

## Toe Cracks in Base Plate Welds – 30 Years Later

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### Abstract

A number of articles (including a series by Electric Light & Power) were published in the 1970's on the subject of toe-cracking in base plate weldments. Despite nearly 30 years of experience, toe-cracks in base/flange plate weldments are still being discovered. This paper will review a Six-Sigma study undertaken by Valmont Industries to better identify the causes and the variables that we feel are essential to minimize the risk of toe-crack occurrences.

### History

In the early to mid 1970's a number of articles appeared in our industry publications largely debating the apparent cracking of base plate welds on galvanized transmission poles. The articles ranged from questioning the safety of these poles to condemnation of galvanizing to questioning if the "problem" was necessarily to be expected. In 1974 Valmont Industries authored an article for Electric Light & Power to investigate the issue as it was understood at the time. At that time it was identified that several large utilities had experienced serious problems with toe cracks. Few had really identified a cause for the occurrences, however, and tried to control the situation through rather draconian measures intended to restrict any reoccurrence (without knowing the cause). The article looked at the various components of fabrication of these poles to isolate the culprit. But while the "smoking gun" was never found, a number of interesting factors were uncovered, such as:

- Galvanizing: As the poles were all galvanized, both thermal shock during immersion and hydrogen embrittlement during pickling were investigated. Although these could certainly be contributors in some way, they were not consistent when compared with other similar weldments and products which did not experience the same problems as a result of the galvanizing operation.

- **Braking:** All of the poles required forming to produce the tubular shapes. Interestingly, it was pointed out that many of the poles produced at the time were 8-sided cross-sections. The braking process to form the tube is a cold working process which increases the hardness of the steel and builds up residual stresses. The fewer the sides in the pole section the sharper the bend and the more cold working occurs. Also, this effect is induced more as the bend radius used becomes tighter. The 12-sided shape with 3T bend radiuses then becomes less of an issue compared to the 8-sided.
- **Welding:** The base plate must be welded to the pole in the classic ‘T’ detail. Welding opened up a number of considerations:
  - Generally, the shaft-to-base plate weld used either flux-cored welding (FCAW) or submerged-arc welding (SAW). Although both are considered low-hydrogen welding processes, research showed that the FCAW process generates considerably more free hydrogen which can be a contributor.
  - The SAW process is more ductile because of the slower cooling rate.
  - Preheat and interpass heat temperatures must be controlled.
  - The contour of the weld is critical. Unless the weld blends into both the base plate and the shaft smoothly, a notch effect will be created and all applied stresses will be intensified at this point.
- **Material:** Variations also occur in the mechanical properties of the steel used in the pole fabrication. It was reported that material can actually be received with actual yields of 75 ksi, higher than the minimum specified 65 ksi.

At the time, there was clearly no one precise cause for toe cracking. Rather, the best safeguard was to consider all contributors identified.

### **Today, 30 Years Later**

After 30 years has anything really changed with toe cracking of the shaft-to-base plate weld? The answer is a very definite “Yes”, and an equally definite “No”. Valmont Industries truly believed that it had control over the toe cracking phenomenon and that it had the test results to prove it. Periodic testing verified that control over the years, so “Yes” when toe cracks began to appear in base welds and verified by further testing, something had definitely changed. But, after much more study, research, and experimentation, “No”, there really was no change – toe cracking is not a single element cause but a multitude of contributing and compounding factors that have become much more difficult to control.

Figure 1 shows the commonly used Ultrasonic Inspection (U.T.) process for our industry, derived through the application of AWS D1.1. A portion of the inspection sound can be lost in the backup seal weld. The sound does not strike the normal crack position in a perpendicular orientation, which results in additional sound loss. Although this method has been in use for many years to detect cracks in the weld joint, it requires higher scanning levels and greater technician skill.

Figure 1 also shows an alternative 45 degree inspection method that can be used to detect toe cracks with higher effectiveness. With this method, the backup bar seal weld presents no interference (a phenomenon known as “corner trap” effect returns a greater percentage of the sound back to the transducer). Because this method is more sensitive to surface conditions, it will result in more false readings rather than missed readings. This procedure requires a follow-up inspection to verify a true presence of a crack.

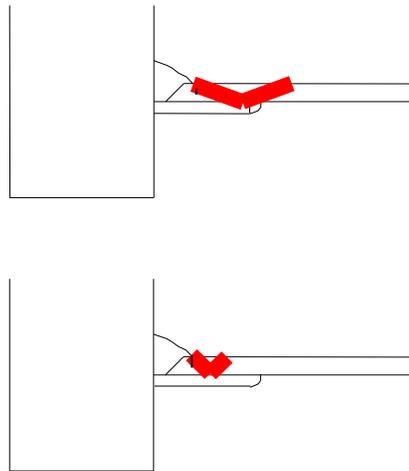


Figure 1. Inspection with a (common) 70 degree & (alternate) 45 degree transducer

The sudden occurrence of toe cracking increased inspection vigilance and drove the change in U.T. procedure to a higher intensity inspection. After backtracking through records and product inspections, the change was pinpointed to the last quarter of 2001. This provided boundaries for investigation and analysis for causes. This time period was established through an effort of product inspection, inventory inspection, and product inspection in the field. Once U.T. provided an indication of a fault the location was marked for further inspection by magnetic particle inspection after grinding the region smooth. A high percentage of “indications” proved to be false and cracks were not found upon further inspection. In either case, however, the region required galvanize repair after crack repair or after the grinding. This inspection process did identify several worthwhile items for moving forward in the investigation and product quality assurance:

- Toe cracking occurred only on galvanized product. Although this was somewhat expected, it was verified during the process.
- Toe cracking occurred much less frequently on Communication and many DOT Highmast Lighting poles. Both Communication and DOT poles tend to use 4 inch bend radiuses for forming pole sections for consideration of wind (shape factor) effects in the design by their codes.

### **What Changed?**

Just as was found in 1974, finding the “smoking gun” for this problem was proving to be elusive. During the early interviews of the investigation it was generally insisted by those involved that processes had not changed. There were no known big change in the way welding was performed, material was purchased, the poles were galvanized, the design and details were derived, or the way poles were generally formed. If that was the case, the changes causing this increase in toe cracking had to be very subtle and considered inconsequential individually.

To drive this investigative process a matrix was established to organize the effort and resulting information. All disciplines involved in the development of the product were considered:

- Welding and Metallurgy
- Purchasing
- Galvanizing
- Product Design
- Manufacturing and Shop Practice

These disciplines were analyzed at each of the four Valmont large pole fabrication sites for each of the years 1998, 2000, and 2002. This matrix resulted in 60 independent areas of investigation.

To manage this volume of information and drive to improvement and process control, the DMAEC (Six Sigma) Process was employed as depicted in Figure 2.

# The Six Sigma Project Roadmap

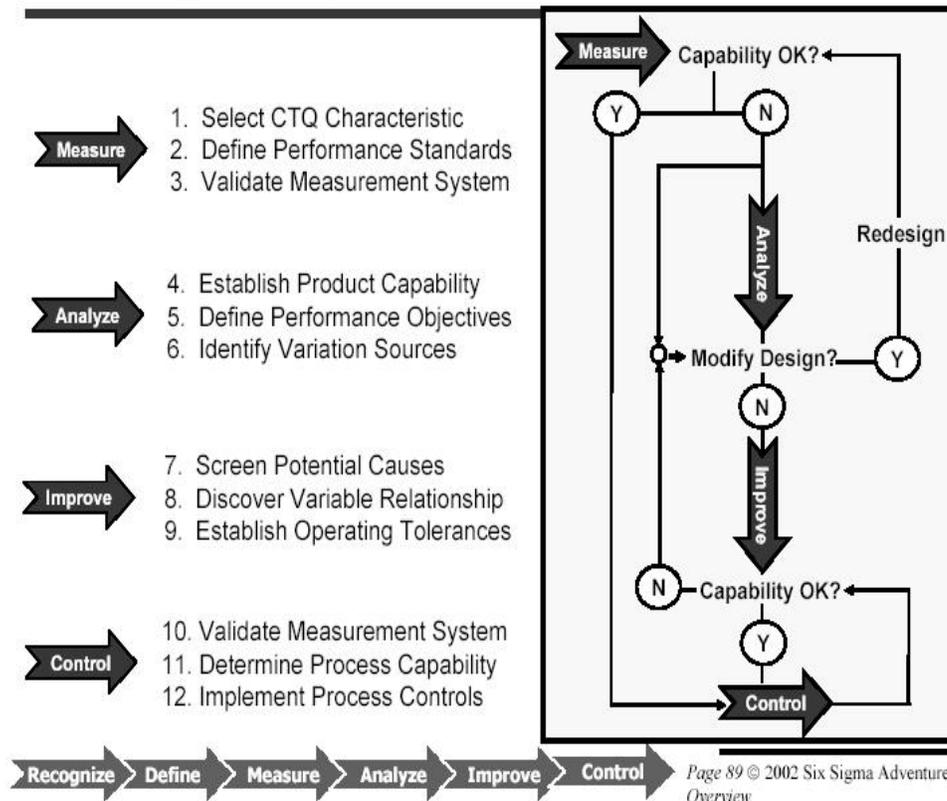


Figure 2. The Six Sigma Project Roadmap

## Analysis and Results

Even with the claims that no changes were made to systems, processes, and material utilization, competitive pressures over the years required “tweaking” and “adjustments” within the various code limits for either productivity efficiency and/or material and process cost improvements. As will be seen in the following discussion, issues were found in most every discipline and some that were not previously within our direct control, such as material (that remained within the ASTM Standards).

## Welding and Metallurgy:

The focus of investigation was performing controlled experimentation (Barkhausen Noise Measurements) for residual stress, calculation of heat input at each manufacturing site, and, metallurgical study performed on a scrapped bottom section (performed by Valmont in-house services in conjunction with seven independent metallurgical service groups).

The residual stress experiment, as expected, showed a buildup of stress in the shaft section and a limited amount in the base plate material. A tubular section with ten bends and two seams cannot be produced perfectly. In reality the longseam welding process includes pressure from the sides to hold the half shells together during the welding process. This creates a desire by the tubes to pull apart but is restrained by the weld which in turn produces the residual stress in the system.

We found that the welding heat input varied by fabrication site. One facility ran at 32 – 38 kJoules per inch while the other sites ran at about 65 kJoules per inch. The one facility was working with a new welding power source that allowed the use of less heat input while maintaining or increasing the weld deposition. This process was later incorporated into the other facilities.

The base weld remained a SAW process but changed from a hand welding procedure to a machine controlled procedure. While the machine procedure added consistency control and productivity improvements, it also deposited discontinuities particularly at bend-lines which ultimately can become stress concentrations. The bend-lines are prone to this for both hand and machine operations because of the change in orientation as the pole is turned around the bend which results in a speed change relative to across the flat.

Independent investigations were sought from the following organizations:

- Lincoln Electric Company
- IPSCO Steel
- Bethlehem Steel (at that time)
- Zinc Corporation of America
- RSI Materials Engineering (formerly the testing lab for Union Pacific Railroad)
- United States Steel (at that time)
- Hobart Brothers
- Supplementary information provided by several others

Each of these organizations was provided with a portion of a scrapped bottom section for review and investigation. A graphical representation of the bottom section and its distribution to the various organizations is shown in Figure 3. A picture of an actual sample sent for study is shown in Figure 4.

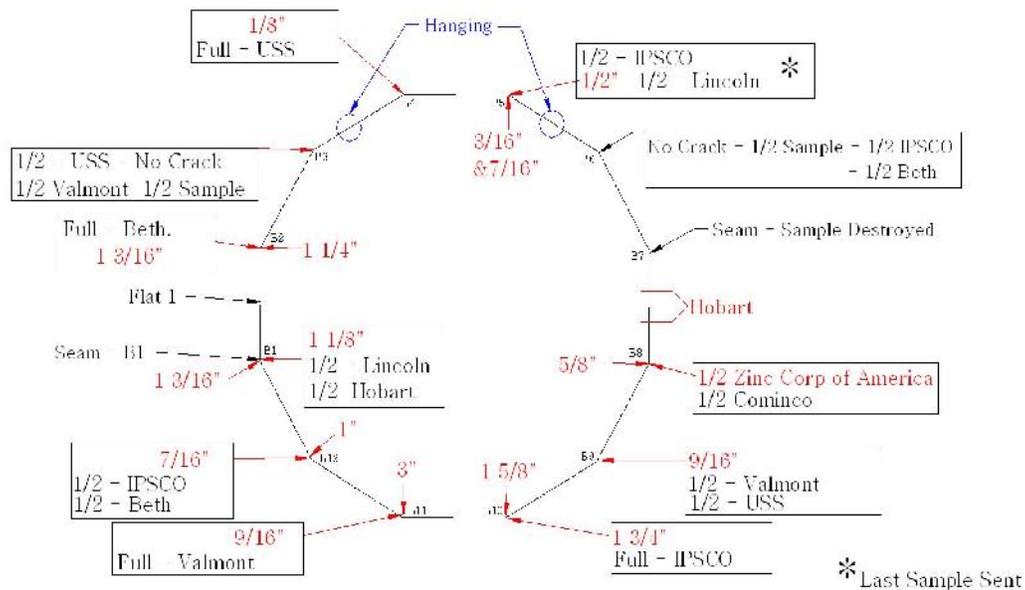


Figure 3. Distribution of Bottom Section Samples



Figure 4. Investigation Sample

The investigating organizations were asked to provide the following information: root causes – primary failure mechanism, contributing/secondary causes, potential/recommended solutions, and, factors and conditions that may be remotely involved. A conclusion and recommended solutions matrix was established from this data and is reproduced in Figure 5.

<b>Residual Stress</b>	<b>Controlling Weld at Corners / Shape</b>	<b>Thermo-shock</b>	<b>Trapped Flux</b>	<b>LME</b>
1, 2, 3, 4, 5, 6, 7	1, 2, 3, 4, 6	3, 7	1, 6	2, 3
<b>Reduced HAZ Toughness</b>	<b>Strain Age</b>	<b>Martensite in Weld</b>	<b>Hydrogen Induced</b>	<b>High Cooling Rate</b>
3	3	2	3	4
<b>Hot Crack</b>	<b>Width of Bead / Depth</b>	<b>Course Grain in HAZ</b>	<b>Not LME</b>	
5	1	2	5	
<b>Increase B/R</b>	<b>Increase Si Shaft / Wire</b>	<b>Lower Pickling Time</b>		
2	3	3		
<b>Simulate Thermal Stress w/o galv.</b>	<b>Acoustic Emission to monitor Cracking</b>	<b>Optical Tracker to control profile at corners</b>		
3	3	3		
<b>Stress Relieve B/4 Galv.</b>	<b>Steels with lower Cu, Ni &amp; Cr</b>	<b>NDE after pickling</b>		
2	3	3		
1. LEC	4. ZCA	6. USS		
2. IPSCO	5. RSI	7. HB		
3. Bethlehem				

Figure 5. Conclusion/Recommended Solutions Matrix

The conclusions derived from this investigative process to identify issues are (in no particular order of importance):

- Weldment tensile stress by solidification and cooling
- Welding joint restraint
- Galvanizing thermal stress
- Weld profile as a stress riser/concentrator (especially at the bend-lines)
- Welding process produce discontinuities ultimately become stress concentrations (especially at the bend-lines)
- NDT methods for crack detection not 100% accurate

This investigation also provided the following additional findings:

- Toughness testing revealed the heat affected zones and deposited weld metal were compliant with the specification at -20 degrees F (average of 56 ft-lbs) after galvanizing
- No strain age embrittlement was discovered

The actions and improvements identified were:

- Lower limits for heat input (keep below 65 kJoules per inch)
- Increase the pre-heat temperature to 400 F
- Add a follow-up manual welding procedure to dress/wrap the welds at the bend-lines at the toe of the weld.

## Purchasing

The focus of investigation was material test report (MTR) analysis for both steel and welding wire consumables and data analysis using the Six Sigma tools. This revealed increases in carbon equivalents (CE), columbium (Cb) and swings in vanadium (V) contents as well as a significant increase in the yield/tensile strength. Material was being received with actual tensile values exceeding 100 ksi (significantly higher than the specified minimum of 80 ksi). Even though the material itself remained within

the specified limits, the actual material did change over time. Some of this change can perhaps be attributed to a general change in material preference from discrete plate to a coil material that is then leveled and provided as plate (commonly referred to as “levelized coil”).

Figures 6, 7 & 8 show the change in the carbon equivalent (CE) value, columbium (Cb), and vanadium (V) over the time of investigation, respectively. Not only does the CE change in value, but also increases the degree of variation. The CE formula used was:  $CE = \%C + Mn/6 + (\%Cr + \% Mo + \% V)/5 + (\%Si + \%Ni + \% Cu)/15$

Time Series Plot Carbon Equivalent for 1999 - 2002

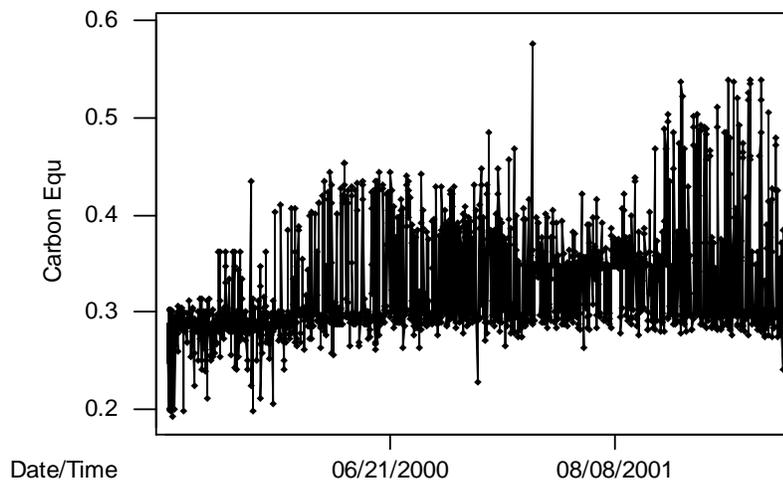


Figure 6. Carbon Equivalent Change

Time Series Plot of Cb for Mill USS (1999 - 2002)

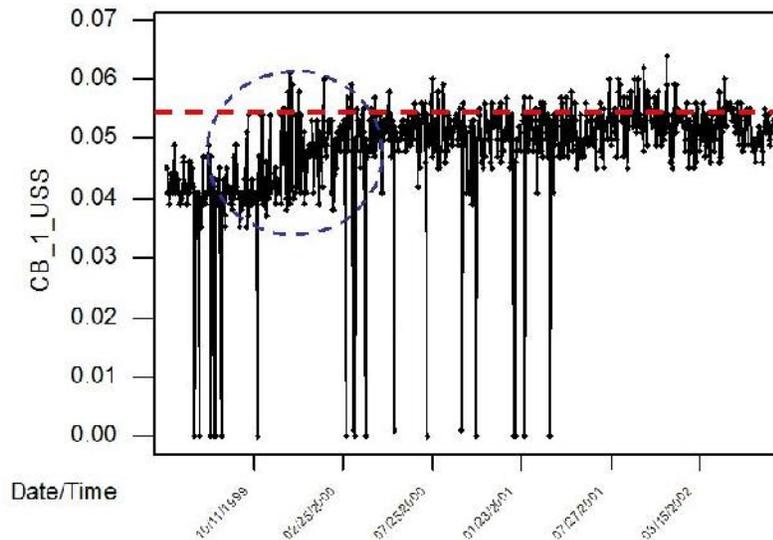


Figure 7. Cb (Columbium) Change



failure mechanism. An explanation of this is that LME may be a crack initiator with propagation via stress.

An event probability plot compared to SLM400 is represented in Figure 9.

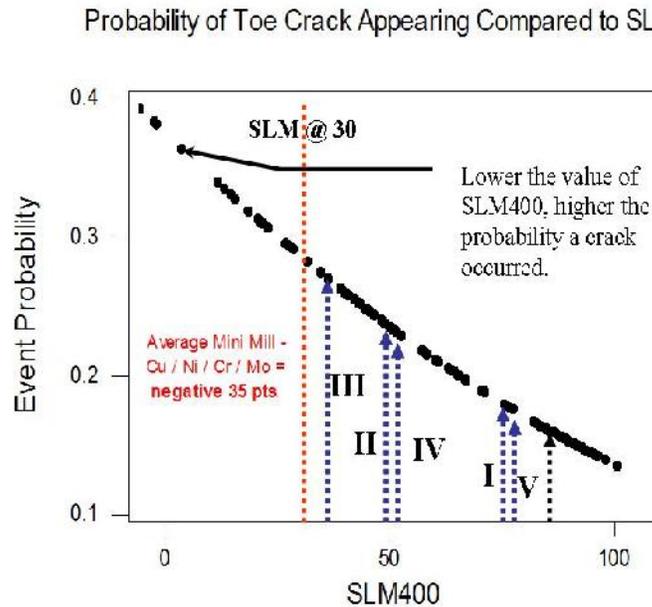


Fig. 9. Event Probability Plot of Crack Occurring Compared to SLM400

Based on these findings for material improvements and control, we have initiated the following for pole shaft material for bottom sections with base plate welds:

- Carbon equivalent (per the above formula) shall be restricted to a maximum of 0.45.
- In addition to silicon (Si) restriction to 0.06% maximum;
  - Free nitrogen (N) content shall be 50 ppm max. (aim for 40 ppm)
  - Vanadium (V) shall be 0.09% max.
- Discrete plate is preferred (particularly for thicknesses greater than 0.375”).
- Tensile strength maximum is 100 ksi (aim for 90 ksi). The “aim for” compliance will be used for vendor evaluation and performance.

## Galvanizing

The focus of investigation was a process audit of the major galvanizers used for our transmission pole product. Although Valmont Industries is the largest galvanizer in the North America, a number of other suppliers are also used based upon geographic location to the fabrication plants and the customer. Suppliers were audited with regard to all processing parameters including very detailed investigations into kettle chemistry segregation and temperature gradient.

In general it was determined that all galvanizing suppliers charge their kettles with either “Super High” Grade (>99.8% Zn) or “Prime Western” (1% Pb + Zn) zinc. Although there were some minor variations between the various kettle content chemistries, there was no correlation between those variations and any incidence of cracks. Independent to this specific investigation Valmont has encountered suppliers who purposely made tin (Sn) additions to the kettle. The results were catastrophic, resulting in scrapped structures; the failure mode was indisputably LME.

### Product Engineering

The focus of investigation was review of designs over the subject years and comparisons of Utility designs with Communication and Traffic designs/details. As was stated earlier, an early identification of difference was that similar poles (diameter, thickness, base plate, etc.) reacted differently if the pole was formed using a 4 inch bend radius instead of a 2 inch bend radius (a standard bend radius to satisfy the 3T recommendation in ASTM A143 for good practice against embrittlement). Toe cracks in poles using a 4 inch bend radius were found to have a lower incidence of occurrence.

A relationship of the base plate weight to the pole shaft weight (bottom 12 inches) was noted in comparing designs that did and did not result in toe cracks. This weight relationship is represented in Figure 10. To a large extent the efficient design is a result of the loading and limitations provided by the Utility customer and specifically modifying the design can create significant cost impact in material utilization and fabrication labor. However, this ratio appears to be an additional consideration.

Probability of Toe Crack Appearing Compared to the Ratio:  
Base Plate Weight / Shaft Weight (Bottom 12")

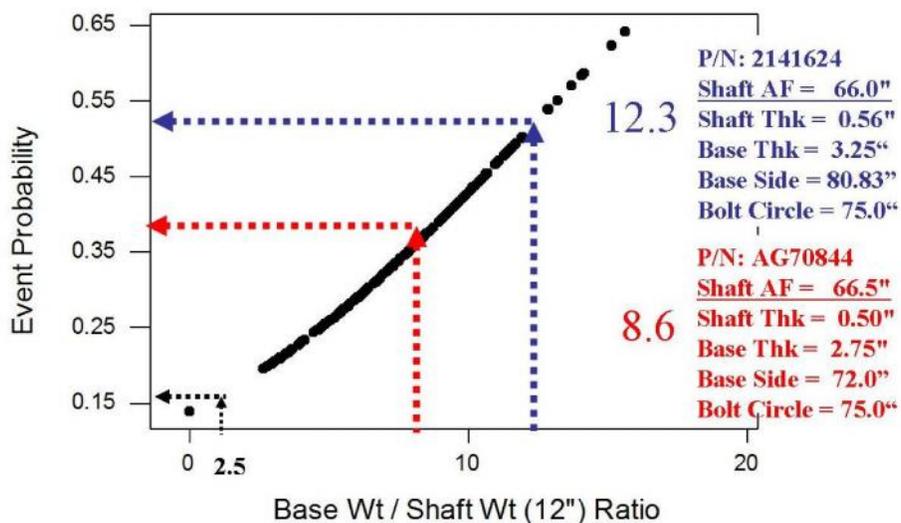


Figure 10. Probability of Toe Crack Compared to Ratio of Base Plate Weight to Shaft Weight (Bottom 12")

An additional action taken in this investigation was to locate a pole with known toe cracks for field strain gauging to assess the rate (if any) of crack propagation. A pole was found and purposely not repaired for this study. The pole location is in Omaha, NE along a freight rail yard, a slight line angle, and dead-end configuration. The weather conditions are variable from hot sun exposure in the summer to extended sub-freezing in the winter. After roughly two years there has been no crack propagation.

### **An Unexpected Find**

The use of “zinc-based solders” is acceptable for hot-dipped galvanize repairs per ASTM A780. During our investigations and repair experimentation we encountered (and could replicate) a new phenomenon that induced post-repair cracks when the galvanizing finish around the repair was itself repaired using “zinc-based solders”. These cracks, however, were wholly different than the toe cracks and would propagate outward longitudinally along the pole and/or through the weld and into the base plate material itself. These “zinc-based solders” are very high in lead (Pb) and tin (Sn). After being able to duplicate the phenomenon, we have discontinued their use for galvanizing finish repairs when a structural component is involved.

### **In Conclusion**

Toe cracks are typically stress related, and are the result of compounding factors that are ultimately displaced across a threshold by galvanizing. This is evidenced by the fact that painted and weathering steel product does not exhibit the phenomenon. Welded, galvanized tubular structures have a phenomenal performance and service record. But many factors must be managed to assure weldment quality at these critical connections.

### **References**

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