the press bend line between two flats on a multi-sided pole is visible with the naked eye (see Figure 7).

2. Cracks may be identified with magnetic particle (MT) testing at the surface or near the surface that are not visible to the naked eye (see Figures 8, 9 and 10).

3. Ultrasonic testing (UT) may identify cracks that cannot be identified with magnetic particle (MT) testing and that are not visible to the naked eye.

4. Cracks may range from one location only to each bend line of the pole base section.

5. Cracks may vary from fractions of an inch to multiple inches in length.

6. The depth of cracks may range from thousands of an inch to clear through the base wall thickness (see Figure 11).

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 subject of debate and confusion for owners and engineers.

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: $¼\,C_S \leq L_c \leq ½\,C_S$
2. Maximum depth of most cracks is less than 1/2 the shaft thickness: $d_c < ½\,t$ (most)
3. No cracks have a depth greater than three-quarters the shaft thickness: $d_c < ¾\,t$ (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

Figure 12. An example of classification calculations.

Proposed Classification

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 cracks in this critical connection and the allowable time frame 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 (see Table 1). 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 versus the pole base circumference percentage as detailed in Table 2 (also see Example No. 1 in Figure 12). The depth of the crack is estimated during the field inspection via ultrasonic testing, 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 60 days.

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						
	$L_C < ¼ C_S$		$¼ C_S \le L_C \le ½ C_S$		$L_C > ½ C_S$		Total Length (L_C)
	$d_C < ½t$	$d_C \ge ½t$	$d_C < ½t$	$d_C \ge ½t$	$d_C < ½t$	$d_C \ge ½t$	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	

Table 3 further corresponds crack depth and length versus the pole age (if known) to a corresponding repair classification (also see Example No. 2 in Figure 13). This alerts the owner and engineer that extensive cracks in a newer structure can be highly detrimental and may indicate more serious problems such as fatigue or an under-designed tower. Table 3 may default a structure into a higher classification category requiring a reduced repair schedule. For example purposes, classification calculations are included in the following information.

Conclusion

The formation of toe cracks at the base connection of tubular steel poles has

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: $d_c \ge ¾ t$
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

Figure 13. An example of classification calculations.

been an industry challenge for many years, and it continues to be a challenge. Many factors contribute to the problem. 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 that restore the original integrity of the structure. The timetable for the required repairs is based on the severity of the weld cracking and age of the structure. A proposed crack classification system is intended to standardize the way the industry deals with inspection, repair and maintenance of pole base connections.

Cracks can develop over time because the structure is constantly exposed to dynamic environmental influences such as wind and fatigue and ever-increasing loading. Routine inspection and maintenance are the only sure ways to reliably protect your assets and extend the service life of your structures.

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