Condition Assessment, Corrosion Risk Assessment, FEA Analysis Of Pack-out For Weathering Steel Transmission Structures

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ABSTRACT

Accelerated corrosion of tens of thousands of aging transmission structures in electric power transmission lines is a leading cause of in-service equipment degradation. Each year, utility companies spend an increasing amount of their revenue on inspection and refurbishment of corroded structures, and maintenance of the large population of aging structures has become a serious engineering and economic problem.

As these assets age, corrosion at or near the ground level is becoming a key risk to weathering steel structures (WS) as metal thickness loss leads to a reduction in structural strength, potential asset failures, reduced system reliability and costly repair or replacement. Preventative maintenance for steel structures has quickly become an important topic for engineers to consider, both during design and in the field, in order to reduce the costs of corrective maintenance many decades later.

Accordingly, effective and economically feasible corrosion mitigation techniques, specifically designed for weathering steel transmission poles, are in high demand.

In this paper the principal corrosion mechanisms for weathering steel utility pole/lattice structures will be discussed, considering specifically; corrosion risk at ground level and Pack-out, Finite Element Analysis (FEA) analysis, corrosion mitigation and repairs.

The case history portion of the paper will include actual case histories that involved both accelerated corrosion at the ground level due to coating degradation/delamination, pack-out formation and FEA analysis to determine the integrity of the joint.

Key words: Weathering Steel, Transmission Tower, Transmission Pole Accelerated Corrosion, Pack-out, Coating, FEA Analysis, Corrosion Risk Assessment, Cathodic Protection, Repair Coatings

INTRODUCTION

Transmission towers are generally made from galvanized steel; however, in the 1960's weathering steels were introduced. Weathering steels are a class of low alloy steels that contain alloying elements such as copper, chromium, nickel, phosphorus and silicon not exceeding three (3) weight percent. Weathering steels appeared to offer a method to reduce structure weight and maintenance of lattice towers through the application of bare, high-strength steel that had natural corrosion resistance. The improved corrosion resistance was attributed to the formation of a dense protective layer that significantly prevented moisture from wetting the bare steel surface and furthering the corrosion process. The oxide provides both a protective coating that is resilient to most atmospheres, requiring no maintenance painting, while maintaining a dark brown and uniform appearance. Weathering steel structures are excellent selection and last very long time in atmospheric environments that form the protective patina. However, in reducing environments, accelerated corrosion may place and cause serious integrity problems many utilities ordered weathering steel for transmission lines based on its low corrosion rate and low maintenance. The same type of joint designs was applied in the case of weathering steel as were applied for galvanized transmission towers. Although the materials were different, the design remained the same. At that time, the limitations and conditions for accelerated corrosion were only obvious to corrosion engineers, and structural designers did not take factors such as cavities, crevices, and the formation of "pack-out" into consideration. Within the first few years of transmission tower installation, an on-site inspection revealed that corrosion products had built up in the joints between faying surfaces and in cavities. This growth, called pack-out, deformed joints significantly, turned up edges, and buckled plates. The initial response was to overlook the problem, and most experts hoped the corrosion products would act as a barrier to moisture penetration and as a result, corrosion would be halted or slowed down as a function of time. However, some utilities were concerned about extensive thinning of the pole shafts and bolts popping out and imminent structural failures that could possibly occur.

Weathering steel transmission towers/poles are exposed to different atmospheric environments, corrosive ions, cycles of wet and dry periods and some may exhibit accelerated corrosion and structural deficiencies due to formation of excessive corrosion products at bolted joints ('pack-out') or loss in thickness on the shaft where accelerated corrosion is taking place.

The sources of corrosion are:

1-Corrosive atmosphere where protective layer dose not form
2-Entrapment of moisture and corrosive ions in crevices produced by coatings or joints
4-Accumulation of dirt or debris and vegetation
5-Faulty drainage systems
6-Corrosive moisture build-up at concrete /WS interface

Understanding that corrosion is an electrochemical process is critical for WS asset owners to effectively anticipate and manage the effects of corrosion attack which is both consists of loss of thickness of the member and build-up of corrosion products at crevices and bolted joints. If a weathering steel structure experiences accelerated corrosion at bolted joints, and if corrosion progresses to a critical loss in thickness or build-up of pack-out at bolted joint structural members

need to be replaced to protect the integrity of the structure. Therefore, it is important to assess active corrosion/pack-out buildup before it can escalate to failure.

Basically, a corrosion risk assessment and condition assessment would identify the current corrosion condition at the existing weathering steel joints that have developed pack-out, based on chemistry of pack-out, electrochemical potential reads and dimensional focused measurements. The potential reads will provide information on corrosion activity at the pack-out, the focused thickness measurement and FEA analysis will provide information if critical pack out thickness has reached for deformation and fracture of bolted joint. The corrosivity of the environment will be assessed by characterizing the patina, atmospheric data and potential mapping.

In the following sections we will present two common problems observed for aging weathering steel transmission structures:

Extensive Loss of Thickness Due to Accelerated Corrosion at Crevices Formed on Weathering Steel Poles:

First generation, direct embedded weathering steel (ASTM A-871) transmission poles have become a focus of ground line inspections and repair in the past several years (
Figure 1). Weathering steel monopoles for direct embedded applications are typically sleeved and coated with a marine grade polyurethane, from 2 feet above grade to pole bottom. The first and second generation of these coatings perform excellent below grade but have typically performed poorly above grade (Figures 2). Coating failure and accelerated corrosion have occurred above the ground-line, causing primary wall thickness loss. It is suspected that coating specification, coating application, and local environment are the primary contributors to the coating failure and accelerated corrosion.

Coating specification errors can include improper specification of dry film thickness (DFT) for 1st generation aromatic polyurethanes. Specifications have also become more complex. To protect against ultra-violet (UV) damage to the aromatic polyurethane coating, modern coating specification for ground-line urethanes now includes a UV resistant top coat for the above grade coating interface.

Coating application errors can include rough edges and poor surface preparation. When combined with higher DFT, these errors contribute to large scale adhesive failure of the coating. For weathering steel, dis-bonded coatings are especially problematic, due to the aggressive crevice corrosion that occurs. In some cases, circumferential sections of coating that are a height of 6-10 inches, can lose adhesion but do not immediately crack or flake. Under the expansive forces of the corrosion, the crevice tends to increase in size while still holding standing water. This is sometimes called the "tulip effect". Eventually, expansive corrosion products put enough internal surface pressure on the protective coating to delaminate and crack it(See Figure 3).

Environmental factors that lead to coating failure and accelerated corrosion for embedded weathering steel structures include high time of wetness (TOW), high water table, un-managed vegetation or crops, and additional localized sources of water such as crop irrigation. Many of these factors are not directly under the owner's control, but local environment driven alloy and foundation selection, coating specification, ground line inspection, and vegetation management should be considered key areas of focus for the industry.

Ground-line inspection for embedded weathering steel monopoles should include visual inspection and excavation as needed. Wall thickness measurements will also be needed if accelerated corrosion is evident. For poles with severe corrosion, additional measurements should be taken for welded sleeve design.

Repair of the ground-line coating for embedded weathering steel monopoles is similar to the repair of painted or galvanized monopoles. During inspection, disbonded coating should be removed. The primary repair method is excavation, surface preparation, and coating application. Other coating repair methods from the underground piping industries, such as petrolatum tapes are also available (See Figure 4).

Case History (Formation of Pack-out at Joints of Transmission Lattice Towers)

The corrosion rate of weathering steel towers was monitored on several transmission towers over an extended period of time prior to 1980, and in 1982 it was found that severe rust growth had continued, as well as corrosion product buildup in excess of 1/8 inch thick (3.18 mm) in some cases. In 1998 another on-site and laboratory investigation was performed which indicated further growth is taking place in joints containing pack-out (>1/2 inch (>12.7 mm)) (See Figures 5, 6 and 7).

ON-SITE INVESTIGATION 1998

The on-site investigation on the transmission towers included thickness measurements of the steel, electrochemical measurements, pitch and distance measurements of the bolt, photographic documentation, and sample collection for subsequent laboratory analysis. The findings indicated a maximum section loss of less than 40% of the original thickness over a service life of 30 years. This maximum metal loss is located at a single point location within the joint, typically, along the very edge of the members. The metal loss is not uniform or measurable across the member cross section of the joint. The corrosion rate within joints requires fifteen to twenty years of service before approaching stability compared to the five to 10 years required for exposed steel under oxidizing conditions.

The corrosion buildup, or pack-out, was measured and indicated a range between 0.50 to 0.625 inches (12.7 to 15.9 mm) on the towers. The average corrosion buildup was greater than 0.50 inches (12.7 mm), a thickness greater than the readings taken during the inspection. Data from previous field tests indicated the corrosion buildup was at least 1/8 inch (3.2 mm) in thickness when measured during early year inspection. The maximum corrosion buildup on two of the towers was found to be 0.626 inches, or 5/8 inches (15.9 mm). This occurred at the splice joints on the tower legs. Compared to the early readings found, this was an increase of corrosion buildup of 0.125 inches (1/8 inches) (3.2 mm), or 7 mils (0.178 mm) per year increase in pack-out.

On-site electrochemical measurements were also performed to measure corrosion activity using a copper/copper sulfate electrode. The potential readings showed less noble potentials compared to deposit free surfaces and indicated active corrosion under pack-out on the faying surface in all cases.

Samples were collected and marked for subsequent laboratory investigation. The following summarizes the laboratory testing and analysis on the physical and corrosion characteristics of the samples obtained during the on-site investigation.

LABORATORY INVESTIGATION

The laboratory investigation consisted of a visual examination, dimensional measurements of the bolts, thickness measurements, chemical analysis of the corrosion products (pack-out), X-ray diffraction analysis, metallographic examination, and electrochemical testing. The following summarizes the laboratory investigation.

Visual Examination, Scanning Electron Microscopy & Elemental Dispersive X-ray Analysis.
The maximum thickness of the pack out between the angle irons was measured to be approximately 1⁄2 inch (12.7 mm). Bending of the thinner tower leg member was observed as shown in Figure 7. After disassembly the pack-out was observed to be a tightly consolidated mass. In addition, the pack-out possessed a wedge shape that was wider adjacent to the edges of angle iron members. The surfaces of the steel under the pack out possessed a white powdery deposit. This white powdery deposit was analyzed using a scanning electron microscope (SEM) equipped with an energy dispersive x-ray spectrometer (EDS). SEM micrographs show a non-uniform porous structure, while EDS results indicated the white colored deposits were rich in sulfur.

The angle irons were cut into segments to facilitate later thickness measurements and were subsequently macro-etched in an inhibited aqueous hydrochloric acid solution. The corroded areas of the angle irons under the pack-out exhibited a relatively smooth evenly corroded appearance. In contrast, the areas of the angle irons exposed to the atmosphere exhibited pitted surfaces. No cracking of the bent angle iron was observed under low magnifications. The corrosion of the bolts was observed to be most severe in the shank to thread transition area. This is the area that would be exposed to the pack-out.

Dimensional Measurements of Bolts

Six bolts were removed from the submitted tower leg splice were briefly cleaned in an inhibited aqueous 50 percent hydrochloric acid solution to remove the corrosion products. The distance between bolt threads was then measured, using an optical comparator, for one of the bolts to determine if the bolt had been plastically deformed by stretching. The pitch between threads should be 0.0909 inches (2.3 mm). The pitch was measured on two diametrically opposite sides of the bolt. No evidence of any significant stretching of the bolt was found.

Thickness Measurements

After disassembly of the spliced leg joint and macro-etching in an inhibited aqueous hydrochloric acid solution, dimensional measurements of the two angle iron members were made to determine the remaining thickness of the steel in areas under the pack-out where the corrosion had been most severe. The original thickness of the thinner tower leg member was reported to be 0.250 (6.35 mm) inches and the original thickness of the thicker leg member was reported to be 0.375 inches (9.53 mm). A maximum corrosion rate of 2.5 – 3.3 mils/year (0.064 – 0.083 mm/year) was established depending on the location.

Chemical Analysis

A quantitative chemical analysis of the corrosion buildup (pack-out) was performed after the sample had been dried in an oven. The results of the analysis indicated 2400 ppm chloride, 880 ppm sulfate, and 930 ppm sulfide.

X-ray Diffraction Analysis

A powder x-ray diffraction was performed on the original corrosion buildup (pack-out). The pattern was very weak, but appeared to contain magnetite (Fe_3O_4), hematite (Fe_2O_3) and iron oxide hydroxide (FeOOH). Concentrations of other compounds were too small to be measured.

Metallographic Examination

A transverse section through the corroded tower leg was prepared for subsequent metallographic examination. Etching with a 2% nital solution revealed the existing microstructure, which was found to consist of dark etching pearlite in a matrix of white etching ferrite.

Electrochemical Testing

Electrochemical polarization and corrosion rate measurements were performed by the Princeton Electro Chemical Measurement Unit on the collected samples in solutions with various chloride and sulfate concentrations at a pH of 4.5. This solution duplicates the chemical composition of the pack-out, as determined by chemical analysis. The pack-out absorbs moisture and corrosive ions as a function of time, and acts as a very corrosive electrolyte to weathering steel.

Using a computerized electrochemical corrosion measurement, it was concluded that the corrosion rate of weathering steel increases as a function of chloride/sulfur containing compound concentration. The corrosion rates measured by electrochemical polarization techniques approximate those found on-site indicating chlorides and sulfur containing compounds were the major contributing factors that accelerated corrosion.

DISCUSSION

As mentioned previously, weathering steel appeared to offer a way to reduce structure weight and maintenance of lattice towers by the application of bare, high-strength steel that had natural corrosion resistance. However, from early on it was well known that the weathering steels in an unpainted condition could not be recommended in very corrosive exposures such as those found in sea environments or the internal parts of joints. It was recommended that designers, using these steels unpainted, must avoid interstices and cavities in which condensed water may result in the accumulation of corrosive ions.

The on-site investigation and laboratory testing revealed the following: The maximum corrosion build-up on two of the towers was found to be 0.626 inches, or 5/8 inches (15.9 mm). This occurred at the splice joints on the tower legs. Compared to 1982 readings, this is an increase of corrosion buildup of 0.125 inches, or 1/8 inches (3.2 mm), which translates into a 7-8 mils/year (0.18 – 0.2 mm/year) increase in pack-out.

What is known as pack-out is a porous structure capable of retaining moisture and corrosive ions, such as chlorides and sulfates. Electrochemical potential indicated active corrosion under the pack-out in most corroded joints. X-ray diffraction indicated magnetite (Fe_3O_4), hematite (Fe_2O_3) and iron hydroxide (Fe OOH) in the pack-out areas. Chemical analysis of deposits indicated a high concentration of chlorides and sulfur containing compounds. Both mating plates exhibited uniform corrosion loss. There was no evidence of galvanic corrosion. Laboratory potential measurements and on-site potential measurements ruled out stray current corrosion. Laboratory corrosion measurements indicated an increase in the corrosion rate with an accumulation of chlorides and sulfur containing salts. The wet corrosion products indicated a low

pH and an acidic chloride condition in the pack-out. The corroded areas of the angle irons under the pack-out exhibited a relatively smooth evenly corroded appearance. In contrast, the areas of the angle irons exposed to the atmosphere exhibited pitted surfaces. The corrosion of the bolts was observed to be most severe in the shank to thread transition area, which was the area exposed to pack-out. The above observations provided clues for life expectancy of the joints, which appeared to be the main determining factor in the remaining life of these towers.

Mechanism of Corrosion Build-Up (Pack-out)

There are various conditions and mechanisms proposed for the formation of pack-out and the accelerated corrosion of weathering steel. The formation of crevices, cavities, and water retention cells due to design flaws, the accumulation of aggressive ions (chlorides, sulfates and other corrosive ions) in cavities, stray current corrosion, galvanic action of faying surfaces, and the formation of concentration cells are all significant contributing factors.

The morphology of the corroded surface indicated a uniform corrosion attack beneath the deposits with no indication of galvanic action between faying surfaces. The relative uniformity of the corroded surface eliminated the concentration cell theory for conditions under the pack-out, and suggested that an acidic environment may be involved. Measurements for the wet pack-out indicated a pH between 4.5 and 5, which was in conformance with this theory. Electrochemical potential measurements rejected the theory that stray currents were responsible for the accelerated corrosion observed in these towers. The same potentials were observed in the laboratory and at the project site.

Corrosion resistance of weathering steel was enhanced in atmospheric exposures due to the formation of a protective layer of insoluble corrosion products. The reaction results in a protective layer, which acts as a barrier to moisture penetration to the bare surface that slows down further corrosion of the underlying metal. In the presence of chloride ions, and in neutral pH exposures, the protective layer forms initially. However, as time passes the accumulation of corrosive ions takes place, which results in accelerated corrosion of weathering steel.

High chloride content in the retained moisture in the corrosion products would be favorable for additional moisture and chloride absorption and retention, which in turn would enhance the corrosion rate as years pass. Chemical analysis of corrosion products and electrochemical potential measurements taken on-site, as well as in the laboratory confirmed this mechanism.

In addition, chloride salts, such as ferrous chloride, probably formed. This in turn resulted in hydrolysis and lower pH conditions, which further increased the corrosion rate. In this condition the cathodic reaction would shift to a hydrogen evolution reaction. Below a pH of 5 the corrosion rate increases rapidly and the hydrogen evolution reaction takes place from the surface in a typical acid reaction manner. Even when fully de-aerated, corrosion will continue as iron is anodic to hydrogen in the electromotive series and will displace hydrogen from dilute acids.

The generated hydrogen may diffuse inside the bolts causing loss of ductility and failure under load, a condition known as hydrogen embrittlement (HE). Above a pH of 7 the corrosion rate decreases as the solubility of the major corrosion product (protective layer) decreases. The film thickens and becomes more protective.

Evaluation and Inspection

To properly evaluate the corrosivity of any atmosphere towards weathering steel, it is not merely enough to look at the chemical composition of the atmosphere surrounding the towers, which only represents the areas where the protective layer has formed due to rain washing the corrosive ions, and as a result no accumulation of chlorides and sulfur containing corrosive compounds takes place. These areas are different from the areas where cavities, crevices or under deposit conditions produce much more aggressive corrosive conditions. Factors affecting corrosion rate are as follows:

- Corrosivity of the atmosphere in the immediate environment
- Build-up of corrosive ions in pack-out
- Wash out situation
- Wind direction
- Soluble solids and concentration of corrosive ions in the immediate environment
- pH and degree of acidity

Low chloride environments (e.g., less than 50 ppm) are not immune when chlorides accumulate. Rain or condensed water can evaporate and concentrate the salt content when trapped in non-draining areas such as crevices, and accumulate as a function of time. Corrosion of steel reaches a maximum at about 6000 ppm chloride ion concentration. Increasing salt content and accumulation of chlorides over a period of time results in hydrolysis and lowering of the electrolyte pH in the cavity. Therefore, weathering steel must be protected under these conditions.

The combination of corrosive sulfur and chloride containing compounds, and the action of water hydrolysis, with or without oxygen, can cause corrosion and even cracking of high strength steel bolts in the pack-out environment. Even in moderately corrosive environments, which seem to have low chloride or sulfur containing corrosive compounds in the atmosphere, the on-going action of condensation and evaporation will result in the accumulation of corrosive ions. As a result, the joints are exposed to high levels of chlorides and sulfur containing corrosive compounds, which are not recommended for weathering steel in an unpainted condition.

Joint Integrity

The small number of bolts in most towers provides little clamping action to prevent moisture entrapment. Two other factors appear to contribute to the corrosion process. The first of which is the continued movement of connections due to flexing of the towers, which breaks the corrosion seal at the splice area and allows continual entrance of moisture. The second less important contributing factor is the occurrence of vegetation that grows up over the foundation and base of the structure, which causes the lower parts of the tower legs to remain wet.

The main problem with weathering steel towers is the accelerated corrosion due to the accumulation of corrosive sulfur containing compounds and chlorides, which results in considerable corrosion buildup between overlapping pieces of structural steel causing separation of the joints and significant deformation of the steel. This occurrence may possibly result in cracking of the plates or bolts in tension or deformation of plates under compressive conditions.

The most important finding of this investigation was that accelerated corrosion and the formation of pack-out is due to accumulation of corrosive chloride and sulfur containing compounds over a period of time plus retained moisture within the crevices and joints. Electrochemical corrosion

testing confirmed that this occurrence was not due to galvanic action or stray currents. Rather, the accelerated corrosion was due to the accumulation of chlorides and sulfur containing compounds in the pack-out. This is an on-going process, and the rates will not decrease as a function of time as some investigators have suggested. It is estimated that the corrosion rate in the joints will increase beyond 3.3 mils per year (0.083 mm/year) for the remaining life of the towers, as chlorides and corrosive ions accumulate.

Pack-out Growth Summary

The on-site investigation on forty five transmission towers included thickness measurements of the steel, electrochemical measurements, pitch and distance measurements of the bolt, photographic documentation, and sample collection for subsequent laboratory analysis. The findings indicated a maximum section loss of less than 40% of the original thickness over a service life of 30 years. This maximum metal loss is located at a single point location within the joint, typically, along the very edge of the members. The metal loss is not uniform or measurable across the member cross section of the joint. The corrosion rate within joints requires fifteen to twenty years of service before approaching stability compared to the five to 10 years required for exposed steel under oxidizing conditions.

The transmission tower case history presented a failure that resulted from several factors, of which, cavity formation, accumulation of corrosive compounds in cavities, hydrolysis of corrosion products, and the formation of pack-out are included. Contrary to recommendations provided by some investigators, the accumulation of corrosive compounds and hydrolysis of water soluble corrosion products in pack-out may result in further increases in the corrosion rate for the remaining life of the towers. At the time of the investigation, the corrosion rate appeared to be in the range of 2.5 – 3.3 mils per year (0.064 – 0.083 mm/year). The pack-out growth may result in cracking or deformation (bowing) under tensile or compressive conditions.

In summary, chemical composition of pack out, corrosivity of environment and electrochemical potential will determine if the corrosion cell inside the joint is active, or passive. ASTM G61 test results and dimensional measurement will provide information on corrosion rate and pack-out growth rate. FEA analysis and engineering calculation will determine the critical parameters for the joint, frequency of inspection and if the member should be replaced.

FEA Modeling and Analysis

Finite element modeling and analysis is used to determine the displacements and stress levels developed in a typical joint exposed to pack-out corrosion. Photographs of this joint are reproduced in Figures 9 and 10. As seen in these photographs, pack-out corrosion has developed between the straps (added possibly for reinforcement) to an existing base with two $5/8$ inch (16 mm) bolts.

The overall FEA model of the connection is reproduced in Figure 11. The initial thickness of the base metal and straps was 0.25 inch (6.35 mm) before being reduced during the corrosion process to as thin as 0.18 inch (4.6 mm) in some locations. The expansion of the pack-out corrosion separated the strap from the base by about 0.6 inch (15.2 mm), as shown in Figure 10 and in the FEA results in Figure 12.

Two opposite forces of 33,200 lbs. each had to be applied to the plates to open the gap by 0.6 inch (15.2 mm) as was measured in the actual sample. Large axial stresses (much greater than

yield), caused by pack-out corrosion, in the bolt's shank cross-section are shown in Figure 13. Figure 14 shows the same stresses but in the bolts cross-section along its length. Linearized membrane, membrane plus bending, and total stresses across the bolt's shank centerline (shown in Figure 13) are presented in Figure 15. No bolt preload was included in the analysis. In addition to bolt overload issues, the reduction in the thickness of the plates reduces the load-carrying capacity of the joint.

The pure axial load carrying capacity is reduced by the thickness ratio while bending carrying capacity is reduced by the thickness ratio to the power of 3 (cubed). These can be established for each individual case.

In summary, field measurements, corrosion risk assessment, and FEA analysis provide specific information on (1) corrosion activity of the pack-out; and (2) reduction in load-bearing capacity of the bolted joint – both of which lead to one of the following recommendations: No action, future inspection, or immediate replacement / reinforcement.

The following steps should be taken to for corrosion risk assessment and condition assessment of joints with pack-out:

1. Defining the atmospheric environment and the solution chemistry at bolted joint,
2. Determining corrosion rate (loss in thickness) based on both field measurement and laboratory electrochemical testing,
3. Determining the corrosion activity (active or passive) at the joint by electrochemical tools,
4. FEA Analysis to determine the critical thickness of the pack-out/member for the fracture/failure of bolted joint,
5. Making recommendation for corrosion mitigation if warranted.

Figure 1 – Embedded first generation weathering steel poles in service for 25 years (Source: Author(s)).

Figure 2 – Embedded 2nd generation weathering steel pole removed from service after 16 years. The coating is in excellent condition above and below grade, with less than an inch of adhesion loss at the coating interface. (Source: Author(s))

Figure 3 – Example of dis-bonded coating and expansive corrosion products in the crevice formed between polyurethane coating and weathering steel substrate (Source: Author(s))

Figure 4 – Example of embedded weathering steel monopoles with field applied coating and petrolatum tape (Source: Author(s))

Figure 5 - Photographs exhibiting buildup of Pak-out and loss in thickness of load bearing member (photo on-right hand side)

Figure 6 - Pack-out formation on bolted joints

Figure 7 - Formation of pack-out between concrete foundation and base plate of WS tower.

Figure 8 - Accelerated corrosion and extensive thinning of the tower leg .Was hidden under dirt/leaves

Figure 9 - Pack out Piece that was used for FEA Analysis

Figure 10 - Joint Cross Section showing porosity in pack-out.
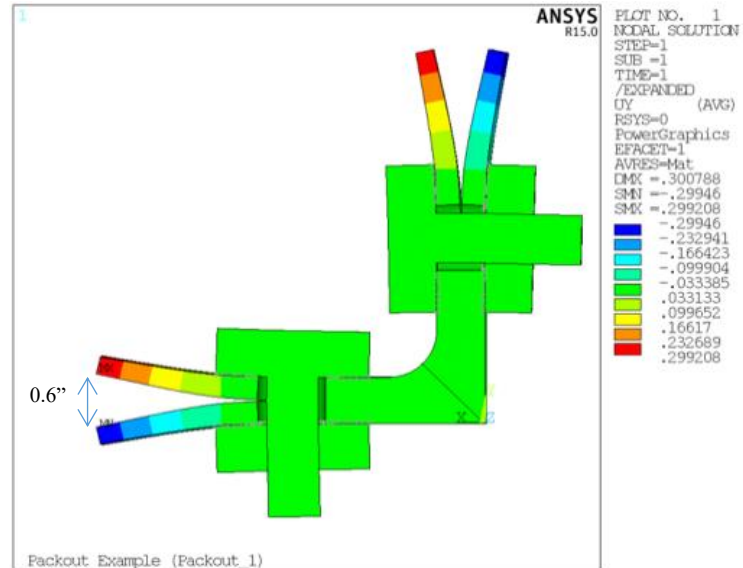
Figure 11 - Overall FEA Model

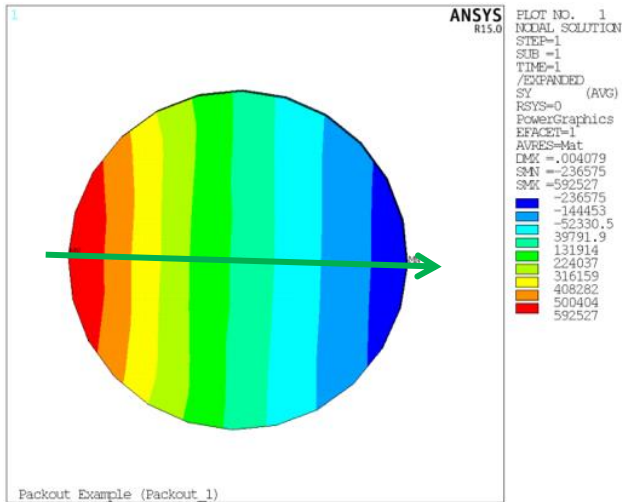Figure 12 - FEA Results Showing 0.6 inch (15.2 mm) Metal Separation Caused by Pak-out

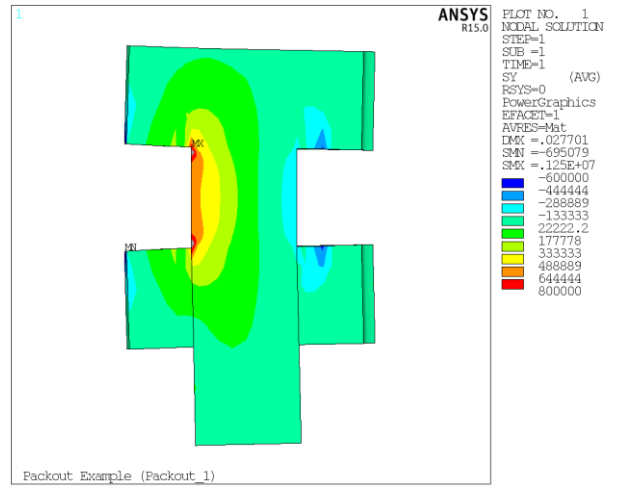Figure 13 - Axial Stresses in Bolt Shank Center

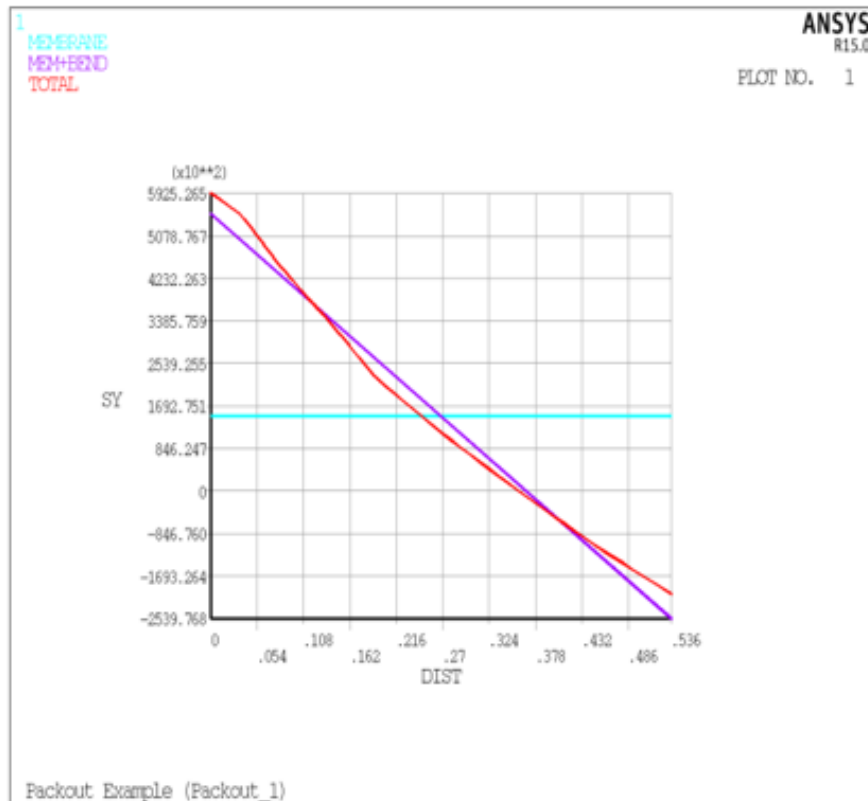Figure 14 - Axial Stresses in Bolt Cross-Section

Figure 15- Membrane and Membrane +Bend along the Arrow Sown in Figure 13