

CORROSION MITIGATION STRATEGIES FOR FLANGE SPLICE CONNECTIONS IN STEEL BRIDGES

by

Edgar Oscary Soriano Somarriba

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Mark D. Bowman, Chair

Lyles School of Civil Engineering

Dr. Robert Connor

Lyles School of Civil Engineering

Dr. Jan Olek

Lyles School of Civil Engineering

Approved by:

Dr. Dulcy M. Abraham

To my mother who has always made sure that I have everything to be who I am today. To my father who has always instructed me with his wise words. To my family who has always been my engine power.

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ABSTRACT

As of 2013, the damage caused by corrosion on highway bridges has been estimated to cost approximately 14 billion dollars annually, and this cost has been increasing over the years. Corrosion is one of the natural phenomena that has been slowly deteriorating infrastructure systems across the United States. One of the most problematic types of corrosion is crevice corrosion, which is defined as the formation of rust between overlapping surfaces such as the case of a splice connection where flanges are attached by splice plates. A significant number of steel bridges in Indiana have developed crevice corrosion in splice connections. Therefore, this research focuses on the crevice corrosion, or “pack rust”, occurring in these structural elements. The application of coatings alone has not been enough to stop pack rust at these connections. In an attempt to look for approaches that can effectively mitigate this problem and maintain the designed service life of bridges, different strategies have been studied and tested. The first objective of this study is to determine the strength reduction as a function of the time of exposure to salt misting. To do this, specimens that simulate the bottom flange splice connection have been exposed to a corrosive environment for different periods of time and later tested under tension to assess the reduction in strength. The second objective is to evaluate the effectiveness of the mitigation strategies under different conditions. First, the mitigating products were initially applied before exposure to salt misting. Second, the mitigating products were applied as a repair, and in this case, the specimens corroded for a given period of time and were then repaired to evaluate any further deterioration. The assessment of the strategies’ effectiveness is based on the strength reduction and visual inspection of the specimens. The ultimate outcome of this study is a series of general guidelines to slow down crevice corrosion based on the results of the laboratory testing.

1. INTRODUCTION

1.1 Background and Economical Impact

Corrosion has been one of most challenging natural phenomena to prevent and it has slowly been deteriorating the infrastructure of the United States and all countries around the world. Different structural elements in bridges start to show signs of deterioration much sooner than the bridges reach their service life. This damage is caused by the environmental conditions and the presence of chemicals, salts, and dirt due to natural and human activities. As of 2013, in the United States almost 33% of the bridges are steel, 38.7% are conventional reinforced concrete, 17.8% are prestressed concrete, and the remaining bridges are made of other construction materials [1]. In the last few years almost 200,000 bridges have been evaluated by the U.S Federal Highway Administration (FHWA) and the outcome is not promising. Around one third of the bridges are structurally deficient or obsolete, and one fourth of the bridges are reaching their design life [1]. All these types of bridges are affected by corrosion, but steel bridges are affected the most due to the level of exposure of the metal substrate.

The cost of the damage caused by corrosion on highway bridges has been estimated to be \$13.6 billion per year in 2013. Moreover, the Federal Highway Administration also claims that the cost has increased to \$20.5 billion per year in recent years [1]. Even though serious consequences such as bridge collapses are not usually caused by corrosion issues, there have been some well documented examples such as the Mianus River bridge collapse (1983) and the sagging of one of the spans of the Leo Frigo Memorial Bridge (2013). Approximately 15% of the bridge's deficiencies are caused by corrosion [2]. Research has been performed over the years, and continues to be conducted, to advocate for strategies that counteract the effects of corrosion, and consequently to minimize the economic impact.

Most steel bridges will eventually suffer from general surface corrosion and pitting corrosion, which causes section loss and reduction of the load capacity. Mitigation efforts against these types of corrosion have been done through the use of coatings systems. In 1997 approximately 5.56×10^9 liters of organic coating material worth \$16.56 billion was used in the United States -for all types

of structures- to address general surface corrosion [3]. Although manufacturers continue to improve these coatings, the focus of the steel bridge industry and research has shifted towards the corrosion happening in other structural elements such as bearings, gusset plates, hinge pins, splice connections, deck joints among others. In this study the effectiveness of different mitigation strategies for pack rust corrosion that occurs between plates of splice connections, and other connections susceptible to pack rust, is evaluated.

Based on the outcome of the INDOT study titled Pack Rust Identification and Mitigation Strategies for Steel Bridges (SPR-4121), some objectives have been set for the present study. Most of the bridges in Indiana built between 1950 and 1960 are reaching their service life and are in need of repair. Approximately one third of the bridges in Indiana were found to suffer from pack rust corrosion [2]. Surveys conducted during the SPR-4121 study demonstrated the importance of finding and implementing effective alternatives to mitigate pack rust corrosion for various structural components, especially splice connections. As a consequence, the current study has the purpose of evaluating different methodologies and commercial products to mitigate the effects of crevice corrosion in splice connections.

1.2 Purpose and Scope of the Research

Corrosion as a long-term natural process affects multiple structural elements of steel bridges, and looking for ways to protect these elements is the aim of many DOTs and the bridge industry. The overall performance and maintenance of these structural elements will influence and often determine the service life of a bridge. Across Indiana, splice connections require foremost attention due to the number of bridges with some level of pack rust in this type of connection. The purpose of this research project is to evaluate and study three mitigation approaches that can be implemented in the field to reduce the effects of pack rust on field splices and other types of plate-to-plate connections.

The first component of this project consists of artificially creating a corrosive environment that can produce similar conditions to the ones in the field. This was designed and performed following the ASTM B117-18 standards “Standard Practice for Operating Salt Spray (Fog) Apparatus”. The second component in this project consists of creating specimens that simulate the behavior of

flange splice connections in bridges. These connections were designed to meet the geometrical, material and coating system specifications in accordance with the AASHTO Bridge Design Specifications, and the INDOT standards for structural painting (Section 619 and 909), respectively.

Furthermore, the third task of this research project consists of studying the effectiveness of three mitigation strategies (two commercial penetrating sealers and one commercial caulk) under an artificial corrosive environment, and studying the reduction in strength due to the corrosion formed between the plates close to the center of the specimens. To evaluate the effectiveness of each one of the mitigation strategies, the commercial products were applied in some of the specimens since the beginning (prior to misting), and in other specimens, the products were applied as a repair (after misting over a given period of time). To evaluate the reduction of the strength affected by pack rust, control specimens (with no corrosion formed) and the specimens exposed to the salt misting were tested under tension loading. The specimens exposed to the corrosive environment were intermittently sprayed with salt solution to accelerate corrosion and observe how much time it takes for pack rust to develop for the base specimens (not protected), and the specimens treated with the commercial mitigation products.

The second most important objective of this research project is to determine if the formation of iron oxide decreases or increases the strength of the modeled flange splice connections. Both protected and unprotected specimens were subjected to tension testing. For this project, the two main loads to determine are load at slippage and ultimate load. This information is useful to develop a deterioration curve as a function of time. Moreover, deterioration due to pack rust was also be assessed through visual inspection.

Finally, the last task of this project consists of providing a set of recommendations for the application of penetrating sealers/caulks in accordance with the procedures of the experiment and the lab results. The implementation of these recommendations in the field are expected to contribute to the overall pack rust mitigation strategy of INDOT to minimize additional pack rust corrosion damage in steel bridges across Indiana.

2. PACK RUST MECHANISMS AND EFFECTS

2.1 Corrosion Fundamentals

2.1.1 Concept of Corrosion

Corrosion can be described as the degradation process of metals and alloys. Thermodynamically speaking, the driving force behind corrosion is the natural tendency of metals to lower their free (Gibbs) energy. This is because production of any metal such as mild steel, which is an alloy of iron and carbon, involves adding a large amount of energy to separate metal atoms from its ore. That uncombined metal atom will be in a high energy state and it will have a strong tendency to return to its native, lower energy oxide (e.g., iron oxide, an insoluble corrosion product) [4]. The amount of energy released during this process, i.e. the difference between the high energy and low energy level, varies from metal to metal [3]. The basic process of corrosion involves movement of electrons, which is opposite to the current flow. For this current to happen, an atom has to lose an electron. This process is known as oxidation. Removing electrons from an atom changes the chemical, electrical and mechanical properties of the material. On the other hand, when an atom gains an electron, the atom undergoes what is known as reduction.

There are four basic components necessary for corrosion to occur: anode, ionic current path, cathode, and electrical path. The ionic current path is the solution capable of carrying positive and negative charges between the anode from the cathode. On the other hand, the electrical path is the metallic body that carries the electrons from the anode to the cathode. The anode is the portion of the body where the loss of electrons and material occurs while the cathode is the portion that gains the electrons and corrosive material is formed [4]. This current flow makes the cathode a positively charged region whilst the anode is negatively charged. If these four elements are present, the corrosion process is predetermined to happen. Moreover, there are other factors that affect the corrosion process of any metal, but amongst the main factors are the susceptibility of the material to lose electrons, the conductivity or resistivity of the material, the acidity/alkalinity of the environment, ambient temperature, presence of other ions, moisture and dissolved oxygen, and the geometry of the body in question.

2.1.2 Anodic and Cathodic Processes

Corrosion can be described as an electrochemical process since it involves the reaction of different elements and ions, and it also involves the movement of electrons from a negative zone (anode) to a positive zone (cathode) of a material. Corrosion takes place when there is a formation of ions, electrons flow, and the anodic-cathodic reactions occur at the same time and rate [3]. The anodic reaction is what is commonly known as corrosion since it is the loss of material. In this reaction, the material loses an “n” number of electrons and becomes a positive ion. Unfortunately, for iron-based materials, iron can lose up to 6 electrons [3]. These electrons move towards the cathodic zone where they combine the hydrogen ions (H^+) to become hydrogen gas (H_2), which increases the alkalinity of the cathodic zone. Other basic compounds such as hydroxyl ($-OH$) form in this area after oxygen, water and electrons combine [3]. Therefore, during the corrosion process, the anodic zone becomes acidic while the cathodic zone becomes alkaline. In order to mitigate corrosion, an important aspect to consider is to look for methods capable of controlling the ratio of the cathodic surface to the anodic surface (S_c/S_a). The current of both, the cathodic and anodic processes is the same, but this is not necessarily true for the current density, which is expressed in units of current per area. Current is simply the product of the current density and surface area. Consequently, having a surface ratio much greater than 1 (the anodic area is smaller than the cathodic area) is an antagonizing factor that can lead to the rapid loss of material.

2.1.3 Polarization

When there is a movement of electrons, a potential difference is formed. During polarization, the anodic zone potential becomes more positive and the cathodic zone potential becomes more negative. Quantitatively, polarization is the difference between the overall resulting potential and the individual reaction equilibrium potential. Basically, there are three types of polarization that contribute to the total polarization: ohmic, activation, and concentration [3]. Ohmic drop ($V = IR$) is defined as the product of the current and resistance between the ends of the dipole, and it is the most contributing type of polarization in crevice corrosion. The electrolytic resistivity of the medium between the cathode and the anode is the source of this potential. Polarization plots (Potential vs $\log(i)$) are created under the influence of variables such as temperature, pH and type of current (cathodic and anodic) for different materials. The projected lines of the cathodic and

anodic curves in these plots are used to find the intercept, which is the current at which both types of currents cancel out ($I_{\text{anodic}} = I_{\text{cathodic}}$) [3]. This intercept is known as the corrosion current, which is divided by the affected area of a material to obtain the current density and thus corrosion penetration rate.

2.1.4 Corrosion Rate

Corrosion is a natural process, so it is impractical to think that it can be stopped. Nonetheless, the reduction of the corrosion rate is what most engineers and scientists are interested in for applications in the bridge industry, machinery, equipment, electrical components, among others. Corrosion rate can be defined as the material loss over time. It is usually measured as weight loss or penetration rate. In the United States one of the most common equations to calculate the penetration rate in mils per year (mpy) is $534 \cdot W / dAT$, where W is the mass loss in milligrams, d is the density of the substrate, A is the corroded area and T is time [4]. A penetration rate from 1 to 20 mpy is considered low to fair corrosion, and from 20 to 50 mpy or above is considered high to excessive corrosion [4]. In accordance to Faraday's laws, scientists and engineers have been able to establish empirical relationships between current (moles of electrons), and mass loss (moles of elements) or corrosion penetration rate. For mild steel ($n = 2$, molar mass = 55.85 g/mol, density = 7.88 g/cm³), the penetration rate is 11.6 millimeters per year (mm/y) for a current density of 1 milliamperes per centimeter square (mA/cm²) [3]. This converts to 457 mpy approximately, which translates to a high corrosion rate for mild steel.

The corrosion rate is remarkably dependent on the four basic components of corrosion. Electron production on the anode during oxidation is proportionally related to the amount that can be consumed during reduction on the cathode. Furthermore, the resistance of the solution playing the role of ionic current path and the conductivity of the metal playing the role of electrical path influences the corrosion rate [4].

2.1.5 Forms of corrosion

Roberge Pierre in his book titled “Corrosion Engineering Principles and Practice” identifies nine types of corrosion attacks that are categorized into three groups [3]. First, corrosion attacks that can be recognized by visual inspection are uniform, localized, and galvanic corrosion. Second, attacks that can be identified by inspection tools are erosion-corrosion, intergranular and dealloying corrosion. Finally, some other corrosion attacks can be present as stress corrosion induced by cracking, high-temperature corrosion and corrosion produced by microorganisms. This research focuses on crevice corrosion, which falls under the category of localized corrosion.

Crevice corrosion is a form of localized corrosion, but it also falls under the category of atmospheric corrosion, which is the degradation where the main components of the bulk environment is air and its pollutants. There are four main types of atmospheric corrosive environments: industrial, marine, rural, and indoor. Industrial environments are characterized by the presence of acid rains. Marine environments are characterized by the presence of salts and moisture. Rural and indoor environments are the most clement environments since the presence of chemical contaminants is low.

There are multiple factors in a corrosive environment that regulates corrosion. For example, moisture and relative humidity, which represent the presence of water in the atmosphere, plays an important role in the abundance of dissolved oxygen in the deep crevice and the formation of hydroxyl (-OH) at the mouth of the crevice. Furthermore, temperature has been observed to play a role due to the fact that for each 10°C increase in ambient temperature, the corrosion activity seems to double [3]. As previously mentioned, another factor that affect the rate at which corrosion happens is the formation of a film on the surface of certain metals. The thickness of this iron oxide film decreases over time, but it deaccelerates corrosion. There are other human-caused factors such as the presence and concentrations of deicing salts used by DOTs such as sodium chloride and calcium chloride during the winter season that promotes corrosive environments.

2.1.6 Coating Systems

Corrosion attack can be diminished by two main methods: a) separation of the interacting phases with physical barriers b) reducing the reactivity of the interacting phases with chemical inhibitors. Coating systems fall under the first category. There are three basic types of coating systems: Organic, inorganic, and metallic. Organic coatings are prepared with inhibitors that oppress the mechanism behind corrosion by creating a physical barrier that interrupts the interaction between the metal and the environment (moisture, ions, pollutants, etc.). Resin polymers used in organic coatings are the based to make acrylics, epoxies, and polyurethanes. Inorganic coatings are made with inert materials that are resistant to most weathers. In this group, hydraulic cements, ceramics, anodizing materials, chromate films among other can be included. Ultimately, metallic coatings provide cathodic or sacrificial protection to the metal. Cathodic protection consists of painting the metal with a layer of another metal-based coat so that this layer acts as the anode instead of the metal substrate. Galvanizing, which has been the most effective and used form of metallic coating, consists in immersing the metal substrate in molten zinc [3] [4].

A typical coating system consists of two or three layers. The first layer is the primer, which should have strong adhesive properties and a significant amount of anodic sacrificial material or inhibitors. The intermediate coat is a transitioning layer between the primer and the topcoat. Finally, the topcoat has multiple functions such as reducing the moisture penetration rate and photodegradation produced by the sun. It also improves the aesthetics of the bridge or structure since color pigments are usually added in this paint.

The effectiveness of the coating systems does not only rely on the properties of these coatings, but also on the surface preparation and other design considerations, especially on bridges. Some of the design practices that can maximize the effectiveness of the paint are: rounding of sharp corners, polishing of surfaces to obtain a smooth metal surface, sealing of gaps between surfaces, the design of effective drainage systems to avoid the collection of dirt and water, among others [3]. A poor surface preparation or improper application of the paint can lead to failure of the protective coating system. Among these events, osmosis, moisture transfer, blistering, surface contamination, surface irregularities, temperature differential on the substrate and water absorption are the most common, and they can lead to cracking of the paint, fisheyes, and uneven thicknesses.

Surface preparation plays an important role on the success of the coating system. This is why 45% of overhauling project cost are directed towards surface preparation [3]. The Society for Protective Coatings (SSPC) offers guidelines for the selection and application of the different cleaning methods and according to the circumstances or level of degradation and corrosion. Solvent cleaning, abrasive cleaning (centrifugal, air-pressure blasting, wet blasting, etc.), water jetting are methods that are standardized by SSPC and should be addressed by manufacturers that commercialize coating systems.

2.2 Pack Rust on Steel Bridges

2.2.1 Concept of Pack Rust

Pack rust can be defined as the formation of corrosion material inside the crevice formed by two overlapping metallic surfaces or a metallic surface with non-metallic surface. Pack rust can possibly compromise the integrity of the structural element in question if not treated before significant corrosion develops. This term is often interchangeably called crevice corrosion. According to previous studies, pack rust can range from simply staining of the overlapping plates to 0.75 in. (or greater) bulging of the plates [2]. Pack rust can be observed in gusset plates, joints, splice, or any kind of bolted connections. The formation of corrosive solid material between two or more surfaces can produce stresses on the plates, and bolts or rivets that connect them.

This research focuses on studying the pack rust development on splice connections and ways to mitigate this problem. In bridges, splice connections are moment connections that are under cyclic loading, and the number of cycles required for a structural component to fail is reduced significantly when it is affected by a corrosive environment [3]. It has been observed that pack rust can develop at high rates depending on the geometrical detailing of the bridge, the properties of the material being used, the proximity to humid environments, the opening of crevice and the presence of contaminants and salts due to deicing agents. Mitigation strategies, as used herein, involve methods that result in the prevention of further pack rust development and, thereby, the prevention of additional structural damage.

The types of steel primarily used in the bridge industry are carbon and high-strength low-alloy steels. Carbon steel in general performs poorly to fairly against corrosion. However, it is highly demanded in this industry due to its mechanical properties, weldability, and relative low cost. Uniform and other types of corrosion have been effectively controlled with different protection methods such as protective coatings, inhibitors, cathodic protection. However, pack rust is still a problem in many steel bridges across the United States and Indiana due to the mechanism that involves this type of corrosion. To counterattack the effects of pack rust, multiple products have been developed in recent years, such as penetrating sealers and waterproof caulks.

2.2.2 Mechanism of Crevice Corrosion

Crevice corrosion, which is the scientific term for pack rust, occurs between mating metallic surfaces when the gap between these surfaces cannot be properly sealed. Even though there is a need of further research to fully explain the mechanism of crevice corrosion, there are two main streams that try to explain this phenomenon.

First, the critical crevice solution (CCS) or traditional mechanism is based on the reactions taking place at the anode (inside of crevice) and cathode (outside of crevice) [5]. The anodic reaction consists of the loss of electrons from the metals, while the cathodic reaction consists of the formation of hydroxyl from water and oxygen. With the formation of the anode and cathode, a potential gradient is formed and attracts chlorides and other salt ions from the atmosphere. Acidification inside the crevice is due to the hydrolyzation of the metal, which forms hydrogen ions, and also due to the presence of acids such as any salt solution. On the other hand, the outside of the crevice is basic due to the formation of hydroxyl ions. The final formation of corrosion product or pack rust happens when the iron ions move outwards to react with oxygen and water.

The second explanation uses the analogy of an electric circuit. In the presence of an aqueous solution, there is a current flowing from the outside of the crevice to the inside. This current produces a potential that drops from the mouth of the crevice inwards. At any point “x” inside the crevice, the potential equals the potential at the mouth (E_{out}) minus the product of the current I_x at that point “x” and the resistance of the aqueous solution, R . Moreover, the passive potential (E_{pass}) of a metal is the potential at which there is no electronic activity. Therefore, corrosion does

not occur. Ultimately, this second theory establishes that crevice corrosion will only happen if I_x times R is greater than $E_{out} - E_{pass}$ [5]. In contrast to the traditional theory, the voltage drop theory is able to explain how corrosion can proceed with isolation of pH, but it cannot explain how the overall corrosion process starts.

Rather than going with one theory or the other, it is more beneficial to create a set of fundamental ideas for one big theory, which can be based on the complementation of both previously discussed theories. This can help to develop solutions that can help minimize the corrosion problem. Furthermore, other academic sources in combination have been able to explain the development of pack rust in the following three stages:

- 1) Dissolved oxygen is consumed with the metal ions at the deep portions of the crevice while the exterior has a plentiful supply of oxygen and, consequently, a differential aeration cell is formed. This differential aeration mechanism starts the corrosion process [3]. Figure 2.1 illustrates the first stage.

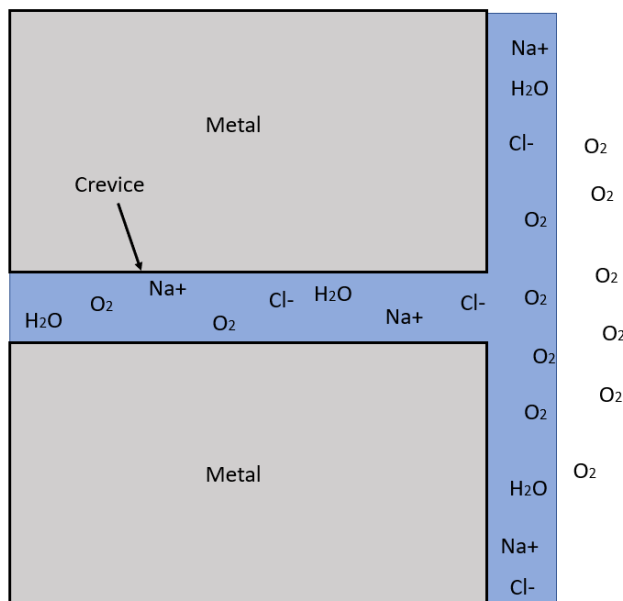


Figure 2.1. First stage of crevice corrosion.

- 2) Inside the crevice, the metal goes under anodic dissolution where the metal loses an “n” number of electrons. These metal ions combine with the anions from the salts to go under hydrolysis and form hydrochloric acid (HCl) and consequently the pH in the deep crevice is low (acid). The increasing concentration of this acid speeds up the rate at which more electrons are scraped off and this phenomenon dissolves more metals into ions plus hydrogen gas (H_2). In the exterior of the crevice, the oxygen, water, and the electrons combine to form hydroxyl ($-OH$) and, consequently, the pH becomes neutral or basic [4]. Thus, since the metal is releasing electrons and these are moving towards the mouth of the crevice, an electric dipole is formed, where the deep portion of the crevice becomes the anode (negatively charged) and the mouth of the crevice becomes the cathode (positively charged). Figure 2.2 illustrates the second stage.

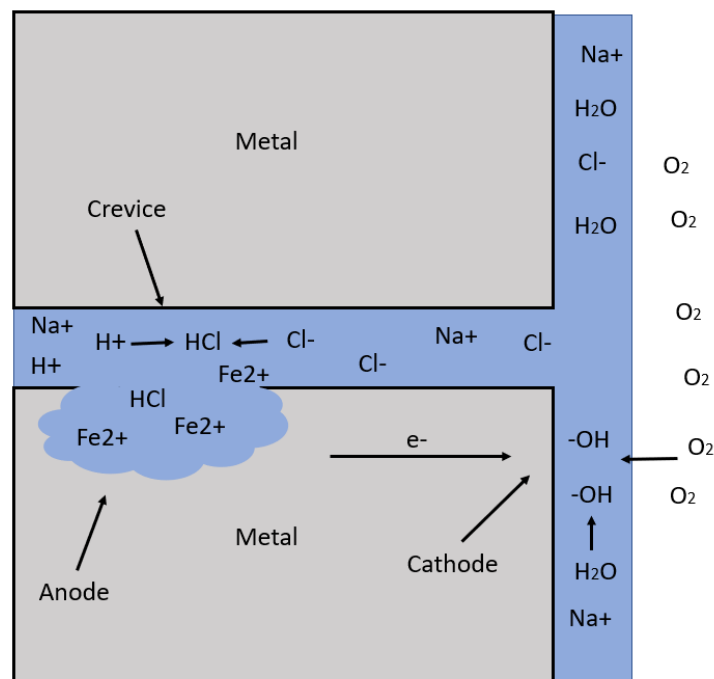


Figure 2.2. Second stage of crevice corrosion.

- 3) There is a constant electron movement and current, which forms a potential difference across the crevice. These electrons move from the anode to the cathode under a repeating cycle, while pack rust is formed at the mouth of the crevice due to the reaction of metal ions with oxygen. Figure 2.3 illustrates the third stage.

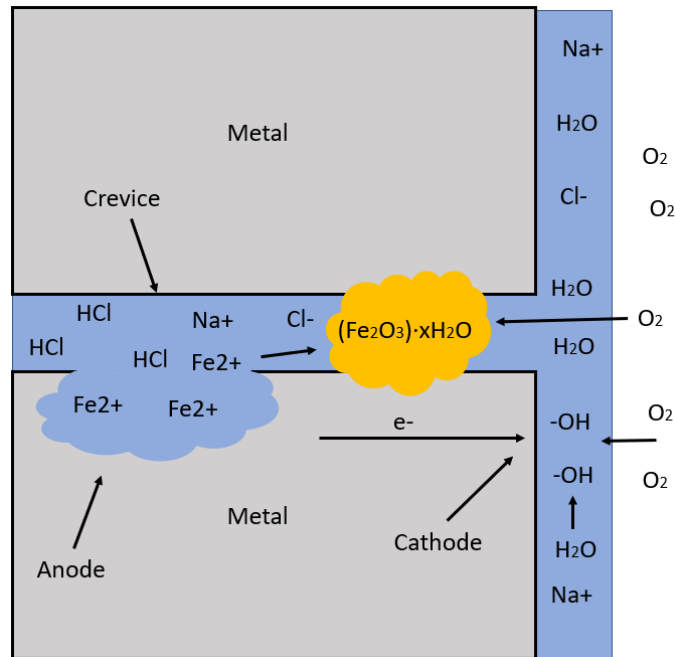


Figure 2.3. Third stage of crevice corrosion.

During the corrosion process there are some factors that can exacerbate the problem. Acidification in the deep portions of the crevice increases the rate of corrosion. Positively charged regions in the electrolyte attract ions such as chlorides and sulfates that increase the acidity and consequently the corrosion rate. Also, the formation of pack rust at the mouth of the crevice seals the entrance of oxygen, which contributes to the differential aeration mechanism. Additionally, as previously mentioned, the ratio of the cathodic area to the anodic area is an aggravating factor. A large ratio means that the area pulling electrons is greater than the area supplying electrons, and consequently this ratio translates into a high corrosion rate [3].

2.2.3 Effects of Pack Rust on Structural Elements

There are four main effects that corrosion, especially pack rust, can cause on structural members: section loss, overstress, unintentional fixity, and unintended movement. Section loss can lead to a direct reduction of the load carrying capacity. Built-up corrosion can produce pressures of up to 10,000 psi, which eventually cause bending and/or spreading away of the elements from each other. Moreover, on compressive members, pack rust is capable of introducing eccentricities and deforming built-up members, which can cause local buckling [6].

In this project, the effects of crevice corrosion on the tensile ultimate strength are studied. Tension stresses experienced by a metallic member combined with corrosion deterioration is one of the most threatening situations that can be encountered in the field [3]. However, other limit states such as fatigue and brittle fracture should also be studied since splice connections are under cyclic loading. Structural components that are exposed to corrosion and cyclic loading can suffer from corrosion fatigue. Stress corrosion cracking can be caused by the exposure to pitting corrosion and repeated loading. For a component that suffers corrosion fatigue the fluctuation of stresses is high, which leads to a significant drop in the number of cycles necessary to produce fracture [3].

Models analyzed in ABAQUS have shown that pack rust can exert a pressure which increase the tension forces experienced by the bolts. For bolts having a tensile strength of 120 ksi, approximately 2500 psi and 2960 psi pressure is required to produce a splice deformation of 1 in for connections with 7/8 in. and 1 in. diameter bolts, respectively. If loss of bolt cross section due to corrosion is taken into consideration, these pressures could be even lower; the additional bolt tension force combined with the shear forces could also compromise the bolt strength. The maximum observed splice deflection on steel bridges in Indiana is one inch [5].

Pack rust formed between the overlapping surfaces can produce additional tension forces in the fasteners that at the same time produces high strains, which may lead to failure of the bolt or rivet. The geometrical properties of the connections play an important role in the formation of crevice corrosion. First, staggered bolt and rivet patterns should be avoided since they allow the entrance of moisture at the corners due to the reduced clamping force at these locations. Another important factor is the thickness of the plates. The corrosion product can cause bending of the plates rather than fracture of the bolts as the plates in the connection become thinner. However, bending the plates also comprises the integrity of the shear strength of the connection, which can lead to failure. One third of the 1,781 bridges in Indiana have been observed to have pack rust that has developed to some degree. Some of them (3%) have been found in critical condition such that welds and bolts have fractured [5].

2.3 Bolted Flange Splice Connections

The AASHTO LRFD Bridge Design Specifications defines splices as a bolted or welded connection capable of transferring moment, shear, axial force, and torque at the ends of two structural elements. In the steel bridge industry, these structural elements are commonly girders and beams [7]. The design of bolted connections and bolted splices are covered in AASHTO LRFD 6.13.2 and 6.13.6, respectively. Some of the design specifications are described as follows. For instance, these connections are required to be designed symmetrically along the longitudinal axis of the primary member, and consequently eccentricities should be avoided. Splices connecting the end sections of stringers, floor beams and girders should be designed with high strength bolts [8].

In this research study, the influence of the pack rust occurring on bolted flange splice connections is of particular interest. Flange splice connections consist of one plate attached to the outside portion of the girder flange and two plates on each side of the web. For alignment and stability purposes during erection and construction, at least two rows of bolts are required on both sides of the web. Moreover, splices connecting flexural members are required to be placed at dead load contraflexure points. Flange splice connections are considered slip-critical, and slip should be prevented under the Service II Load Combination and the loads produced during casting of the concrete deck [7]. Furthermore, the number of flange splice bolts required can be determined by dividing the required flange force by the slip resistance of the bolts. This resistance can be calculated in accordance with section 6.13.2.8 of the AASHTO manual as $R_n = K_h K_s N_s P_t$. Coefficients K_h , K_s and P_t are obtained through tables 6.13.2.8-1 to 6.13.2.8-3. N_s refers to the number of slip planes per bolt, which is two in this case [8].

Regarding strength limit state, flange splice plates and their connections should be able to develop the yield resistance of the smaller flange at the connection. The yield resistance of the flange is defined as $P_{fy} = F_{yf} A_e$, where F_{yf} is the specified minimum yield strength of the flange, and A_e is the effective area of the flange. Complementary to the slip resistance method, at the strength limit the number of flange splice bolts required on each side of the web can be determined by dividing the smaller design yield resistance by the factored shear resistance of the bolts [8]. Finally, the number of bolts will be determined based on the number of bolts required to satisfy both conditions.

2.4 Laboratory Corrosion Testing

The purpose of corrosion testing is to assess the response of materials against corrosive environments, and to obtain information that can provide a better understanding of the mechanism behind corrosion. Even though the overall idea is well understood and explained by the science community, there are some gaps in the different corrosion theories. Corrosion involves many independent variables, which makes testing difficult.

Corrosion tests are classified in laboratory, pilot-plant, and field testing [4]. First, laboratory testing is performed to obtain information regarding the reliability of a coating or material to improve the service life of another substrate material. The evaluation of these protective coatings is performed over weeks and months and the results are scaled up to match with the service life of a bridge (approximately 75 years or more). Corrosion rate is another parameter that can be studied in a laboratory test by electrochemical means and immersion tests. In these accelerated tests different parameters such as temperature, acidity of the environment and exposure are intensified to compensate for the lack of time. Second, pilot-plants tests are basically small-scale tests that are intended to duplicate a bigger environment. Finally, field testing consists of exposing the material to the actual in situ environment, which is the most accurate, but also requires a long time [4].

Laboratory tests are the most widely used tests in the corrosion industry. There are basically three types of laboratory testing: simulated atmosphere, salt spray and immersion. First, simulated atmosphere tests consist of storing the specimens in chambers where temperature (0-150°F) and relative humidity (20-100%) are thoroughly controlled. This test also involves the condensation of moisture inside the cabinets and introduction of corrosive agents into the encapsulated atmosphere. Second, salt spray tests are the most accepted tests for testing protective coatings and materials. It consists of spraying the samples with a corrosive solution. Finally, in immersion tests, specimens are completely, partially or alternately immersed on a target solution composition depending on the environmental condition to simulate. The pack rust research in this study will employ the salt spray test (ASTM B117) to assess the effectiveness of three mitigation strategies/products that can reduce the formation rate of pack rust. Salt spray test have been extensively used over more than 90 years since its variables contribute to simulate an aggressive marine environment [4].

3. LITERATURE REVIEW

3.1 Strategies Implemented by other DOTs.

Various mitigation strategies are being used by the Departments of Transportation across the United States in order to extend the lifespan of their existing bridges. The strategies being employed across the United States are stripe coating (24 states), caulking (13 states), penetrating sealers (8 states) and backer rods (2 states) [2]. Moreover, the mitigation strategies do not only involve the application of coating or paint in order to delay corrosion, but they also include a surface preparation in the case a of new bridge, or a mechanical cleaning in the case of an existing bridge. The set of standards for surface preparation is provided by The Society of Protective Coatings (SSPC), while the cleaning methods used prior to the application of the mitigating material will depend on the recommendations of the manufacturer.

3.1.1 General Mitigation Approaches used by other DOTs.

Over time four main mitigation strategies have been applied in the field in an individual or combined way to minimize the formation of pack rust on the different structural connections. The following sections provide a brief description and some of the characteristics of each approach.

3.1.1.1 Caulking

Caulking involves the application of a waterproof, low viscous material at the mouth of a crevice in order to prevent the entrance of moisture and salts. The utility of caulk is not reliable on the long term since it tends to crack due to movements caused by changes in temperature, which can allow moisture to get into the crevice. Under this circumstance, the corrosion rate can then be reactivated. In the recent years, multiple caulk manufacturers have been able to improve caulking products through the addition of other chemical components. These additives have made some caulking products more resistant to cracks produced by joint movement and thermal expansion. As of 2020, caulking is one of the methods utilized by INDOT to deal with pack rust [5].

3.1.1.2 Penetrating Sealer

The difference between caulking and penetrating sealers is that the sealers have enough viscosity to infiltrate into the crevice. The efficiency of this method highly increases when the sealers are alkaline, since the acid environment inside the crevice is then partially or fully neutralized. Basically, penetrating sealers have two main functions: a) neutralize the acidic environment inside the crevice, and b) seal the crevice in order to avoid the entrance of salt ions and water. The requirements for these penetrating sealers vary from state to state. For example, the state of Delaware and Missouri require 100% solid rust sealers and calcium sulfonate rust sealers, respectively [5].

3.1.1.3 Stripe Coating

Stripe coating consists of the application of extra mils of coating at surfaces where the underlying film thickness of the coating system is thin. The application of the stripe coat follows after deposit of the primer or intermediate coats, or in some cases following each of the three coats. At the welds, edges and interfaces of plates, the thickness of the paint is less compared to the rest of the flat parts of the connections due to geometry and surface tension. Therefore, an extra layer of coating is applied at these locations. The thickness of this extra layer of topcoat is not often controlled by measuring it with dry-film thickness gages due to the irregularities of the area of application. Nonetheless, it is important to avoid a thick extra layer since other surface anomalies such as pinholes and cracking can occur [9]. The addition of this layer minimizes the entrance of moisture into the gap. In the same way as caulking, cracks will form eventually as thermal expansion happens and will allow the presence of moisture inside the crevice [5].

3.1.1.4 Backer Rod

These rods are used to fill joints, fissures, and gaps and are made of flexible polyethylene or polypropylene material. After the rod is placed into the crevice, a layer of caulking is applied to fully seal the gap [5].

3.1.2 DOTs Mitigation Strategies for Pack Rust Removal and Treatment

The following sections provide a description of what the states of New York, Minnesota, Illinois and Louisiana have been doing to mitigate general and crevice corrosion. Moreover, a technique employed by a contractor has also been included since its application has been found across multiple states. This section compiles standards, manuals, and procedures developed by the corresponding DOTs. Ultimately, Table 3.2 provides a summary of this section.

3.1.2.1 New York State Department of Transportation Approach

The New York State Department of Transportation offers in its website a series of documents called “Special Specifications” to provide guidelines on how to perform certain works that are not commonly done. These specifications are divided into series (200-800) and each series group has multiple items that correspond to a specific type of task in a project. The item that dictates the guidelines to mitigate pack rust is under Item 564.21010011 – PACK RUST REPAIR [10]. This item describes the materials and methodology to use when built up steel members have suffered a decrease in strength, section loss and other consequences due to pack rust. This item specifies the materials to use as follow:

1. Epoxy penetrating sealer shall be one of the following:
 - Rustbond Penetrating Sealer, as manufactured by the Carboline Company, St. Louis MO
 - Amerlock Sealer as manufactured by PPG, Montvale NJ
 - MACROPOXY 920 Pre-Prime as manufactured by The Sherwin Williams Company, Cleveland OH
2. Polyurethane Sealant meeting the requirements of Federal Specification TT-S-00230 C, Type II, Class A, Non-Sag, One Component
3. Preformed, closed-cell foam material meeting the requirements of 705-08.

First, the areas to repair will be those determined by the engineer and those areas where more than 3/8 in. deformation is observed. The Engineer will determine the number of the rivets and bolts to replace based on the deterioration level of the plates. During replacement, two adjacent rivets or bolts should not be removed at the same time. In accordance with Sections 573-3 or 574-3, all the

old paint needs to be removed. Then, pack rust is removed by means of power tool cleaning; removal of pack rust by pressure washing is not allowed. After the corrosion material has been removed, the affected area is dried with heat until the temperature of the steel surface reaches 250° F without damaging the remaining coating present on the steel.

The application of the selected epoxy penetrating sealer should be instantly after the surface has dried and in accordance with the instructions given by the manufacturer. Thereafter, once the penetrating sealer has dried, the new rivets or bolts will be placed in accordance with Section 586.3.03 of the Specifications. The bolt installation should bring the deformed plates together. Before the final step, the surfaces should be clean without any loose paint, dirt, or rust. Finally, the application of caulking is performed on the repaired surface and on the edges to encapsulate the gap with closed-cell foam material and polyurethane sealant. The caulk is applied as recommended by the manufacturer.

Moreover, there is another item related to pack rust mitigation, Item 573.99000011- LOCALIZED CLEANING, APPLYING PENETRATING SEALER & CAULKING EXISTING STEEL [11]. This item was implemented in a proposed bridge maintenance project (D264125 F.A Proposal, September 1st, 2019) for 10 bridges in Orange and Westchester counties in the state of New York [12]. This item explains the guidelines for the cleaning and application of the penetrating sealers and caulk on areas of existing structural members such as splices, joints, and back-to-back angles.

The steel cleaning equipment consists of brushes, discs, wheel, scrapers, descenders, blast cleaning and vacuum-shrouded tools, as needed. The use of paint brushes, roller, spray equipment and caulking gun is usual in the application of the caulking material and sealer. A series of accepted penetrating sealers are identified in Item 564.21010011 – PACK RUST REPAIR [10]. The penetrating sealer should meet the requirements dictated by Item 564.21010011 such as: being able to remain hidden after a single layer of paint coat; Low V.O.C.; No lead, chromate, or mercury components in the formulation; and lastly, 100% volume solids, no shrinkage, and low viscosity. The caulking material should be compatible with the paint system and be able to remain hidden after a single layer of coating has been applied.

The procedure starts with the steel cleaning and the collection of the dust, dirt, and pack rust. Shoveling, dry sweeping, wet sweeping, or air blowing is not permitted in this step. Vacuum with high efficiency particulate (HEPA) filters are then used to collect the remaining materials after the first cleaning. The next step is the removal of the pack rust to a point of 1/8" below the surface. The use of a dull putty knife to remove tight pack rust is not allowed in order to avoid nicking the steel. Then, brush, roller, or airless spray methods are permitted for the application of the penetrating sealer. It is recommended to apply the penetrating sealer before the appearance of the flash-rusting condition. Therefore, the sealer should be applied at a maximum of 16 hours after the cleaning of steel. It is recommended that the penetrating sealer be applied at a temperature range between 41°F and 100°F and a relative humidity below 85%.

Finally, caulk is spread over areas with gaps, edges of connecting plates, and joints. Caulk should be applied between the applications of the intermediate and finish coat of the paint system, and in accordance with the manufacturer's recommendations and guidelines.

3.1.2.2 Minnesota Department of Transportation Bridge Maintenance Plan

MnDOT's approach to mitigate pack rust is a combination epoxy penetrating sealer and stripe coating application. Chapter 8 of their Bridge Maintenance Manual addresses five different types of maintenance painting depending on the degradation level of the steel. The visual coating condition determines which of the following strategies should be applied: Do Nothing, Spot Repairs, Spot repairs and Overcoating, Spot Repairs and Replacement (Zone), and Removal and Replacement. Out of all these strategies, pack rust is treated in Spot Repairs and Replacement (Zone). This section applies to bridge elements that have suffered a 2% material loss or more. Moreover, elements that lie under expansion joints, beam ends, supports, and connecting elements with pack rust belong to this section [13]. In summary, this strategy consists of cleaning the pollutants from the structural elements in accordance with SSPC standards, removal of pack rust and existing paint, and full replacement of the coatings.

The MnDOT procedure consists of a pre-cleaning, cleaning, surface preparation and application of coating. Pre-cleaning is defined as the removal of visible contaminants such as bird droppings, trash, debris, loose rust, and any corrosion product (including pack rust) that does not compromise

the integrity of the structure. Removal of oil, grease, dust, and any other chemical in accordance with SSPC-1 “Solvent Cleaning” is done in the cleaning procedure. Furthermore, surface preparation is practically performed by means of abrasive blast in accordance with SSPC-10 or SSPC-11 one foot beyond the area to be recoated. Finally, the cleaned areas are painted with a brush, spray, or roller. Other elements and zones such as nuts, bolt heads, rivets, crevices, edges, etc. are stripe coated [13]. The application of epoxy penetrating sealer is based upon judgement of the engineer [14].

During the National Bridge Preservation Partnership Conference 2018 in Orlando, Florida, MnDOT presented updates regarding their maintenance of steel bridges. They pointed out that around 50% of the time they have employed the Spot Repair and Overcoat strategy plus commercial power tool cleaning when pack rust is present. In this conference, they also explained their systematic approach to evaluate the condition of the coatings, the surface preparation, and the selection of the mitigating strategy. In the surface preparation portion, MnDOT added that water pressure washing might be a technique to use in their approach when recommended [14].

3.1.2.3 Illinois’s Cleaning and Painting Procedure for Existing Steel Structures

The treatment of general corrosion for the state of Illinois is specified in the Guide Bridge Special Provisions (GBSP 25 – Cleaning and Painting Existing Steel Structures). This document addresses the procedure related to the examination of pack rust severity, cleaning, surface preparation, repair/paint methodology, among other topics. The first step in these provisions is to test the affected sections. The test is performed over an area of 10 sq. ft. and its purpose is to assess the conditions of the coatings and components affected by corrosion. Along this line, this test is also performed to show the operation of the different tools that will be employed during the work and to determine the procedure to follow in the surface preparation. This assessment is performed in accordance with the SSPC visual standards [15].

The cleaning portion of the work groups multiple tasks such as compressed air cleanliness in which the contractor makes sure that there is no oil, dust or any contaminant in the air stream used in accordance with ASTM D 4285. After air cleaning, the contractor pressure washes the surface at a minimum pressure of 1000 psi and a maximum pressure of 5000 psi using potable water along

with other requirements of SSPC-SP WJ-4 “Low Pressure Water Cleaning”. The water jet should be capable of removing bird droppings, loose mill scale, rust, nests, dirt, etc. Only under the engineer’s approval is the use of additives in the water jet allowed. Given the presence of gasoline deposits, grease, or oil, a solvent compatible with the coating system should be applied in accordance with SSPC-1. Another note in this section is that pack rust built-up on mating plates should be removed without separating the plates from each other. The remaining corrosion products should be left intact so that it can be examined with a dull putty knife [15].

During the surface preparation there are other steps that should be taken previous to the application of the penetrating sealer and the new coat. The surface preparation should also include one or more of the following methods: near-white metal blast cleaning (SSPC-SP 10), commercial grade power tool cleaning (SSPC-SP 15), and power tool cleaning (SSPC-SP 3). Other methods for special situations are also described in their provisions. The surface profile created during the blast cleaning should be between 1.5 and 4.5 mils. Salt removal is another step that can be included in the pressure washing step, sometimes with the help of a chemical, or can be done by means of steam cleaning. The painting should be started before rust appearance [15].

Finally, the paint is applied based on the manufacturer’s recommendations, but generally is applied with a spray gun, roller, or brush. IDOT has developed a series of six systems with different coating types and penetrating sealers combinations used for different situations in the field. For each repair project, one of the six systems is selected depending on the conditions of the coatings and the nature of the material (bare steel or previously coated). Three of these systems are applied on new structures or bare steel, while the remaining are applicable to existing structures. It should also be highlighted that the state of Illinois establishes two requirements for the epoxy penetrating sealers that are used in repair projects: be clear in texture and need to be $98\pm 2\%$ volume solids. The paint systems applicable to existing structures that have suffered any form of corrosion, including pack rust, are detailed in Table 3.1.

Table 3.1. Painting systems for existing steel structures in Illinois [15].

System	Coating	Dry Film Thickness (mils)	Application
System 2 – PS/EM/U	Epoxy Penetrating Sealer	1 to 2	Full coat
	Aluminum Epoxy Mastic	5 to 7	Spot intermediate coat
	Aliphatic Urethane	2.5 to 4	Stripe coat and full finish coat
System 4 – PS/EM/AC	Epoxy Penetrating Sealer	1 to 2	Full coat
	Aluminum Epoxy Mastic	5 to 7	Spot intermediate coat
	Waterborne Acrylic	2 to 4	Stripe coat and full finish coat
System 6 - MCU	Moisture Cure Urethane (MCU) Sealer	1 to 2	Full coat
	MCU	3 to 4	Spot intermediate coat
	MCU	2 to 4	Stripe Coat and full finish coat

3.1.2.4 Louisiana’s Painting and Protective Coatings Specifications

The Louisiana Department of Transportation and Development addresses the pack rust problem on existing steel structures in Chapter 8 – Structures of their Engineering Standard Specifications under section 811 – Painting and Protective Coatings. In summary, this section outlines the cleaning, surface preparation, application of penetrating sealers, coatings, and caulk products. Moreover, the standards address the testing (Soluble Salt Test, SSPC-Guide 15) of the material being recoated.

First, removal of old coatings, caulk, rust, mill scale, and any other contaminant is done as part of the cleaning procedure. Surface imperfections such as sharp edges, slivers, tears are grinded prior to the solvent cleaning. Following the removal of the debris and pack rust, solvent cleaning is performed in accordance with SSPC-SP-1 as the second step. Pack rust can be removed using chipping or scaling hammers as long as the structural steel is in good shape and is not affected during the process. Third, wash the surface at a minimum pressure of 5000 psi to meet the requirements of SSPC-SP WJ. After washing, determine the concentrations of chloride, sulfate,

nitrate, and other ferrous ions on the surface being treated using SSPC Guide 15 Method A2. Concentrations should not exceed 7,17,10 and 10 micrograms per square centimeters, respectively. If the limits are exceeded, the surface is rewashed. If the concentrations have not fallen below the limits yet, the use of water additives is permitted. The last step before the application of the ultimate product consists in abrasive blasting to the SSPC-SP 10 level. Other mechanical specialized equipment is allowed to satisfy contract requirements as long as the structure is not compromised [16].

Recoating consists of the application of different protective products, that combined, contribute in mitigating corrosion over the affected area. First, a full coat of the selected paint system is applied using an airless or conventional spray in accordance with the manufacturer recommendations, SSPC-PA1 and the contract. The full coat is applied on the surfaces being treated, except on crevices treated with a penetrating sealer and where pack rust has remained after surface preparation. Once the penetrating sealer has been brushed onto the crevice, the area (rivets, bolts, nuts, crevices, edges, welds, etc.) is stripe coated with an organic zinc layer by means of a brush or roller. The penetrating sealer should be an un-pigmented epoxy sealer, 100% solids and fluid enough to infiltrate onto the surfaces between the plates. Drying times have to be considered in this part of the process. In addition to the penetrating sealer, the standards also suggest the use of a class 3 rust preventative compound such as MILC-C-11796C [16].

The last step consists of caulking, in which a caulking product conforming Federal Specification TT-S-00230 C, Type II, Class A should be used. The caulk should be paintable and its color distinguishable from the intermediate and topcoat unless it is being applied on weathering steel. The caulking product is applied in accordance with the manufacturer's instructions on cracks, joints, crevices, and gaps with less than a one-half inch width [16].

3.1.2.5 Bach Steel Pack Rust Removal Technique

Bach Ornamental and Structural Steel Inc. is a contractor in the state of Michigan that rehabilitates wrought iron and steel structures that have been damaged over time. Their work plan consists of disassembling, restoring, sometimes relocating, and reassembling these structures (bridges) to bring back their structural capacity. In the restoration task, they perform pneumatic pack rust

removal, straightening of plates, and welding. Bach Steel is a DOT preapproved contractor in the states of Michigan, Indiana, Pennsylvania, and Ohio, where they have performed riveting and rehabilitation work on historical bridges. They have also executed projects in Arkansas, Colorado, Texas, and New Mexico [17].

Bach Steel follows a pack rust removal work plan that aligns with the requirements of the 2012 Standard Specifications for Construction of the Michigan Department of Transportation [18]. The steps in the plan are detailed as follows:

1. Oxygen-Acetylene or propane gas is used to heat up areas where the bulge of the plates due to pack rust exceeds 1/4 in. A temperature device (Raytek Laser Thermometer) is used to make sure that the heat being applied increases the temperature of the buckled area to 800°F.
2. Above the heated structural steel plate, a 3/8 in. thick plate is placed before hammering it with a Michigan Pneumatic Riveting hammer model MP 90R. Hammering is performed until the rust begins to come out and the structural steel plate is semi straight.
3. Repeat the procedure until most of the pack rust has been removed and the plates have been flattened to 1/16 in. maximum. To complete the flattening, hand jacking may be used.
4. Bach Steel avoids applying too much heat in adjacent affected areas at the same time to prevent distortion and annealing of the steel.
5. Finally, the section is inspected to guarantee that the repaired areas are ready for repainting by the painting Contractor in accordance with the specifications of the DOT.

Additionally, Bach Steel performs other tasks such as removal and replacement of rivets/bolts. The replacement of rivets/bolts is done if they have been damaged due to pack rust, removal of the pack rust, or if they interfere with other work. Bach Steel removes the rivets using one of the following methods: drill/grinding, pneumatic rivet buster or using a scarfing tip. New high-strength steel bolts, nuts and washers of same dimensions are placed in the holes; rivets are placed with a Michigan pneumatic riveting hammer model MP 90R, hand jacks or rose bud tip [18].

As previously mentioned, Bach Steel has worked on restoration of bridges in Indiana such as the Shelby County Bridge #13, which was relocated to the Blue River Park in Shelbyville. This 95-foot wrought iron pin-connected Pratt truss bridge was disassembled, restored, and relocated between September 2018 and April 2019. This project included pack rust removal, heat straightening, and rivet replacement among other tasks for a total cost of \$150,352.00 [17].

Another highlighted project of Bach Steel is the M14 – Hudson River Bridge in Ann Arbor, 2016 (MDOT 81075 109751 M14). The removal of pack rust was performed in accordance with the 2012 Standard Specifications for Construction of the Michigan Department of Transportation and their pack rust removal plan. This job was performed specifically on the bottom cover plates of the primary girders close to the piers. After the removal of pack rust, the bridge elements were cleaned and repainted in accordance with Bridge Painting Section 715 of the Standard Specification (Cleaning and Coating Existing Structural Steel). A sealant from the MDOT Qualifying Product List was used to caulk the gaps of the repaired areas and prevent moisture penetration [18].

Additional details were provided by Bach Steel through an email interview [18]. In this interview, they affirm that usually an epoxy penetrating sealer is used after the pack rust removal. On the other hand, other DOTs for which they have worked, require the use of caulking as the mitigating system accompanied by repainting. They also clarified that when the bulge is less than 1/4 in., they (or the painting contractor) use abrasive blasting instead of their typical pneumatic pack rust removal technique. During the removal of pack rust, they do not use any sort of chemical for removal of salt ions. Nonetheless, they use compressed air to remove the loose rust material after hammering. Mr. Nathan Holth, representative of Bach Steel, also mentioned that their technique is relatively new, and they are still working with MDOT to incorporate the procedure to the Special Provisions for Pack Rust as well as to modify some of the current specifications. In this questionnaire/interview, Mr. Holth added: “Pack rust is formed when moisture comes into contact with pieces of steel that rest against each other. The best way to prevent pack rust is to prevent this moisture from entering these areas. Painting is typically how this is done on steel structures, usually a DOT Standard 3 Coat Epoxy-Urethane system. Pack rust usually forms as the result of a bridge whose painting system has failed and gone for a period of time without being repainted”

Table 3.2. Summary of the mitigation strategies used by state DOTs and a private contractor.

DOT	Surface Preparation/ Pack Rust Removal	Penetrating Sealer	Caulking	Stripe Coat
New York	Power Tool, Heat up steel (max 250°F) to dry	Yes. Rustbond, Amerlock, MACROPOXY 920	Yes. Polyurethane Sealant	No.
Minnesota	Solvent cleaning, abrasive blasting, pressure wash (depends)	Yes. Epoxy sealer (depends)	No.	Yes. Affected area is repainted
Illinois	Pressure wash (5000 psi max), solvent cleaning, power tool/abrasive blasting	Yes. Epoxy sealer or Moisture cure urethane sealer (depends on selected system)	No.	Yes. (Depends on selected system)
Louisiana	Chipping hammers, pressure wash (5000 psi min), solvent cleaning	Yes. Un-pigmented epoxy sealer	Yes. Paintable caulking material	Yes. Organic zinc
Bach Steel	Heat up steel (max 800°F), pneumatic hammering, compressed air	Yes. Epoxy sealer	Yes. Masterseal NP1, Bostik 2020	Yes. Affected area is repainted.

3.2 Strategies Tested by this Research

The goal of this research is to evaluate the effectiveness of mitigation strategies that can minimize the further development of pack rust and, consequently, halt further deleterious effects on the strength of a structural member. While all structural connections are of interest, a flange splice connection was specifically studied herein.

Indiana is currently using the stripe coating and the caulking method. This research will study and compare the effectiveness of caulking and penetrating sealers in a highly corrosive environment. First, caulking as explained previously is the application of a waterproof sealer on the mouth of the crevice. The caulking product used in this project is the GE Advanced Silicone 2 Door and

Window Sealant. Furthermore, the two commercial penetrating sealers tested in this research project are Fluid Film and Termarust.

3.2.1 Fluid Film

Fluid Film is a penetrant and lubricant used in highly corrosive marine environment. It has been used in ships and offshore drilling for over 55 years. It has not been known to be used in the steel bridge industry yet. This product is a wool-wax, refined petroleum oil, which once it gets into the crevice is capable of displacing the water and moisture inside. The manufacturer suggests that it can be used to restore metallic parts that have been under the effects of corrosion. This product does not have any known negative effect on paint. The surface preparation for this product consists in simply removing any loose material, oil, and dirt so that the surface is clean. This product can also be used to soften rust material that cannot be removed by regular mechanical methods [19].

Fluid film can be applied using a brush, roller, or airless paint sprayer. For airless sprayers a pressure of 2000 psi is recommended. This product can be applied directly on rusted surfaces with little surface preparation since this wax soaks into the base of the corroded material preventing the corrosion products from progression. For bridge applications, the coating is required to be present around the crevice's mouth before the application of this wax in this zone. Inside the gap, there should not be a concern regarding paint-wax effects since this portion of the gap is not painted during repairs. Once the product is applied, it penetrates 4-6 inches into the crevice depending on the thickness of the rust. The recommended dry film thickness of Fluid Film to apply is 4-5 mils. Relevant technical data of this product is present in the following table.

Table 3.3. Properties of Fluid Film [19].

Appearance	Clear
Viscosity	16800-21600 cps
Flashing Point	405°F minimum
VOC	Less than 25% for aerosol; less than 1% for non-aerosol/bulk
Specific Conductivity	9 ohm/cm @ 1 mHz
Specific Gravity	0.875-8.885
Effect on paint	No effect
Repaintability	Contain no silicones. Surfaces are recommended to be washed with hot water or steam detergent at 120°F.
ASTM D-1735 - Standard Practice for Testing Water Resistance of Coatings Using Water Fog Apparatus	Passes 50 days
ASTM D-1748 - Humidity Cabinet	Passes 30 days
MIL-C-16173 Corrosion Requirement	Grade 2 – Soft Films.
MILC-C-23411	Displaces water from all metal surfaces
Toxicity	Non-toxic, LD-50 greater than 3 grams per kilogram.

This product has been used in a diversity of applications that are under ambient conditions similar to the conditions that steel bridges face. Among its diverse applications, automotive and trucking, industrial, heavy marine, and winter equipment are the most comparable. Corrosion occurring on the under-bodies and electrical connections of cars and trucks can cause rapid corrosion of the metal, which at some point can produce safety concerns. Fluid film can be applied on parts of an automobile that perform similar functions as those parts of a bridge. For example, nuts, bolts, studs, bearings, hinges, etc. Fluid Film has lubricating properties that allow it to penetrate into the gap of structural elements such as hinges, and at the same time these properties do not affect the ability of these elements to rotate or move. The penetrating sealer creates a protective layer against contaminants such as calcium and sodium chloride, pesticides and fertilizers. Fluid Film states on its website that the penetrating sealer maintains its viscosity at sub-zero temperature and stays in a soft-gel state through its life period. These characteristics are suitable for snowplows, trucks, and other winter equipment to counterattack the effects of the salinity in snow caused by deicing agents [19].

Heavy marine platforms, oil drill rigs, void tanks, and ships are the most susceptible structures to suffer from corrosion due to intense moisture and high concentrations of salts. This highly salt-water resistant penetrating sealer has been utilized in these applications for more than 60 years [19].

3.2.2 Termarust Technologies

Termarust offers a series of products to combat crevice corrosion such as TR 2200HS HRCSA and the TR 2100 HRCSA. Their High Ratio Co-Polymerized Calcium Sulfonate (HRCSA) is one of the Termarust products capable of chemically neutralizing corrosion. TR 2200HS is a co-polymerized calcium sulfonate penetrating sealer with excellent wet properties that can be applied with or without TR 2100 topcoat. Opposite to Fluid Film, Termarust has years of history in the bridge industry of the United States and Canada. The manufacturer claims that this combination of products is highly resistant (700% elongation) to microcracks induced by vibrational and/or thermal loads, that their average creepage is very low over time, and that this combination reduces the cost of surface preparation since pressure washing replaces sandblasting. HRCSA products have a wide range of structural applications such as dam gates, towers, storage tanks, penstocks, steel bridges (bearings, connections, overlapping plates, etc.), among others [20] [21].

HRCSA Termarust products have already been utilized in U.S bridges such as the Pennsylvania Turnpike bridge in Harrisburg, Pennsylvania built in the 1970's [22]. In 2006 several structural elements of the bridge were found to be in poor condition. Webs and flanges were bent while many connections had overstressed rivets due to pack rust. The repair project consisted of replacing some of the steel members, pressure washing with Chlor*rid at 5000 psi and a 6 in standoff distance, and applying the HRCSA coating system. Termarust presented a report of this bridge, five and a half years after it was coated with HRCSA products. Overall, the condition of the coating was excellent without any delamination. Minimum fading of the coating developed on the surface during this period of time. Some dark red stains were observed, but no indication of active corrosion was detected. Additionally, some old rust was observed in the inspection, but the risk of undercutting or delamination caused by old rust was neutralized by the polar attraction to steel of the Termarust products [22].

Table 3.4. Properties of TR 2200HS HRCSA penetrant sealer [21] [23].

Appearance	Tan milky fluid
Odor	Little or no odor
% Total solids	100%
Flashing Point	284 °F
VOC	0%
Specific Gravity	1.0305±0.03
Effect on paint	No effect
ASTM B117 Salt Spray Testing	Passes 750 hours (31 days)

Table 3.5. Properties of TR 2100 HRCSA topcoat [21] [23].

Appearance	Varies depending on client's request
Odor	Normal for the materials permitted (ASTM D1296)
% Total solids	72-79%
Flashing Point	122 °F
VOC	2.25-2.85 pounds per gallon
Specific Gravity	1.05-1.19
Effect on paint	No effect
ASTM B117 Salt Spray Testing	Passes 5000 hours (208 days)

Before application of the products, a surface preparation is required. First, the pack rust is removed by pressure washing the rust material at a minimum of 40000 cleaning units with a zero-degree rotating tip. Cleaning units is equivalent to multiplying the flow rate (GPM) times the pressure (psi). In accordance to Termarust, 7000 psi pressure washing is the most effective to remove pack rust, dirt and contaminants. Nonetheless, pressure washing can be performed at a minimum of 5000 psi with cold water (as in the Pennsylvania Turnpike Bridge) or at 4000 psi with hot water (140°F) at a standoff distance of 4 inches [24]. This procedure follows the guidelines of SSPC SP 12 WJ4. The area being treated should be free of black oxide to avoid future delamination. The water used in pressure washing is mixed with Chlor*Rid at a ratio of 1:100. This chemical helps to remove residual salts inside the crevice. The removal of any organic material and salts should be done in accordance with SSPC SP2 and SP3. Then, all the connections are blown out to a dry condition with compressed air at 100 psi [24] [25].

Ultimately, TR 2200 is applied into crevices or joints, and around bolts, plate edges, nuts and washers in a pressurized manner. Termarust recommends the use of HVLP, LVLP, conventional or airless spray over the use of a brush [23]. Both products need to be applied at temperatures

above 35.6 °F. Immediately after TR 2200, TR 2100 is applied (on the wet penetrating sealer) with a brush to a minimum dry film thickness (DFT) of 10 mils (15-18 mils wet). This is why Termarust calls it a one coat system. Additionally, application of another layer of TR2100 so that the resulting minimum DFT is 20 mils is recommended for areas that have suffered high level of pack rust. For areas where bare steel is being treated the minimum total DFT is 10 mils, and for areas that are already painted and free of contaminants, the minimum total is 5 mils [23] [25]. More information regarding the surface preparation and application can be found in their painting specifications and technical data.

3.2.3 General Electric Advanced Silicone 2 Door and Window Sealant - Clear

GE Advanced Silicone 2 sealant is a full impermeable material designed for indoor and outdoor applications, and under harsh weather conditions. This silicone caulk was selected based on the results of a separate experimental study as part of this research project. In this experimental study, three silicone based commercial caulks were tested. The discussion of this testing will be presented in the experimental procedure section. The advanced silicone 2 caulk was found to be the most efficient in terms of durability and resistance. This flexible, shrink and crack proof sealant has a neutral and rapid curing. This material is strongly adhesive to most common civil engineering material such as wood, aluminum, bricks, concrete, asphalt, glass, painted surfaces, and most metals, among others [26].

The first step of the surface preparation consists of the removal of contaminants and chemicals such as dirt, oil, soaps, moisture, old caulk, etc. Second, the surface should be dried and clean with the help of solvent-damped rags. The most common solvent is isopropyl alcohol (IPA). For substrates painted with coatings, the solvent should be approved by the coating manufacturer to avoid harm of the finish. The surface preparation should be performed one to two hours prior to the application of the caulking product. Backer rods are recommended when gaps are larger than ½ in. in width or ½ in. by ½ in. in area. Since moisture and ambient temperature affect the curing rate, it is recommended to apply this sealant at a temperature above 32 °F [26]. The following table presents the properties of the GE Advanced Silicone sealant.

Table 3.6. Properties of GE Advanced Silicone 2 sealant [26].

Appearance	Clear
Odor	Low odor/ light ammonia
CARB Chem curing VOC	Less than 3wt%
Specific Gravity	1.00
Tack free time	30 minutes at 72°F(22°C) and 50% RH
Elongation	347% (ASTM D412)
Joint movement capability	±35% glass (ASTM C719)
Tensile strength	145 psi (ASTM D412)
Temperature range	-60°F to 400°F (-51°C to 204°C)
Specifications	Meets ASTM C-920, Type-S, NS, Class 35

Besides the caulking product tested in this research project, other commercial caulks have been identified and compared based on their material specifications to provide guidance of which caulks are appropriate to implement in the field. Therefore, based on this review, some new caulking material requirements should be incorporated along with the requirements already established by INDOT. There are four common base polymers for caulks: latex, polyurethane, rubber, or silicone. In the specifications, INDOT requires the use of 100% silicone clear sealants. Silicone caulk has superior adhesion to steel and durability properties over the other types of caulks. Nonetheless, some silicone caulks and sealers can release acetic acid or other weak acids during curing [27]. These acids can contribute to corrosion of metal substrates. Silicone caulks can be of two types:

1. Acid-cure silicone:

- Releases acetic or other weak acids that promote corrosion on copper, zinc, brass, and galvanized steels.
- Can also lower their adhesion ability to metals during curing. However, when this type of silicone is applied on aluminum the adhesive properties are not affected.

2. Neutral-cure silicone:

- Releases Methyl ethyl ketoxime/acetone, which is non-corrosive and thixotropic.
- Better adhesive and waterproofing properties than acid-cure silicones. Therefore, neutral-cure silicone caulks should be selected over of acid-cure silicone caulks for field applications.

The following table is constructed based on the available online information that these caulks have on their websites and product information tags. Some of these caulks are recommended since they develop neutral curing, and do not release any weak acid that could affect the metal substrate.

Table 3.7. Commercial caulking products comparison and suitability for pack rust mitigation.

Product	Base	Note
White Lighting Silicone Ultra Gutter - Roof	Silicone	No comment on corrosion.
GE Advanced Silicone 2 Clear Window and Door Sealant*		No comment on corrosion. Neutral curing.
Momentive/GE RTV6708, 10.1 oz. Cartridge		
Noncorrosive, Dow Corning 737, 10.1 oz. Cartridge		
Loctite® Model Si 5011 CL, 10.1 oz. Cartridge		Do not apply on metals sensitive to corrosion including brass and galvanized metals.
Gorilla 100% Silicone Sealant-Clear*		
DAP 100% Silicone Rubber Window, Door and Siding Sealant		Corrodes some metals. Not recommended for use on or near brass, copper or copper alloys, zinc, iron, galvanized metals, or other surfaces prone to attack by weak acids.
DAP 100% Silicone Rubber Kitchen, Bath, Plumbing Bath Sealant		
Loctite Polyseamseal Caulk All-purpose Adhesive Caulk	Acrylic Latex	Do not apply on mirrors or metals that corrode.
White Lighting 3006 Original Formula	Siliconized Acrylic Latex	No comment on corrosion.
DAP Alex Plus All Purpose Acrylic Latex Caulk Plus Silicone*		
DAP 3.0 High Performance Gutter and Flashing Sealant	Advanced Hybrid Polymer	

Note: This product has been tested in this research.*

Additionally, the following table presents a summary of the characteristics and properties of two types of caulks that contain silicone: a pure silicone caulk and an acrylic latex silicone blend.

Table 3.8. Comparison between Silicone and Acrylic Latex Siliconized caulks [28].

Properties	Silicone	Acrylic Latex Silicone Blend
Adhesion	Almost any surface. Non-porous surfaces (metals, plastics).	Almost any surface.
Application	Can be bothersome and messy. Indoor and Outdoor. Gutter sealants are recommended since they are designed for extreme conditions.	Easy to apply. Indoor and Outdoor.
Flexibility	Joints can stretch and compress without cracking the caulk due to its excellent movement capabilities.	Used in low movement joints with a maximum of $\pm 7.5\%$ movement.
Durability	Most efficient out all types of caulks. Expected to last more than 40 years.	Comparable to silicone. Could last up to 35 years.
Temperature	Resistant to extreme temperatures	Less resistant to extreme temperatures and sunlight
Paintability	Not usually	Can be painted depending on painting system
Shrinkage	Minimum	Shrinks as it dries.
Effects on metals	Some types can cause corrosion	No corrosive effect
Moisture Resistance	Offers waterproof seal and its waterproof barrier can last longer due to its resistance to shrinkage or cracking.	Offers waterproof seal, but as it shrinks over time, this capacity can be reduced.

4. EXPERIMENTAL PROCEDURE

The experiment consists in fabricating and exposing specimens that model the bottom flange splice connection to a corrosive environment. These specimens will be tested under different conditions: a) Control (no exposure to salt misting) b) Base specimens, which are exposed for a determined period of time c) Initially treated specimens, which are protected with the mitigating products since the beginning d) Repaired specimens, which are exposed to corrosion and later repaired with the mitigating product to see if there is any further deterioration. These specimens will be tested for strength and visually inspected to assess the effectiveness of the mitigation strategies. The experimental program can be divided into five main tasks: Set up of the testing room, Preparation of the specimens, Misting test, Application of mitigation strategies and Strength testing.

4.1 Set Up of the Testing Room

The first task of the experimental program was to create a corrosive environment so that the mitigation strategies could be tested for different periods of time and circumstances. The testing room temperature requirements were based on ASTM B117-18. The room was isolated with 2-in isolation foam sheets on the exterior wall and any opening that could lead to heat loss. At the beginning, two 5100 BTU industrial heaters and temperature controllers were employed to maintain temperature requirements. Nevertheless, during the cold months some modifications were implemented due to the difficulty to keep the temperature requirements. First, a third heater was incorporated in the testing room. Second, the encapsulating space of the specimens was reduced by building a frame around the table containing the specimens and wrapping the frame with plastic sheets.

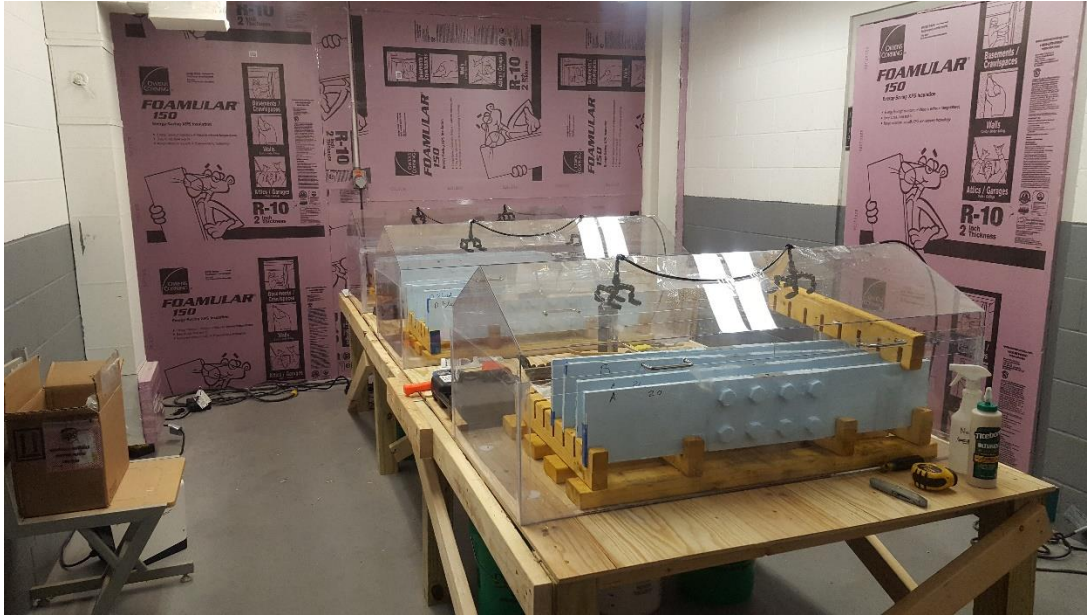


Figure 4.1. Initial set up of the testing room.



Figure 4.2. Modified set up of the testing room.

4.1.1 Lexan Boxes

Three Lexan boxes were used to store the steel specimens during the accelerated corrosion test. Each one of these boxes is capable of handling 8 specimens at a time. The dimensions of these boxes are 24 inches wide, 48 inches long and 20 inches tall. Each box contains six ½ inch diameter drain holes to let the residual solution escape for collection and disposal. Also, two 9/32-inch diameter holes were placed in the roof to secure the atomizers, and provide access for the supply tubes.

The material of these boxes was selected because Lexan's material properties allow it to be resistant enough to hold the specimens in a corrosive environment. Lexan is a polycarbonate resin thermoplastic, which means that this material can resist high temperature. The accelerated corrosion test is performed at temperatures ranging from 90 °F to 100 °F. Moreover, Lexan is highly resistant to acids and other chemicals [29]. In the case of this research project, the three boxes are subjected to a corrosive environment produced by the sodium chloride solution plus the elevated temperatures.



Figure 4.3. Lexan boxes.

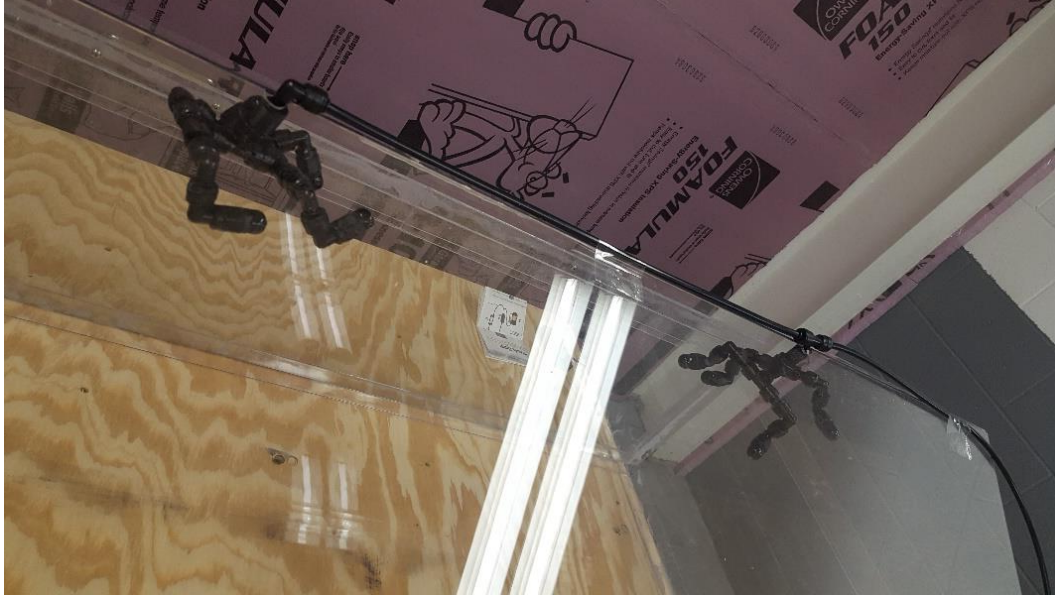


Figure 4.4. Roof of Lexan boxes holding the atomizers.

4.2 Preparation of the Steel Specimens

4.2.1 Specimens Description

The specimens consist of four bolted plates that simulate the bottom flange portion of a splice connection in a steel bridge. Pack rust has been observed to occur in the gap region of the bottom flange splice connection [2]. The dimensions of the connected plates are 6.5 in. wide by 18 in. long by $\frac{1}{2}$ in. thick, while the dimensions of the connecting plates are 6.5 in. wide by 12.25 in. long by $\frac{1}{4}$ in. thick. Other components such as bolts, holes, nuts, and washers meet the geometric requirements per AASHTO LRFD Section 6.13.2.3 [8]. The bolts were sized such that the plates failed before the bolts. The size of the bolts was determined to be $\frac{7}{8}$ in., which is greater than the $\frac{5}{8}$ in. minimum diameter required by the standards. Two different types of specimens were fabricated: a) specimens with a $\frac{1}{4}$ in. gap between the connected plates b) specimens with $\frac{1}{2}$ in. gap between connected plates. The project focuses more on the $\frac{1}{4}$ in. gap specimens (32 units fabricated) since this is the gap size most commonly used by INDOT. The other $\frac{1}{2}$ in. gap specimens (3 units fabricated) are used to study the gap size as a parameter and compare with the other specimens.

The geometric detailing is shown in Figure 4.5 and Figure 4.6. The diameter of standard holes was determined to be 15/16 in. since 7/8 in. bolts were used in this project. The center-to-center distance between bolts is three inches for both the 1/4 in. and the 1/2 in. gap specimens. Finally, the minimum edge distance was 1.5 inches and 1.375 inches, respectively, for the 1/4 in. and the 1/2 in. gap specimens. Both types of specimens met the minimum distance requirements per the standards [8]. Bolts, nuts and washers meet the requirements and recommendations of ASTM F3125/3125M, A563, and F436/F436M, respectively [30] [31] [32]. The following elements were used in the specimens:

1. 7/8 in. by 2.25 in. ASTM 3125 GradeA325 Plain Finish Steel Structural Bolts
2. 7/8 in. ASTM A194 2-H Plain Finish Heavy Hex Nuts
3. 7/8 in. ASTM F436 Type 1 Plain Steel Structural Flat Washers

The steel material used to fabricate the specimens is A572 Grade 50 since it is similar to ASTM A709 Grade 50, which is widely used in the bridge industry. The plates were cut by using plasma burning with a tolerance of 1/8 in. The material test reports and metallurgical certification provided by Alro Steel are attached in the appendix section. The material is fabricated in accordance with ASTM A572/A572M [33].

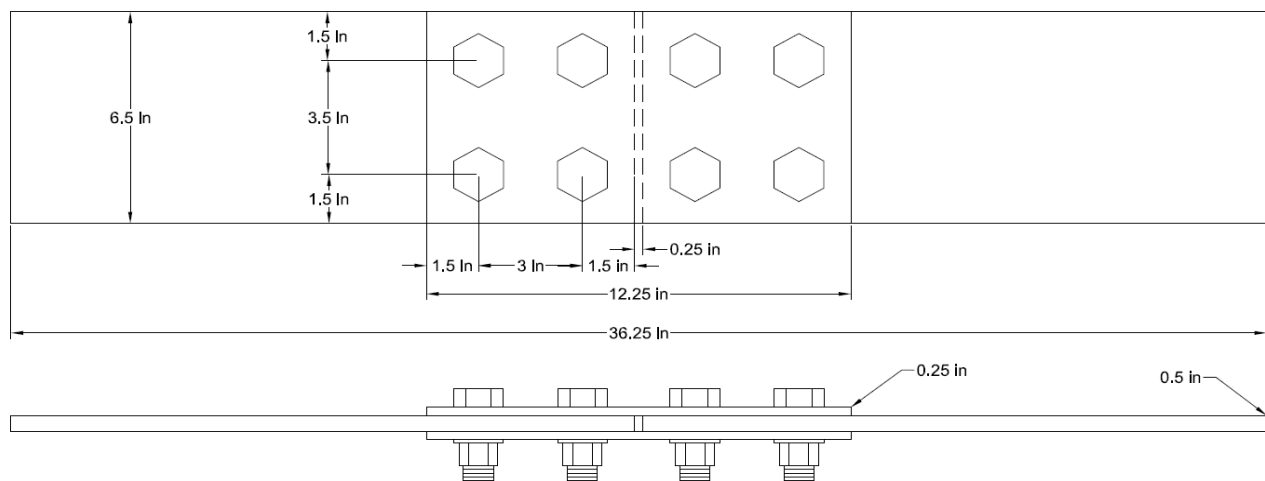


Figure 4.5. Dimensions of the 1/4 in. gap splice connection specimen.

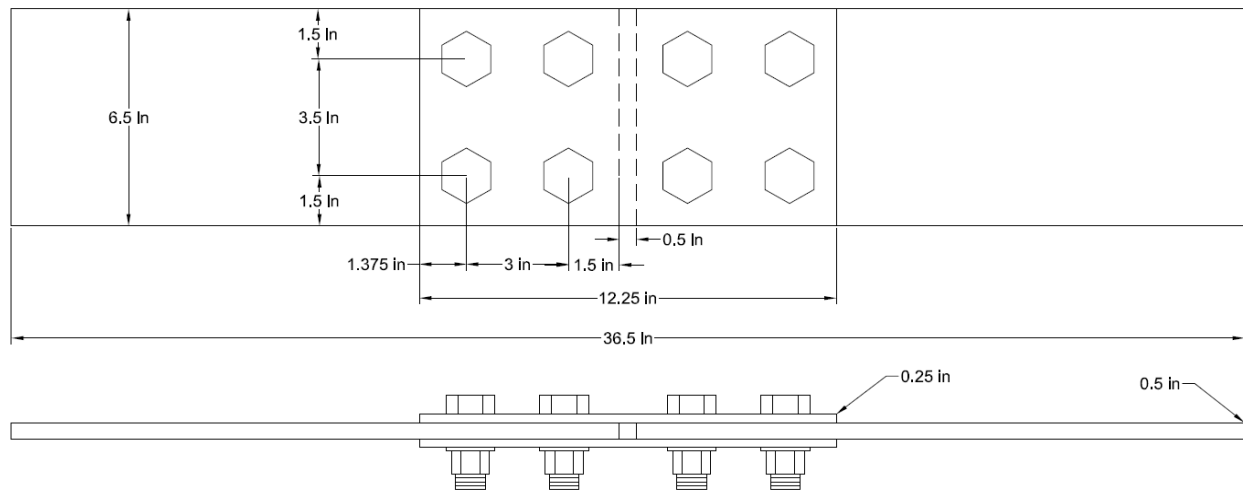


Figure 4.6. Dimensions of the 1/2 in. gap splice connection specimen.

Different strength failure modes were considered for the specimens tested in this research to determine the diameter of the bolts and the critical failure mode. The total number of bolts was predetermined to be eight for each specimen, with four bolts on each side of the double lap splice connection. The expected strength values of the specimens were computed based on the yield and tensile strength obtained from testing coupons to account for the variability of the material. The results of these tests are attached in the appendix section. A sample calculation for specimen 36 (Q-S2-36) is presented in the appendix section to show the critical failure mode. In this sample, the average values of yield and tensile strength of the middle and splice plates are used to compute the average expected strength of the connection specimens.

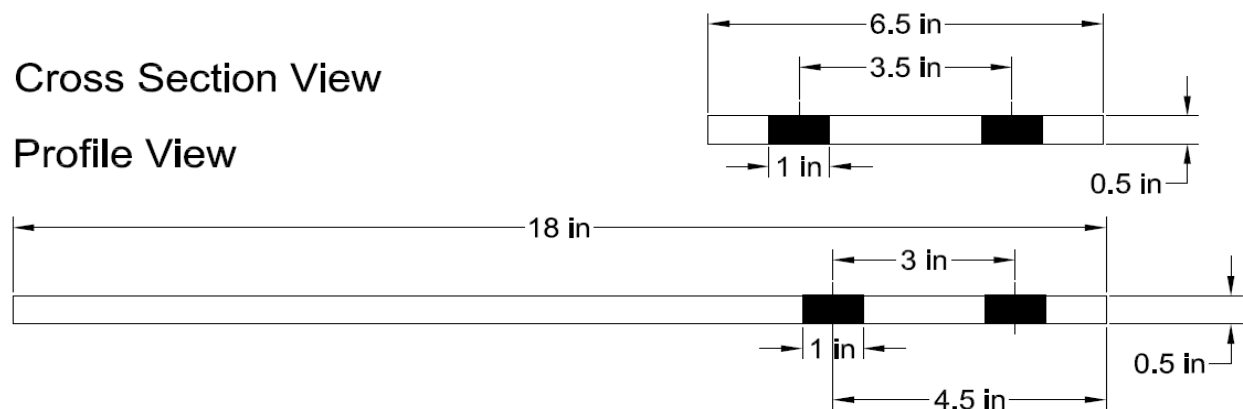
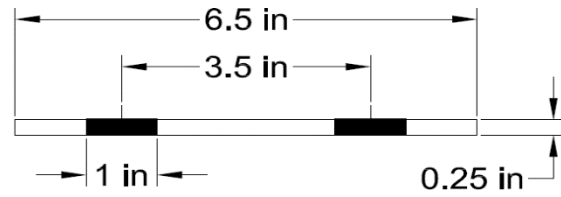


Figure 4.7. Typical cross section and profile of middle Plates.

Cross Section View



Profile View

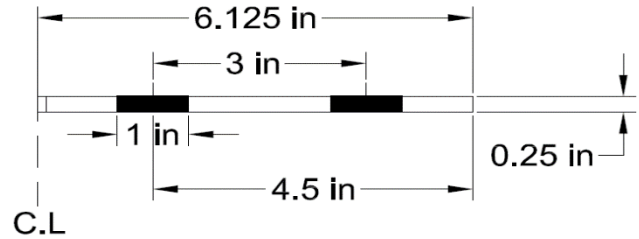


Figure 4.8. Typical cross section and profile of splice plates.



Figure 4.9. Uncoated specimen.

4.2.2 Surface Preparation of the Specimens

This section describes the procedure used to clean the steel plates before applying the 3-coating system. The procedure employed in this project is based on SSPC-SP 1 “Solvent Cleaning” with some deviations [34]. The selected procedure was adjusted to the time and other project constraints. The surface preparation conducted in this project consists of the following steps:

1. In order to remove the dust and mill scale in a more time efficient way, the plates were pressured washed at 3800 psi. They were placed in a vertical position to let the water run downwards and avoid puddles of water. The pressure wand was at a distance of 6 to 12 inches from the plate and the angle of the nozzle was 15 degrees.
2. After the plates dried, Klean Strip Acetone was applied with rags to remove paint stains, remaining dirt, rust stains, and any oily substance from the surface. Each plate was wiped with acetone at least twice.
3. Finally, the plates were brushed with a stiff bristle brush to remove any dust and cotton left from the rags. Once they dried, they were ready to be painted.



Figure 4.10. Plate's dirt removal with a 3800-psi pressure washer.

4.2.3 Turn-of-Nut Bolting Method

This method of bolting consists in rotating the nut or bolt at a specific angle depending on the bolt length while the other element is held to prevent any rotation. The bolts and nuts used in this research project are 7/8 in. by 2.25 in. ASTM 3125 Grade A325 Plain Finish Steel Structural Bolts, and 7/8 in. A194 2-H Plain Finish Heavy Hex Nuts, respectively. Using table 8.2 from the 2014 Specification for Structural Joints Using High-Strength bolts, the rotation was determined to be 1/3rd of a turn from snug tight with a tolerance of 30°. Before all the bolts and nuts were tightened by the Turn-of-Nut method, they needed to be in the Snug-Tight condition, which means that the plates have to be drawn together in firm contact. This is achieved by applying a few impacts with an impact wrench or the full effort of a person. For this condition, there is not a specified level of tension required to be applied on the bolts [35].

4.2.4 Painting of the Steel Specimens (INDOT 3 Coat System)

The INDOT 3 coat system consists of three different layers of coatings. The first layer is a zinc primer, which can be a multi component inorganic zinc silicate primer or an organic zinc primer. The inorganic primer should meet the requirements in accordance with AASHTO M300 while the organic primer should follow the requirements in accordance to the INDOT standards Division 900 – Material Details (Section 909 Paint and Liquid Epoxy) [36]. The second and third coat consist of an epoxy intermediate paint and a polyurethane finish coat, respectively. Both of their requirements are specified under the same division as for the organic primer. Division 600 – Incidental Construction under the section 619 – Steel Bridge Painting explains the different procedures that should be followed and under what set of standards [37]. In this project, two of these procedures were performed: a) Solvent cleaning the steel plates (SSPC-SP 1) b) Measurement of dry film thickness (SSPC-PA 2). However, fully efficient surface cleaning was not possible since this procedure was performed outdoors, and consequently some specimens could have caught dust during cleaning and transportation. This was permitted since this research project is not evaluating the quality of these paints or the effectiveness of the 3-coating system.

Since the goal of the project is to assess different approaches that can mitigate pack rust, a strip of approximately 3 inches along the length of the crevice was not coated to isolate the portion of the specimen being studied (Figure 4.11). The gap was left as bare steel to accelerate corrosion in that part of the specimen. The rest of the specimen was painted with the 3-coat system. It should be noted that the normal practice for bridges in Indiana is to apply the primer coat in the shop, and then the intermediate and top coats are applied in the field after the bridge is erected. Consequently, the gap region of the splice connection would normally contain the primer coat only. The difference for the test specimens was that the gap region was not coated at all to help accelerate the development of corrosion in the gap region.

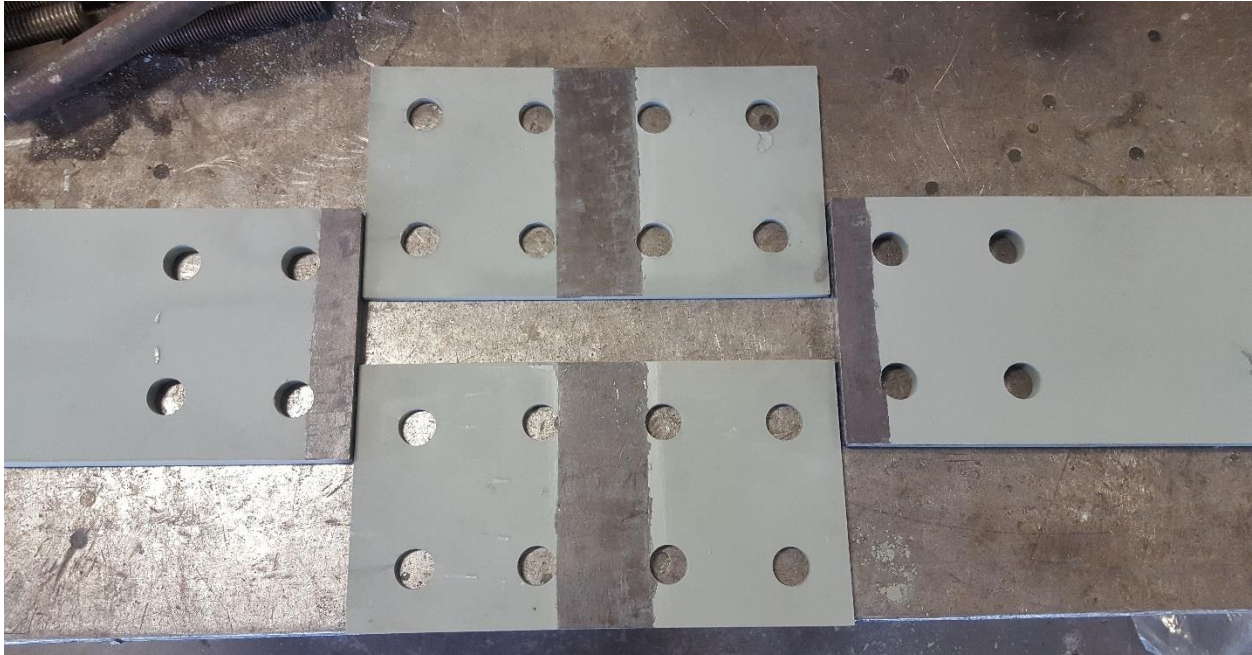


Figure 4.11. Portion of the specimen being isolated for accelerated corrosion.

The paints used for this project, bought from US coatings, were the following:

1. Zinc primer: ZincGard 1000 Part A and ZincGard Dust Filler.
2. Epoxy: EpoxyGrip 2000 Part A and EpoxyGrip 2000 Part B.
3. Polyurethane: UreGrip 3000 HS VOC Part A and UreGrip 3000 HS VOC Part B.

The coating application can be summarized as follows:

1. Approximately, three mils of the Zinc primer were applied on the steel plates except on the areas isolated with duct tape (Figure 4.11). The zinc primer was applied with a spray gun and with brush. After the primer dried, the thickness of the primer was measured with a DFT gauge (Elpidan E200). Measurements were performed on four different randomly selected spots on each one of the four plates of the specimens, and averages were computed.
2. After measuring the thicknesses, the plates were assembled and the bolts were tightened using the Turn-of-Nut bolting method.
3. Approximately, four mils of epoxy were applied on the splice connections except on the areas covered with tape to avoid coating seeping into the gap. This coating was applied

with a brush. Similar to the primer, this layer was allowed to cure and dry for one day before measuring the dry film thickness.

4. Finally, approximately three mils of polyurethane were applied with a brush on the splice specimens except on the gap areas covered with tape. Similarly, dry film thicknesses were measured after the layer dried.



Figure 4.12. Application of epoxy layer.



Figure 4.13. Application of polyurethane layer.

Figure 4.14 shows the final product after the application of the coating system. Moreover, the area outside the gap was only painted with zinc primer as shown in Figure 4.15. Table B.2 shows the coating thickness information for each one of the specimens.



Figure 4.14. Final coated specimen



Figure 4.15. Close up image of the 1/4 in. gap specimen and 1/2 in. gap specimen.

4.3 Salt Spray Test for Accelerated Corrosion (ASTM B117-18)

This section describes the procedure used to simulate the atmospheric conditions in the field that induce corrosion. In accordance to the standards, the field conditions are adjusted to increase the corrosion rate in the steel specimens, and perform what is known as an accelerated corrosion test. This test was performed in accordance with ASTM B117-18 “Standard Practice for Operating Salt Spray (Fog) Apparatus” [38]. This standard practice consists of spraying a saline solution onto the specimens over a period of time, which is arbitrary. Moreover, this ASTM standard provides the pH, temperature and solution concentration requirements. These are three of the most important parameters related to the development of corrosion.

4.3.1 Salt Solution Preparation

The salt solution composition is 5.3% of Sodium Chloride (NaCl) and 94.7% distilled water by mass. The masses of the two components of the solution were weighed in a scale. This solution should have impurities equal to or less than 0.3%, halides less than 0.1%, copper less than 0.3 ppm and no anti-caking agents [38]. The salt used for this research project was Culinox 999 Morton Salt since it is a refined salt that is easy to dissolve. This salt met all the impurities requirements stated above. The product data sheet is attached in the appendix section. The distilled water used in this project was Great Value distilled water from Walmart. According to ASTM D1193-06, the selected distilled water is a type IV water, which translates to a limit of 5 micro-Siemens per centimeter for electrical conductivity and a pH range of 5 to 8 [39]. The Great Value distilled water was tested for these requirements, and its pH at 77 °F (25 °C) was 5.68. However, the electrical conductivity was 10.78 micro-Siemens per centimeter. Even though this value was above the limit, it was close enough so the project proceeded with this distilled water.

The standard specifies a pH range of 6.5 to 7.2 at a temperature of 95°F (35°C) for the salt solution collected after misting. The standards recommend checking the pH periodically with a maximum interval of 96 hours between measurements. In this project, pH levels were measured every three days with a SX823-B Portable Multi parameter meter from Apera Instruments. This device is capable of measuring pH, electrical conductivity, total dissolved solids (TDS) and temperature.

The characteristics of the solution (ionic current path) plays an important role on the ions transport. First, conductivity is the ability to transport current or ions and it is inversely proportional to the resistivity of the solution. Distilled water itself has a very low conductivity due to the absence of ions, but when it is mixed with a salt such as sodium chloride, these salts decompose into ions and can freely flow in the solution. Sodium chloride (1 N) can have a resistivity of 11.6 ohms-cm at 70 °F (20 °C) [4]. One normal (1 N) is defined as one gram of equivalent weight per liter of solution, or in this case, the mass that will react with one mole of hydrogen ions per liter of solution. The prepared solution supplies the chloride ions that will react with hydrogen ions and form hydrochloric acid.

Second, the alkalinity of the solution, which represents the concentration of hydrogen ions in the solution, is an important parameter that helps to determine the magnitude of the corrosive environment. Hydrochloric acid (1 N) has a pH of 0.1 at 70 °F (20 °C), which is highly acid and corrosive [4]. If hydrochloric acid is poured onto mild steel, an energetic formation of bubbles can be observed. The corrosion rate of mild steel can be described as aggressive and rapid when in contact with a hydrochloric solution [3]. Furthermore, there are other characteristics of the solution that affects corrosion such as oxidizing power of the solution, ionization or dissociation of the salt and solubility, but the two most important were discussed already.



Figure 4.16. SX823-B portable multi parameter meter.

4.3.2 Conditions of the Testing Room

ASTM B117-18 specifies certain temperature conditions for the encapsulating space holding the specimens. The exposure zone should be at 95 ± 3 °F (35 ± 2 °C). As noted earlier, this condition was met with the help of two 5100 BTU industrial heaters and temperature controllers that would turn off the heaters when temperature was above 98 °F and turn on the heaters when the temperature was below 92 °F. Additionally, to prevent significant loss of heat in the room, 2 in.-thick insulation foam sheets were placed on the exterior wall and at the door connecting the testing room to the adjacent room. Also, Visqueen plastic sheeting was used to cover the three vents in the room. Measurements of temperature were not recorded for the first three months since not much trouble was found in controlling this parameter at the beginning. The temperature controllers

were the means to verify the temperature in the room. However, as the timeline approached the beginning of the cold months (October-November), it was observed that temperature was dropping below the limit. Therefore, it was decided to include a third heater and to reduce the encapsulating space by building a frame around the table holding the specimens. This frame was covered with visqueen plastic sheeting to keep the heat inside the exposure zone. After these modifications were done, temperature was recorded by means of a digital thermometer. Temperature measurements are present in Figure A.3 and Figure A.4.

4.3.3 Misting Schedule

Part of the salt solution application plan was developed with the guidance of the publication “Bridge maintenance to enhance corrosion resistance and performance of steel girder bridges” by Luis Moran [40]. The system used for this project was the MistKing Advanced Misting System, which included a timer to set up the misting schedule. The misting plan consisted of spraying eight times per day every three hours starting at 12 midnight. After testing the misting system, the flowrate at the nozzles was determined to be 10.4 L/day (2.742 gallons/day). The spray duration was 45 seconds to guarantee full coverage of the mist over the specimens, and to keep the environment inside the chambers moisturized. The drainage rate had a maximum value of 2 mL/hr./chamber in accordance with the standards. The target concentration of the solution was 5.3 % Sodium Chloride (NaCl). However, two extra gallons of distilled water were added to the reservoir in two occasions to reduce the concentration and meet the pH requirement.

The reservoir had a capacity of 30 gallons, and it was replenished every nine days. The amount of solution prepared every nine days would vary depending on the amount required to fill the reservoir to capacity. This variation considered contingencies such as failure of a nozzle or fitting connections that would cause high solution consumption. The pH was measured from the solution collected in the buckets by the drainage system every three days. The pH of the solution in the reservoir was measured as well at the same frequency for completeness. The pH measurements plots are attached in the appendix section.

The misting period can be divided in two parts: a) August 12th, 2020 to December 16th, 2020 (127 days) and, b) January 9th, 2021 to June 21st, 2021 (164 days). The misting of the specimens was

halted during a shutdown of the laboratory for three weeks over the holiday break. The time that the specimens spent in the chambers during the shutdown of the misting is not considered as time of exposure even though the corrosion can be considered to still be active during that time.

4.4 Testing Program and Application of the Mitigation Strategies

4.4.1 Testing Program of the Specimens

In this research project, the commercial products (Fluid Film, Termarust and GE Silicone Caulk) were tested under three different conditions. In the first condition, known as “Initial condition”, the three products were applied on specimens that had not been exposed to corrosion. The area surrounding the mouth was protected with Zinc Primer and inside the gap the surface was not protected with any coating. The specimens under this condition were exposed in the chamber for 172 days. The response of the mitigating products was observed throughout the time the specimens were in the chambers. At the end of the exposure time, the specimens were tested for strength and visually inspected.

The second condition is known as “Condition A”. This condition is related to the first stages of pack rust development where noticeable corrosion is leaching out of the splice gap region [2]. The specimens were exposed to corrode for 111 days, and then repaired with the mitigating products. Before applying the mitigating product, a layer of Rust-Oleum was applied to the area near the crevice’s mouth. After repair, the specimens were exposed to misting for another 41 days before the strength test and final visual inspection.

Finally, “Condition B” was exposure of the specimens to corrosion for 175 days with a second period of exposure of 79 days after repair. This condition is related to the middle stages of pack rust development where less than ¼ in. bulging of the plates is observed [2]. These specimens were repaired in the same manner as “Condition A” specimens. All specimens regardless of their assigned condition were flipped after three months since it was observed that more corrosion was building up on the bottom end of the gap than in the top end of the gap. Images about these observations are shown in the results section. Lastly, the testing described above utilized specimens with a ¼ in. gap.

Along with the specimens treated with the mitigation strategies, additional specimens were exposed to salt misting without any product application to determine the deterioration in strength based on the time the specimens were exposed to misting. These specimens are known as “Base”. Table 4.1 shows the distribution of the ¼ in. gap specimens for each one of the conditions being tested. Additionally, Table 4.2 shows relevant information for each one of the specimens such as the assigned condition, total time of exposure, bulging at testing, etc. The name of the specimens is encoded in the following way:

- a) First letter: Q (Quarter inch gap) or H (Half inch gap)
- b) Second letter: S (Primer applied with spray) B (Primer applied with brush)
- c) First number: Day of work on which primer was applied.
- d) Second number: Number of the specimen.

The following lines describe the different tested conditions. Figure 4.17 helps to visualize the different conditions tested in this experiment.

- a) Control: Initial condition with no exposure and corrosion deterioration.
- b) Initial: Initially treated specimen was exposed for 172 days.
- c) Condition A: Time of exposure was 111 days.
- d) Condition B: Time of exposure was 175 days (For Base B, 172 days).
- e) 10M: Time of exposure was 284 days (Approximately 10 months) with no repair.

Table 4.1. Distribution of the ¼ in. gap specimens for the conditions being tested.

	Condition	Number of specimens tested
Protected: Specimen treated with the mitigation strategies.	Initial	6
	Condition A	6
	Condition B	6
Unprotected: Base specimens without treatment.	Control	4
	Condition A	4
	Condition B	4
	10M	2

Three extra ½ in. gap specimens were fabricated to monitor and compare the corrosion development with the ¼ in. gap specimens. These specimens were exposed under Condition A and without the application of any of the mitigation strategies. The only purpose of testing these three specimens is to provide a qualitative comparison between the narrow gap and the wider gap specimens in terms of the corrosion formation rate.

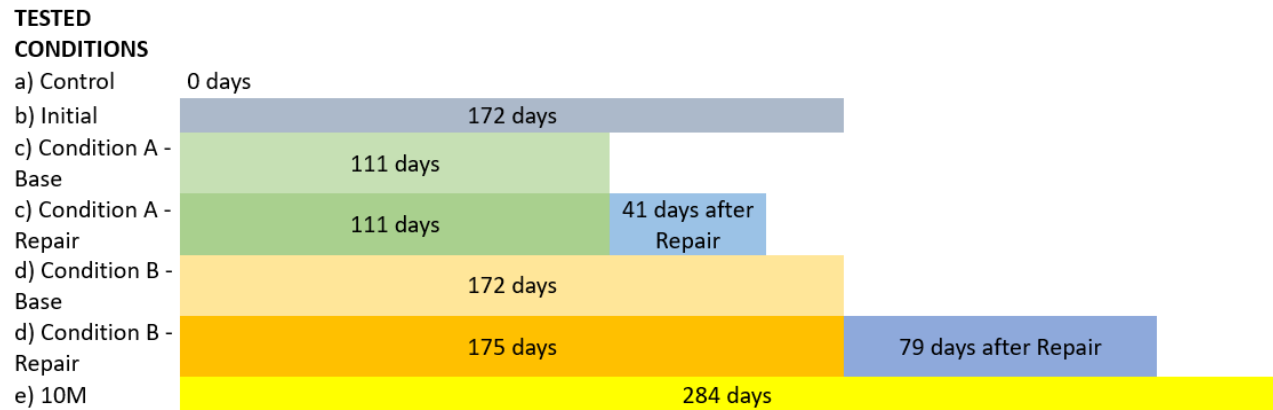


Figure 4.17. Conditions Tested.

Table 4.2. Inventory of the specimens with assigned conditions, time of exposure and bulging.

Inventory of the Specimens							
Specimen	Chamber	Position	Assigned Condition	Date In	Date Out	Total days	Bulge at Testing
Q-S1-1	3	1	Base A	2/23/2021	6/14/2021	111	N/A
Q-S1-2	3	2	Base A	2/23/2021	6/14/2021	111	N/A
Q-S1-3			Control			0	N/A
Q-S1-4	2	5	B Fluid	8/12/2020	5/19/2021	257	0.050
Q-S1-5	2	4	Base A	8/12/2020	12/1/2020	111	N/A
Q-S1-6	2	5	Base A	8/12/2020	12/1/2020	111	N/A
Q-S1-7	2	1	Base B	8/12/2020	2/23/2021	172	0.041
Q-S1-8	2	2	Base B	8/12/2020	2/23/2021	172	0.027
Q-S1-9	3	2	Base B	8/12/2020	2/23/2021	172	0.019
Q-S1-10	3	1	Base B	8/12/2020	2/23/2021	172	0.020
Q-B1-11	1	8	A Caulk	12/1/2020	5/27/2021	155	N/A
Q-B1-12	1	7	A Caulk	12/1/2020	5/27/2021	155	N/A
Q-B1-13			Control			0	N/A
Q-B1-14			Control			0	N/A
Q-B1-15			Control			0	N/A
Q-B1-16	1	6	A Fluid	12/1/2020	5/27/2021	155	N/A
Q-B1-17	3	4	Initial Caulk	8/19/2020	3/2/2021	172	0.052
Q-B1-18	1	1	10M	8/12/2020	6/14/2021	284	0.081
Q-B2-19	1	2	10M	8/12/2020	6/14/2021	284	0.075
Q-B2-20	2	3	B Caulk	8/12/2020	5/19/2021	257	0.043
Q-B2-21	2	4	B Caulk	8/12/2020	5/19/2021	257	0.075
Q-B2-22	2	7	B Terma	8/12/2020	5/19/2021	257	0.023
Q-B2-23	2	6	B Fluid	8/12/2020	5/19/2021	257	0.082
Q-B2-24	3	3	Initial Caulk	8/19/2020	3/2/2021	172	0.018
Q-B2-25	3	7	Initial Terma	8/19/2020	3/2/2021	172	0.030
Q-B2-26	3	8	Initial Terma	8/19/2020	3/2/2021	172	0.014
Q-B2-27	3	5	Initial Fluid	8/19/2020	3/2/2021	172	0.006
Q-B2-28	2	8	B Terma	8/12/2020	5/19/2021	257	0.022
Q-B2-29	3	6	Initial Fluid	8/19/2020	3/2/2021	172	0.022
H-B3-30	3	3	A Base	3/2/2021	6/21/2021	111	N/A
H-B3-31	3	4	A Base	3/2/2021	6/21/2021	111	N/A
H-B3-32	3	5	A Base	3/2/2021	6/21/2021	111	N/A
Q-S2-34	1	5	A Fluid	12/1/2020	5/27/2021	155	N/A
Q-S2-35	1	4	A Terma	12/1/2020	5/27/2021	155	N/A
Q-S2-36	1	3	A Terma	12/1/2020	5/27/2021	155	N/A

In accordance with “Pack rust identification and mitigation strategies for steel bridges” pack rust occurring in splices can be categorized in ratings 1 to 5 depending on the level of deterioration and bulging [2]. Condition A tries to replicate rating 4 of pack rust in which excessive rust bleeding can be observed. Rating 4 accounts for 34% of the bridges with pack rust in splice connections in Indiana. Rating 3 corresponds to slight bowing of the splice plates, an amount that is less than ¼ in. Rating 3 accounts for 33% of the bridges with pack rust in splice connection in Indiana. Condition B represents additional time of exposure to accelerated corrosion misting beyond condition A. The additional exposure should result in increased corrosion and perhaps achieve some degree of bulging of the specimen. Therefore, bulging of the plates were measured on condition B specimens at different points in time and before the strength tests. For both types of specimens, treated and non-treated, tension strength tests were performed on the specimens with the goal of obtaining a correlation between time of exposure and strength reduction.

4.4.2 Application of the Mitigation Strategies

The mitigating products were applied as “Initial” on a specimen without corrosion or as “Repair” on a specimen that had already reached a level of corrosion. Under the initial condition, no surface preparation was required prior to the application of the products. At the moment these specimens were treated, the surface of the plates was clean and free of any major contaminant. On the other hand, in order to repair the specimens with the mitigating products, removal of the pack rust, to the extent that is possible, was required. In accordance with Termarust Technologies, a minimum pressure of 5000 psi using cold water is required to remove pack rust. A Simpson Water Shotgun professional pressure washer was used to remove the corrosion material at a standoff distance between 4 and 8 inches. This procedure was also done for all the mitigation strategies. The only difference is that for Termarust, the specimens had to be pressure washed with a mix of Chlor*Rid and water at a ratio of 1:100.

For Condition B specimens, this mix was sprayed and poured into the crevice due to technical difficulties with the pressure washer. For Condition A, the specimens were pressure washed with the mix without any problem. At least for this project, results seem not to be affected by the difference in the application of Chlor*Rid. After pressure washing, the crevice of the specimens was dried with compressed air while the areas surrounding the mouth of the crevice were dried

with rags. These areas were later coated with Rust-Oleum to protect the bare steel. After this step, the mitigating products were applied.



Figure 4.18. Pressure washer and pack rust removal set up.



Figure 4.19. Surface and gap condition before and after pressure washing the connection.

a) Fluid Film:

Due to the size of the areas being treated, aerosol cans were used to apply this product. This spray has a 5 to 6 in. long wand which makes the application easier. To apply the product, the wand was inserted into the gap and the product was applied until it would overflow. This was done to make sure the product was applied over the entire inner surfaces. Then, the specimens were turned upside down to apply the product in the same way, but on the other end of the gap. Additionally, fluid film was applied on the surfaces surrounding the mouth of the gap. In most cases the gap was sealed during the application of the product, but the thin wall sealing the gap would break during or after curing.



Figure 4.20. Fluid Film application for initial and repair condition.

b) Termarust:

Termarust was applied in a manner similar to Fluid Film. A syringe was used to insert 30 milliliters of penetrating sealer TR 2200HS into the gap and between the overlapping surfaces. This penetrating sealer was applied from both ends of the gap until it would overflow on the opposite end (giving a total of 30 milliliters usage). Same procedure was used to insert 10 milliliters of TR 2100 (topcoat) into the gap, but due to the high viscosity of the topcoat material, full coverage of the inner surfaces was not guaranteed. Finally, the topcoat was applied with a brush on the areas surrounding the mouth of the crevice. The gap of the specimens was typically sealed during brushing, but throughout or after curing it would open up.



Figure 4.21. Termarust application for initial and repair condition.

c) GE Silicone Caulk:

Using a caulking gun, GE Silicone caulk was applied along the interfaces of the overlapping plates close to the mouth of the gap. Additionally, a small amount of caulk was pushed into the gap to create a small barrier between the mouth of the gap and the inner portion of it. The thickness of the bead was approximately $\frac{1}{4}$ in.

As previously mentioned, different caulking products were tested before selecting GE Silicone caulk. Besides this one, Gorilla 100% Silicone and DAP Alex Plus All Purpose Acrylic Latex Caulk Plus Silicone caulk were tested to determine the most resistant caulk. Three-inch-long beads of caulk were applied at the interface of two bolted plates. They were exposed to the environment outside of the Bowen Laboratory for 3 months and sprayed weekly with a 5.3% salt solution. GE Silicone caulk seemed to be the most resistant at the end of the period. On the other hand, DAP Alex Plus shrank significantly, and the Gorilla 100% Silicone had problems with adhesion at the ends of the bead. Photographs of these observations are attached in the appendix section.



Figure 4.22. Caulk application for initial and repair conditions.

The application of all mitigation products extended approximately 1.5 to 2 inches away from the mouth of the crevice. For the initial condition specimens, the products were allowed to cure for 5 hours in a warm environment (80 °F or above). For Termarust, this curing time did not seem to be enough for one of the specimens even though the topcoat dried in the outside surface. Runoff material was observed at the bottom of the chamber after the specimen was placed back. The other initially treated Termarust specimen did not have this problem. This was also not helped by the fact that the specimens were in a sideways position inside the chambers (i.e., the gap runs parallel to the vertical axis). Fluid Film and GE Silicone caulk did not exhibit any problems with curing time. Therefore, for Condition A and B repairs, the products were allowed to cure for three days in a warm environment. However, three days did not seem to be enough for the TR 2100 topcoat to cure inside the gap as a small amount of runoff was still observed. More details about these observations are explained in the results chapter.

After the Fluid Film and Termarust products cured and dried on the zones surrounding the mouth of the gap, dry film thickness measurements were taken and tabulated in the Table 4.3. The recommended dry film thickness for Fluid Film application is 5 mils [19]. The minimum dry film thickness required for the application of Termarust is 10 mils. In the Pennsylvania Turnpike bridge project, 20 mils of topcoat were applied over connections [22].

Table 4.3. Thicknesses of Fluid Film and Termarust products.

Thicknesses of Applied Products							
			Measurements				
Type of Repair	Product	Specimen	1	2	3	4	Average
Initial	Fluid Film	27	3.08	2.93	5.82	3.00	3.71
Initial	Fluid Film	29	2.34	4.72	3.16	2.86	3.27
Initial	Termarust	25	19.49	11.99	14.53	8.07	13.52
Initial	Termarust	26	23.50	13.58	15.28	9.60	15.49
Condition A	Fluid Film	4	3.03	3.72	2.71	6.01	3.87
Condition A	Fluid Film	23	2.09	2.14	3.76	5.16	3.29
Condition A	Termarust	22	8.02	22.20	8.33	18.59	14.29
Condition A	Termarust	28	15.59	15.85	8.08	12.76	13.07
Condition B	Fluid Film	16	3.98	5.57	0.91	3.05	3.38
Condition B	Fluid Film	34	3.97	3.49	1.75	3.34	3.14
Condition B	Termarust	35	10.21	22.20	7.70	10.62	12.68
Condition B	Termarust	36	15.89	19.10	17.95	7.92	15.22

4.5 Strength Testing Program (ASTM E8/E8M-21)

4.5.1 Splice Connection Tension Tests

These tests were performed to determine the tensile strength of the splice connection specimens at different pack rust conditions. Estimating the level of strength deterioration due to pack rust is an important parameter to study since it can help to approximate the remaining service life of a structure and to anticipate any unsafe event. Usually, it is expected to have a decrease in strength in the structural element when it goes under the effects of corrosion because of the loss of cross section. Moreover, in the case of a bolted connection, excessive pack rust that exhibits bulging can create high pressure and exert tensile or pulling forces in the direction normal to the plates, which can lead to bolts coming off. For this test, a 700-kip MTS machine was used to pull the plates to failure. The load rate for the load control portion of the test was 10 kip/min until a load of 80 kip was reached. After this, the test was switched to displacement control with a rate of 0.1 in/min. Two points of interest were obtained from the load vs displacement plot: a) Load at slippage and b) Ultimate load. Load at slippage is the load at the early stages where significant displacement is

observed at a nearly constant load (i.e., a continuous horizontal line in the plot). Finally, the ultimate load is the highest load reached by the structural element.



Figure 4.23. MTS machine used for strength testing.

4.5.2 Coupon Tension Tests

In order to account for the variability of the material used to fabricate the specimens, four “splice plate” coupons and four “middle plate” coupons were fabricated and tested in accordance with ASTM E8/E8M – 21 [41]. Different types of coupons are described in the standards. The “middle plate” coupons are plate-type while the “splice plate” coupons are sheet-type since the overall lengths are 18 in. and 8 in., respectively. Unlike the tension test of the splice connections, the coupons were tested completely under stroke (displacement) control with a rate of 0.45 in/min for the “middle plate” coupons and 0.1125 in/min for the other coupons. In accordance to the standards, the rates should be different because these two types of coupons have different lengths of reduced section. Extensometers were used to determine strain during testing. The strain at failure was calculated manually since the extensometer had to be removed before rupture. Stress vs strain curves were plotted, and used to determine the yield and ultimate strength. Yield strength was calculated using the Offset Method with a 0.2% strain offset.

5. RESULTS AND ANALYSIS OF DATA

5.1 Misting Test Results and Qualitative Analysis

This section describes the qualitative results based on visual inspections of the specimens at different points in time. Furthermore, photographs are provided so that the reader can have a better understanding of the observations provided. General remarks of the results are highlighted in this section.

First, corrosion formation was faster for non-treated specimens than for treated specimens as expected. The description of the deterioration levels for the specimens during misting was based on two parameters: a) The formation of surface corrosion around the mouth of the gap and, b) The formation of corrosion “bumps” inside the gap. These bumps started as little spikes that grew up, and eventually filled the gap “gluing” both middle plates of the connections. The surface corrosion developed around the mouth of the crevice was observed throughout the entire misting period. On the other hand, it was only possible to observe the corrosion formation along the cross section of the specimens after pulling the specimens in two parts. Therefore, it was not possible to have a full conclusion of the performance of the mitigation strategies until the strength tests were performed.

Another parameter used to describe the deterioration rate was the bulging of the splice plates. However, no significant bulging was developed in the specimens so this parameter did not contribute much in the conclusions regarding the deterioration due to pack rust. The bulging measured for each specimen at different points in time is shown in Table 5.1. The maximum bulging observed in this experiment was 0.0809 in. in specimen 18, which was exposed to approximately 10 months of salt misting. Specimen 23 had a “higher degree of bulging”, but this value is not representative since the coating in the area where the measurements were taken was thick. While enough corrosion developed during the accelerated corrosion test to “close the gap”, additional testing time was needed to develop further corrosion growth inside the gap to create pack rust pressures sufficient to cause bulging of the plates.

Table 5.1. Bulging measurements of the Condition B and 10M specimens.

Bulging of the specimens					
Specimen	Assigned Condition	Time of Exposure			
		146 days	172 days	257 days	284 days
		Bulging (in)	Bulging (in)	Bulging (in)	Bulging (in)
Q-S1-4	B Fluid	0.0339	0.0417	0.0496	N/A
Q-S1-7	B Base	0.0405	0.0405	N/A	N/A
Q-S1-8	B Base	0.0269	0.0269	N/A	N/A
Q-S1-9	B Base	0.0185	0.0185	N/A	N/A
Q-S1-10	B Base	0.0117	0.0195	N/A	N/A
Q-B1-17	Initial Caulk	0.0440	0.0519	N/A	N/A
Q-B1-18	10M	0.0575	0.0575	0.0731	0.0809
Q-B2-19	10M	0.0674	0.0674	0.0674	0.0752
Q-B2-20	B Caulk	0.0119	0.0197	0.0432	N/A
Q-B2-21	B Caulk	0.0593	0.0749	0.0749	N/A
Q-B2-22	B Terma	0.0147	0.0147	0.0225	N/A
Q-B2-23	B Fluid	0.0823	0.0823	0.0823	N/A
Q-B2-24	Initial Caulk	0.0184	0.0184	N/A	N/A
Q-B2-25	Initial Terma	0.0299	0.0299	N/A	N/A
Q-B2-26	Initial Terma	0.0141	0.0141	N/A	N/A
Q-B2-27	Initial Fluid	0.0064	0.0064	N/A	N/A
Q-B2-28	B Terma	0.0141	0.0219	0.0219	N/A
Q-B2-29	Initial Fluid	0.0218	0.0218	N/A	N/A
	Max value	0.0823	0.0823	0.0823	0.0809
	Min value	0.0064	0.0064	0.0219	0.0752

5.1.1 Control and Base Specimens

Analysis of Base Specimens

A steady formation of rust bleeding was observed at the interface of the plates during the first three months. As the specimens approached one month of misting, the formation of small corrosion “bumps” was visible. These bumps increased in size and number rapidly. After seven weeks (1.75 months approximately), the visibility through the gap of the specimens was compromised. At three months, significant deformation of the mouth was observed on both ends of the gap. The shape of the mouth was deformed from a rectangular shape to an irregular shape. After three months, all specimens were flipped on the side. The bottom end of the gap showed more aggravated surface corrosion and deformation of the mouth compared to the top end of the gap. This can be attributed to the fact that the plates were positioned sideways, letting the corrosion material seep through and solidify at the bottom end of the gap. At this point, it was not possible to see through the gap of most of the specimens. At 111 days (4 months approximately), condition A was reached and visibility through the gap was no longer possible for any specimen.

The corrosion rate decreased significantly after 120 days, but some swelling around the gap was observed for some of the specimens. Between day 120 and 210, changes were not progressive on the area near the mouth. For specimens reaching condition B (172 days of misting), material started to seal the mouth of the crevice. At the 240th day, the crevice was completely sealed and a small solution pond was observed on the sealed gap. Towards the end of the misting period slight bowing was observed in specimens 18 and 19 (0.0809 in. and 0.0752 in. were measured, respectively). Specimen 23 exhibited a higher measured value of bowing (0.0823 in.), but this specimen also had thicker coating along the edge where measurements were taken. Therefore, the maximum bulging of the plates for the maximum degree of exposure was 0.0809 in.

Table 5.2 shows the development of corrosion on the Base and 10M specimens at different points in time. Additionally, Table 5.3 shows the cross section of the specimens at different stages. The control specimens show no corrosion formation since they were not exposed to misting. Condition A specimens exhibit orange/yellow and black rust. Iron oxide-hydroxide ($\text{FeO}(\text{OH})\text{H}_2\text{O}$) is the orange/yellow type of rust and it is produced as a result of high moisture content [42] [43]. On the other hand, iron (II) oxide (Fe_3O_4) is a black colored corrosion product, also known as magnetite,

and it is produced due to an environment with limited oxygen [3] [44]. The black rust was mostly observed in specimens 1 and 2, meaning that the gap was sealed by the time they were tested for strength. Conversely, specimens 5 and 6 show more orange/yellow type of rust, meaning that oxygen was able to travel through the gap. The difference between these two sets of specimens is related to the corrosion formation rate. Specimens 1 and 2 sealed faster than specimens 5 and 6, allowing black rust to form quicker and in more quantities. The pH of the collectors was found to be lower during the second period of misting (January 9th, 2021 to June 21st, 2021). Specimens 1 and 2 were placed in the chambers during this period. In accordance with the theoretical review, high concentrations of hydrochloric acid and low pH increase the corrosion formation rate. The pH measurements are attached in the appendix section.

Specimens that reached condition B (7,8,9, 10) showed a similar pattern in the rust formation along the cross section when compared to condition A (5, 6). These six specimens were placed in the chambers during the first period of misting (August 12th, 2020 to December 16th). The only difference for condition B specimens is that the orange color of the rust turned darker. Specimens under condition 10M exhibited more formation of black rust, which can be attributed to longer misting exposure time and “sealed” time (i.e., the time of period during misting after the gap sealed with corrosion material).

Table 5.2. Comparison of corrosion stages for non-treated specimens.

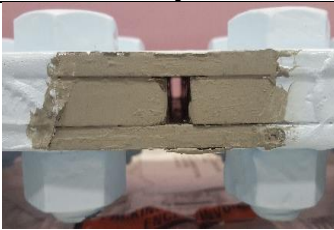












Condition/ Specimens	Time of exposure			
	0 days	7 days	60 days	90 days (Splices Flipped)
Control (3,13,14,15) A Base: 1,2,5,6. Specimen 5 shown in the pictures.	 (Specimen 29)	 (Specimen 5)		 
B Base: 7,8,9,10. Specimen 8 shown in the pictures.				 
10M: 18,19. Specimen 19 shown in pictures				 
Remarks	Specimen has not been exposed to corrosion.	Small corrosion staining and rust dots are observed mostly inside the crevice.	Corrosion staining is mostly happening at the interface of the plates and near the mouth of the gap. Inside the gap, small bumps are observed.	Corrosion spread over the surrounding area of the mouth on the top ends (top images). More corrosion and “spikes” formed on the bottom gap end.

Table 5.2. Continued.







Condition/ Specimens	Time of exposure			
	111 days/Testing Day	120 days	165 days	172 days/Testing Day
A Base: 1,2,5,6. Specimen 5 shown in the pictures.				
B Base: 7,8,9,10. Specimen 8 shown in the pictures.				
10M: 18,19. Specimen 19 shown in pictures				
Remarks	Built up material was present on the surface surrounding the mouth of the gap. The gap was completely sealed so it was not possible to see through it.	The gap is completely filled for all specimens. Swelling edges are observed at the middle of the splice plates. Slight bulging seems to start for some specimens.	Very small change in bulging and corrosion formation was observed with respect to the last stage.	No change was observed with respect to the last stage.

Table 5.2. Continued.




Condition/ Specimens	Time of exposure		
	210 days	240 days	284 days/Testing Day
A Base: 1,2,5,6. Specimen 5 shown in the pictures.			
B Base: 7,8,9,10. Specimen 8 shown in the pictures.			
10M: 18,19. Specimen 19 shown in pictures			
Remarks	Rate of corrosion formation seemed to decrease since not much change is observed for a long period of time.	Salt solution is stagnant at the mouth of the crevice. A slight increase of bowing of the plates is observed.	No significant change is observed in the specimens. A slight increase of bowing of the plates is measured.

Table 5.3. Rust formation in the cross section of non-treated specimens.

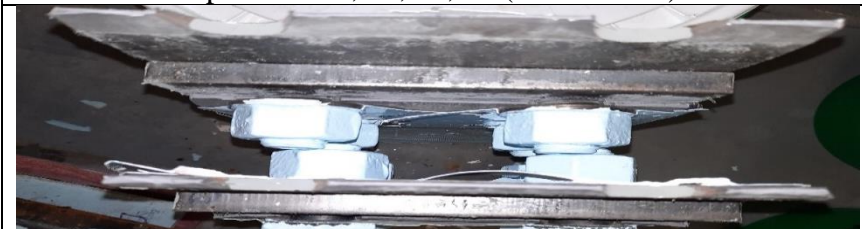





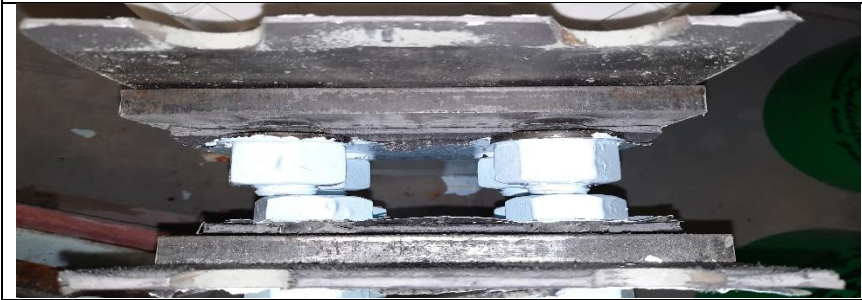
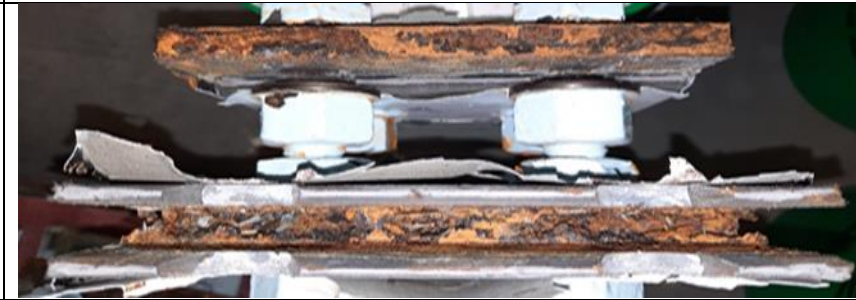





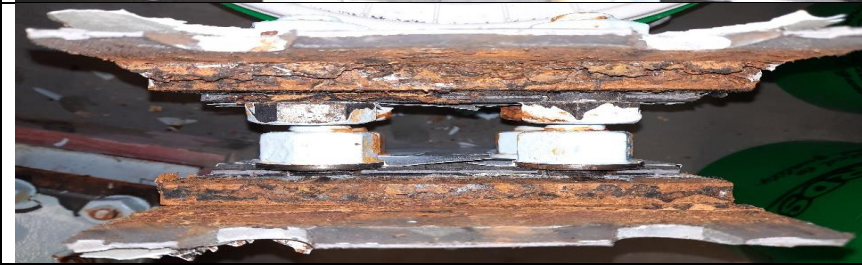
Condition/Time of exposure	
Control/0 days	A Base/111 days
Specimens 3, 13, 14, 15 (Downwards)	Specimens 1, 2, 5, 6 (Downwards)
	
	
	
	






Table 5.3. Continued.

Condition/Time of exposure	
B Base/172 days	10M/284 days
Specimens 7, 8, 9, 10 (Downwards)	Specimens 18, 19 (Downwards)
	
	
	
	

Analysis of Half Inch Base Specimens

Specimens 30, 31 and 32 were half inch gap specimens exposed for a period of time to reach condition A. These specimens can be compared with the specimens with a one-quarter inch gap. In a similar way, a steady formation of rust was observed between the interface of the overlapping plates for the first three months followed by a slow corrosion formation between the third and fourth month. The orangey formation of rust around the surface of the mouth is similar to that observed for the specimens with a quarter inch gap. The only difference is the formation of corrosion inside the gap. Since there is more space for corrosion to develop, it would take more time to seal the gap. At 111 days (approximately 4 months), the gap was not sealed. This was not the case for the quarter inch gap specimens in which the gap sealed by the end of the third month. Increasing the space within the gap does not affect the corrosion rate, but it delays sealing of the gap, which can be beneficial for future maintenance practices. However, further research is required to obtain more conclusive results. Table 5.4 shows the corrosion development of one of the specimens (Specimen 32) at different points in time.

Table 5.4. Corrosion development for ½ in. gap specimens.

Time of Exposure	Specimen 32
14 days	 A photograph of a metal specimen with a central gap. The metal surface is relatively clean and grey, with some minor brown staining around the gap.
1 Month	 A photograph of the same specimen after one month. The area around the gap is more heavily stained with a reddish-brown color, indicating the start of corrosion.
2 Months	 A photograph of the specimen after two months. The corrosion is more pronounced, with a larger area of reddish-brown rust surrounding the gap.
3 Months	 Two photographs of the specimen after three months. The top photo shows a significant area of dark, porous corrosion product around the gap. The bottom photo shows a similar view with even more extensive rusting and some yellowish staining on the surrounding metal.
4 Months	 A photograph of the specimen after four months. The corrosion is very severe, with a large, dark, irregular mass of rust completely obscuring the gap and spreading across a large portion of the specimen's surface.

5.1.2 Initially Treated Specimens

Analysis of Initially Treated Specimens

By the end of the first three weeks, small orange rust dots were visible on the Fluid Film and caulked specimens. For caulked Specimen 24, these rust spots were noticed around the caulk application area and not on the caulk. Moving towards day 30th, some visible surface corrosion is observed on all specimens that were initially treated. This surface corrosion worsened after 60 days of misting exposure, especially for the Fluid Film and Termarust protected specimens. Specimens were flipped after 90 days. Visual inspection showed that the Termarust specimens had runoff of material on the bottom end of the gap. This means that the material did not cure properly. Orange rust was observed on both ends of the gap for the Fluid Film and Termarust specimens. Additionally, small black dots were observed on the bottom end of the caulked specimens. The infiltration of moisture and lack of oxygen of the caulked-sealed gap produced the chemical conditions to form black rust. From day 120 to day 172, Termarust did not exhibit further corrosion on the surface around the mouth of the crevice. On the other hand, Fluid Film exhibited an increase in surface corrosion, which later stabilized. Furthermore, GE caulk did not show signs of deterioration or discoloration by the end of the exposure period.

Table 5.5 shows the corrosion development over time while Table 5.6 shows the cross-section photographs of the specimens. For the caulked specimens, the surfaces inside were in good condition. Only small staining and some dark spots are observed. For the Fluid Film specimens, the wax material of this mitigating product worked as a sacrificial layer. The photographs showed an orange material similar to rust. However, opposite to rust, this material is not “crunchy” and can be easily removed with rags. The wax seemed to absorb the acidic solution and to turn orange due to rust staining. For Termarust, two different scenarios were present. One of the specimens (25) was effectively protected by the combination of the penetrating sealer and the topcoat while the other (26) suffered severe corrosion. The failure of Specimen 26 can be attributed to curing problems. However, both specimens were treated at the same time and with the same procedure. For the specimen that performed effectively, the topcoat appeared to adhere to the metallic surface without problem for most of the crevice surface. Some orange and dark spots were still visible within the cross section, but overall, the surface was well protected.

Table 5.5. Comparison between mitigation strategies for specimens initially treated.











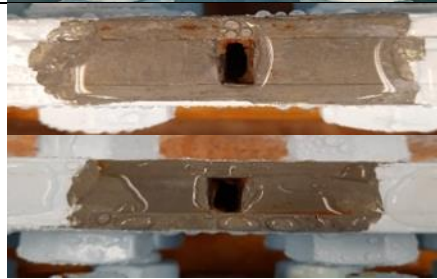

Condition/ Specimens	Time of exposure			
	0 days	21 days	30 days	60 days
Caulk: 17 and 24 (Top).				
Termarust: 25 and 26 (Top).				
Fluid Film: 27 and 29 (Top).				
Remarks	The specimens have not been exposed to corrosion.	Small rust dots are formed around the caulk and on the surface of the Fluid Film specimens.	Rust dots are increasing in size, but there is no caulk deterioration. Termarust specimens have little corrosion staining. Fluid Film rust spots have not increased in size.	Rust dots are progressive, but there is no caulk degradation. Termarust staining is intensifying. Fluid film staining had a significant development over the last 30 days.

Table 5.5. Continued


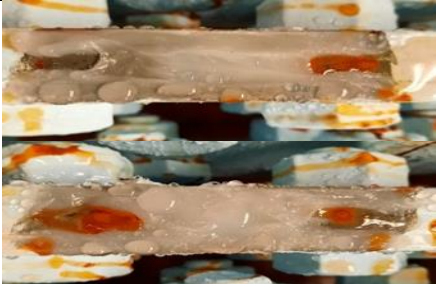



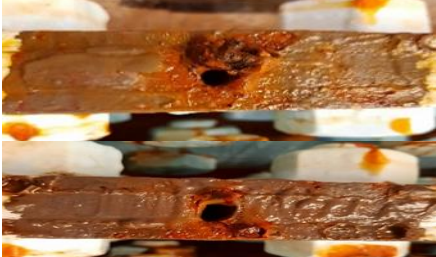












Condition/ Specimens	Time of exposure			
	90 days (Splices Flipped)	120 days	165 days	172 days/Testing Day
Caulk: 17 and 24 (Top).				
Termarust: 25 and 26 (Top).				
Fluid Film: 27 and 29 (Top).				
Remarks	Specimens have been flipped. Black rust dots are observed around the caulk. Termarust has material runoff and some corrosion built up. Fluid Film specimens show some rust staining.	Orange staining appears around the caulk while a few black dots remain, but the caulk shows no degradation. Termarust specimens do not show significant change. Fluid Film staining increases significantly over the last 30 days.	Orange staining around caulk intensifies. Termarust and Fluid Film specimens do not show significant change with respect to the previous stage.	Ultimately, the caulk did not show visible deterioration. Termarust and Fluid Film specimens did not have notable changes in the last 50 days. The level of corrosion staining on the Fluid Film specimens is higher than on Termarust specimens.

Table 5.6. Rust formation in the cross section of initially treated specimens.

Condition B/Time of exposure: 172 days	
GE Silicone Caulk Specimens 17, 24 (Downwards)	Fluid Film Specimens 27, 29 (Downwards)
	
	
Termarust Specimens 25, 26 (Left to Right)	
	

5.1.3 Repaired Specimens

Analysis of Repaired Specimens

Repaired specimens were treated for two exposure conditions: Condition A and Condition B. For the first condition, base specimens were allowed to corrode for 111 days before repair. The specimens were exposed for a second cycle of 41 days. For the second repair condition (Condition B), base specimens were allowed to corrode for 175 days before repair, and then were exposed for a second cycle of 79 days. Table 5.7 shows the development of corrosion at different points in time for this group of specimens.

For the first 30 days of Condition A repair, the Termarust topcoat was not affected by the corrosive environment while Fluid Film showed considerable surface corrosion. The caulked specimens showed surface corrosion around the caulk application area, but the caulk product itself did not show any signs of deterioration. At the end of the second repair cycle, Termarust specimens showed a few orangey spots near the plate interfaces. Also, black rust was leaking from the bottom end of the gap for one of the specimens. This means that the topcoat was obstructing air from flowing through the gap. This problem is related to the viscosity of the topcoat and its difficulty to be applied in such a small space.

The Fluid Film wax developed a semi rustic and porous surface around the mouth during misting. This porous surface developed during misting may be indicative of a chemical reaction. The specimens initially treated with Fluid Film were stored in the chambers mostly over the period of time when the pH of the solution was within the recommended range. On the other hand, the specimens repaired with Fluid Film were stored in the chamber over the period of time when the pH solution was slightly below the recommended range. Therefore, it is possible that the Fluid Film product cannot bear progressively acidic environments. Further experimental studies are required to examine this effect. Finally, the caulked specimens showed signs of discoloration, but no problem with adhesion to the metallic material. This can also be attributed to a more corrosive environment during the second period of misting.

The following paragraph provides some observations based on the cross-sectional photographs of the specimens. Table 5.8 shows the cross-section of the specimens that were repaired for condition

A and condition B. Black rust staining is observed for the caulked specimens and the Termarust specimens. For the caulked specimens, the formation of black rust is caused by sealing the gap at the ends. During repair, the corrosion products were removed by means of pressure washing. Nonetheless, 100% rust material removal is not guarantee during this step. Consequently, the remaining rust plus the action of sealing the gap is not a recommended step towards mitigating corrosion. For the Termarust specimens, the topcoat did not flow smoothly in the small confined gap. Additionally, it was observed that at the moment strength tests took place, the topcoat inside the specimens was still wet despite the specimens being allowed to cure for three days. The clogging of the gap with the topcoat did not allow air to flow and dry the surfaces. Clogging the gap also allows black rust to form by restricting the air flow in that space. For the Fluid Film specimens, the action of the sacrificial wax is observed again (similar to the initially treated specimens), but concerns regarding its capability to bear more aggressive conditions rose. Likewise, black rust developed in these specimens, but in a moderate degree.



Figure 5.1. Black rust in Termarust (left) and caulked (right) specimens for Condition A.



Figure 5.2. Discoloration of caulked specimen.

The specimens that were going to be tested for condition B and then repaired, were exposed to salt misting for 175 days. The overall results for all specimens were catastrophic for the area surrounding the mouth of the crevice. At 35 days after repair, the Termarust protected specimens had already developed considerable surface corrosion. The caulk material and Fluid Film product did not show signs of excessive deterioration. However, 82 days after repair (3 days of curing plus 79 days of misting), the surface surrounding the mouth of the gap was significantly damaged for all specimens. Surface corrosion spread on top of the fluid film wax and the Termarust topcoat. Similar to the caulked and Termarust protected specimens under condition A, black rust was observed on the bottom end of the gap. The caulk material showed discoloration, but not adhesive deficiencies.

Table 5.8 shows the cross section results for condition A and B repaired specimens. Inside the gap, similar results were observed for repaired specimens under condition A and condition B. It is important to mention that the main concern of the project is to assess the performance of the products within the gap and between overlapping surface, but the performance of the mitigating products around the mouth of the gap is also an indicative of their effectiveness.



Figure 5.3. Black rust in Termarust (left) and caulked (right) specimens for Condition B.

Table 5.7. Comparison between strategies for specimens repaired for condition A and B.













Condition/ Specimens	Time of exposure			
	111 days/Before Repair	111 days/After Repair	30 days After Repair (141 days)	44 days After Repair (155 days)
Caulk: Cond A: 11 (Top) and 24.				
Termarust: Cond A: 35 (Top) and 36.				
Fluid Film: Cond A: 16 (Top) and 24.				
Remarks	Specimens reached condition A of corrosion.	Specimens were pressure washed for removal of pack rust. Then, Rust-Oleum was applied on the outside surface, and the mitigation products were applied.	Significant staining occurs around the caulk, but no caulk degradation. Termarust shows little to none staining. One of the Fluid Film specimens shows significant staining around the mouth of the gap.	The caulk had some yellowish color degradation. Termarust staining had a slight increase in quantity. Fluid Film had significant surface corrosion. The consistency of the material changed from waxy to porous and semi rustic.

Table 5.7. Continued


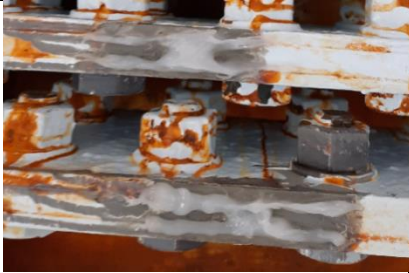










Condition/ Specimens	Time of exposure			
	175 days/Before Repair	175 days/After Repair	35 days After Repair (210 days)	82 days After Repair (257 days)
Caulk: Cond B: 20 and 21 (Top).				
Termarust: Cond B: 22 and 28 (Top).				
Fluid Film: Cond B: 4 and 23 (Top).				
Remarks	Specimens reached condition B of corrosion.	Specimens were pressure washed for removal of pack rust. Then, Rust-Oleum was applied on the outside surface, and the mitigation products were applied.	There is no sign of caulk degradation. Termarust specimens developed significant surface corrosion. Fluid Film specimens developed some surface corrosion.	Black rust was spotted on the bottom end of the gap for the caulked and Termarust specimens. Caulk had slight yellowish degradation. Termarust and Fluid Film show significant degradation on the surface.

Table 5.8. Rust formation in the cross section of specimens repaired for condition A and B.









Repaired Condition A/Time of exposure: 155 days (44 days after repair)	
GE Silicone Caulk Specimens 11, 12 (Downwards)	Fluid Film 16, 34 Specimens (Downwards)
	
Termarust Specimens 35, 36 (Left to Right)	
	

Table 5.8. Continued

Repaired Condition B/Time of exposure: 257 days (82 days after repair)	
GE Silicone Caulk Specimens 20, 21 (Downwards)	Fluid Film Specimens 4, 23 (Downwards)
	
Termarust Specimens 22, 28 (Left to Right)	
	

5.2 Strength Test Results and Quantitative Analysis

The tension strength test had two main objectives: a) determine the strength reduction in the specimens as a function of time of exposure to salt spraying, and b) determine the strength reduction in the specimens after repair with the mitigation strategies and additional exposure. Two points along the load versus displacement curve are of interest: load at notable slippage of the bolts and the ultimate load. Table 5.9 shows the experimental and expected strength values for each of the specimens.

The first part of the analysis corresponds to specimens that did not have any protection in the crevice. These are control, base/condition A, base/condition B and 10M specimens. The second part corresponds to the specimens that were initially treated and repaired after exposure. The analysis provided takes into consideration the variability of the material. To obtain conclusive statements about the effects of corrosion in this experiment, it is important to determine whether a specimen had more or less strength due to corrosion or due to the variability in the material.

It is shown in Table 5.9 that all the experimental values of strength were higher than the theoretical values. The theoretical values were computed based on the average ultimate strength of the coupons tested and the corresponding cross-sectional area of the specimen. Due to the small number of samples, the coupon testing did not likely exhibit the complete range of ultimate strength values. Second, instrumental error due to calibration of the MTS tension test machine used to test the specimen can cause discrepancy between theoretical and experimental values. Nonetheless, this instrumental error should not affect the assessment of strength reduction due to corrosion since all specimens were tested in the same tension test machine. The assessment is based on relative values to determine how much the strength decreased with respect to the previous stage.

Table 5.9. Experimental and theoretical strength values for all specimens

Strength Measurements					
Specimens	Test Date	Assigned Condition	Load at Slippage	Ultimate Load	Expected Ultimate Load
Q-S1-1	6/14/2021	Base A	54.61	160.75	151.14
Q-S1-2	6/14/2021	Base A	30.54	157.61	151.95
Q-S1-3	2/23/2021	Control	40.93	159.10	153.04
Q-S1-4	5/19/2021	B Fluid	40.60	158.76	151.34
Q-S1-5	12/1/2020	Base A	35.50	158.96	149.72
Q-S1-6	12/1/2020	Base A	45.09	161.90	152.44
Q-S1-7	2/23/2021	Base B	34.44	161.61	150.73
Q-S1-8	2/23/2021	Base B	36.56	160.52	152.95
Q-S1-9	2/25/2021	Base B	27.43	159.62	149.72
Q-S1-10	2/25/2021	Base B	36.17	160.45	151.74
Q-B1-11	5/27/2021	A Caulk	20.00	172.31	153.86
Q-B1-12	5/27/2021	A Caulk	19.54	159.25	153.17
Q-B1-13	11/17/2020	Control	18.15	161.43	151.13
Q-B1-14	11/19/2020	Control	25.63	173.47	154.24
Q-B1-15	11/19/2020	Control	28.06	174.34	156.51
Q-B1-16	5/27/2021	A Fluid	22.59	158.95	148.73
Q-B1-17	3/1/2021	Initial Caulk	22.40	175.20	156.27
Q-B1-18	6/14/2021	10M	26.85	172.75	152.47
Q-B2-19	6/14/2021	10M	28.41	171.71	155.98
Q-B2-20	5/19/2021	B Caulk	28.67	161.38	152.04
Q-B2-21	5/19/2021	B Caulk	22.62	161.40	151.75
Q-B2-22	5/19/2021	B Terma	28.59	161.55	151.65
Q-B2-23	5/19/2021	B Fluid	23.41	162.54	150.53
Q-B2-24	3/2/2021	Initial Caulk	23.00	163.55	149.72
Q-B2-25	3/1/2021	Initial Terma	23.45	160.56	149.93
Q-B2-26	3/1/2021	Initial Terma	20.09	170.63	153.86
Q-B2-27	3/2/2021	Initial Fluid	24.61	160.60	149.51
Q-B2-28	5/19/2021	B Terma	28.66	160.15	150.62
Q-B2-29	3/2/2021	Initial Fluid	26.01	161.92	150.23
H-B3-30		A Base			N/A
H-B3-31		A Base			N/A
H-B3-32		A Base			N/A
Q-S2-34	5/27/2021	A Fluid	27.46	172.84	155.07
Q-S2-35	5/27/2021	A Terma	29.68	174.05	154.99
Q-S2-36	5/27/2021	A Terma	26.74	173.27	157.42

5.2.1 Strength of Control and Base Specimens

Table 5.10. Average slippage, ultimate and expected loads of Control and Base specimens.

Control/Base Specimens								
Slippage Load			Maximum Load			Average Expected Load		
28.19	kip	Control	167.09	kip	Control	153.73	kip	Control
41.43	kip	Base A	159.80	kip	Base A	151.31	kip	Base A
33.65	kip	Base B	160.55	kip	Base B	151.29	kip	Base B
27.63	kip	10M	172.23	kip	10M	154.22	kip	10M

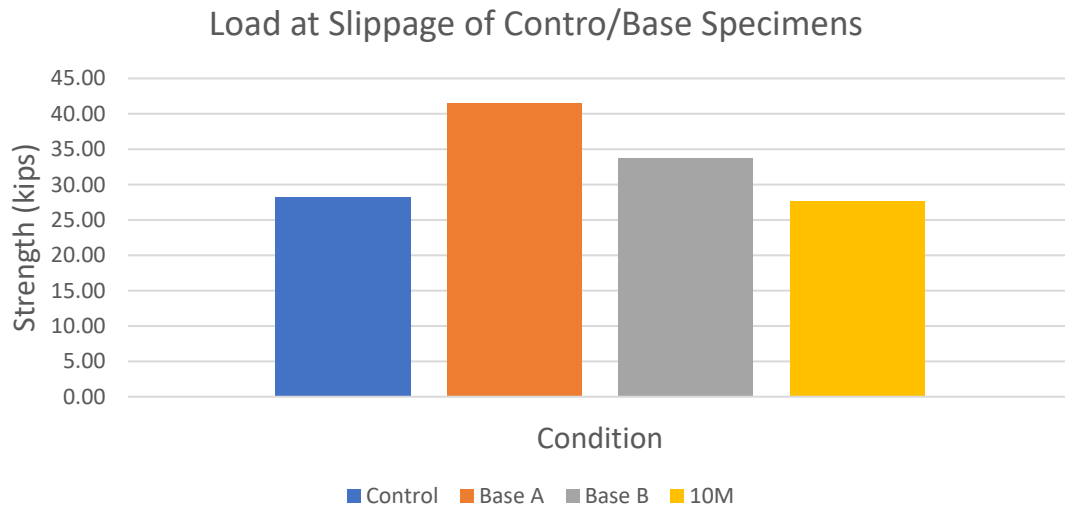


Figure 5.4. Load at slippage of control and base corroded specimens.

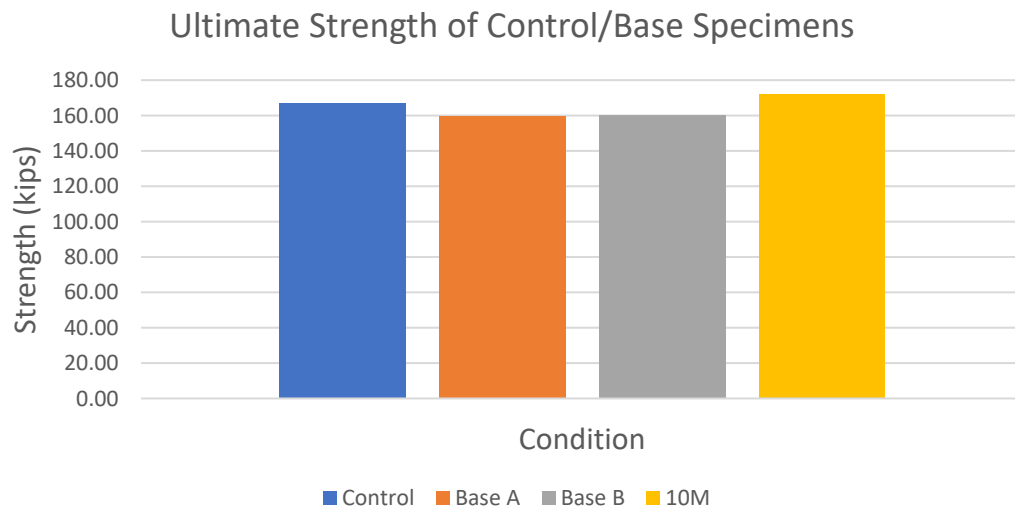


Figure 5.5. Ultimate load of control and base corroded specimens.

The slip resistance of the connection increased with the presence of corrosion within the gap. However, it decreased after further corrosion developed. As seen in the Table 5.10 and Figure 5.4, the load at slippage increased for Base A specimens and later decreased for Base B and 10M specimens. The increase in slippage load may be attributed to the formation of rust in the gap, which “glued” the middle plates, allowing for an “extra” resistance for slippage. During tension testing, snapping sounds were heard, which probably means that the bonding effects of the “gluing” rust was being broken.

With respect to ultimate strength, there is not an identified pattern. Base A and Base B specimens exhibited an approximate 4% strength reduction with respect to the control specimens. However, the 10M specimens exhibited 3% higher strength than the control specimens. It is important to spotlight that only 2 10M specimens were tested due to limited material. The results are an indicator that there is variability of the connection strength due to the variability of material strength, and not due to corrosion deterioration.

A similar pattern is observed when comparing the experimental and theoretical values of strength. For instance, the average expected load for the control specimens was already higher than the Base A and Base B specimens. Also, the 10M specimens average expected load was higher than the rest of the specimens. Already considering the instrumental error, it can be concluded that there is no structural deterioration of the splice connections since the experimental values follow the pattern of the theoretical values.

Additionally, there is no physical evidence that the corrosion affected the cross-sectional area where the fracture failure occurred. Figure 5.6 shows that the area where the fracture occurred is mostly clean and exhibited ductile behavior. Only some rust staining was able to reach that zone because the specimens were protected with the coating system on the sides, not allowing the salt solution to infiltrate. Photographs of the cross-sectional areas can be seen in the qualitative analysis section. Finally, it can be determined that there is conclusive evidence that no deterioration of the connections occurred due to the corrosion produced under the set of conditions established in this experiment.



Figure 5.6. Specimen 19 cross-sectional area, exposed to 284 days of corrosion.

5.2.2 Strength of Initially Treated Specimens

Table 5.11. Average slippage, ultimate and expected loads of initially treated specimens.

Control, Base B and Initially Treated Specimens								
Slippage Load			Maximum Load			Average Expected Load		
28.19	kip	Control	167.09	kip	Control	153.73	kip	Control
33.65	kip	Base B	160.55	kip	Base B	151.29	kip	Base B
21.77	kip	Terma	165.59	kip	Terma	151.90	kip	Terma
25.31	kip	Fluid	161.26	kip	Fluid	149.87	kip	Fluid
22.70	kip	Caulk	169.37	kip	Caulk	153.00	kip	Caulk

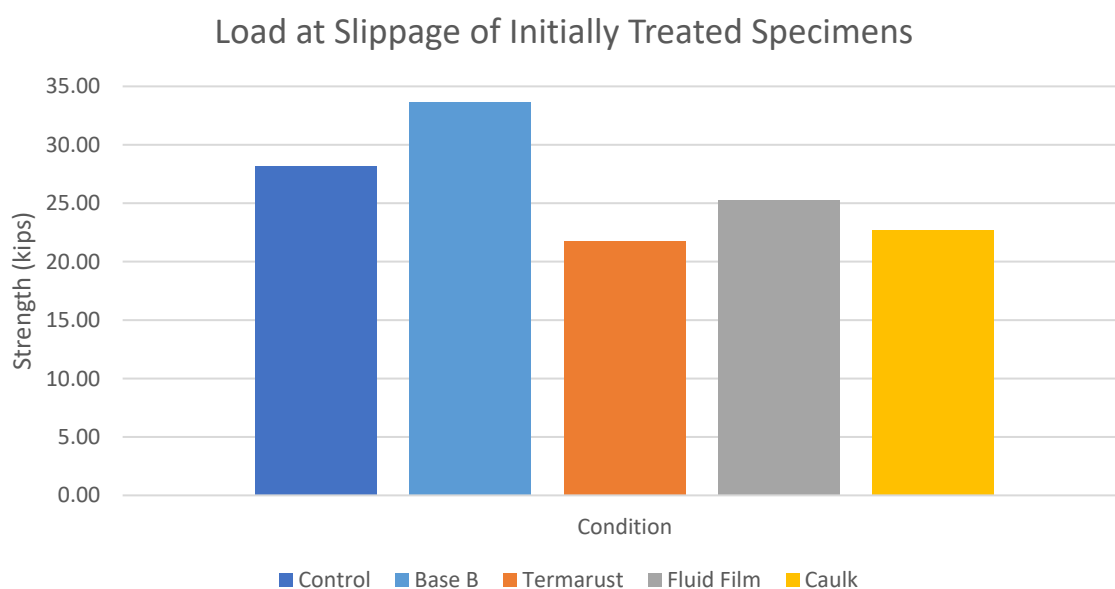


Figure 5.7. Load at slippage of initially treated specimens.

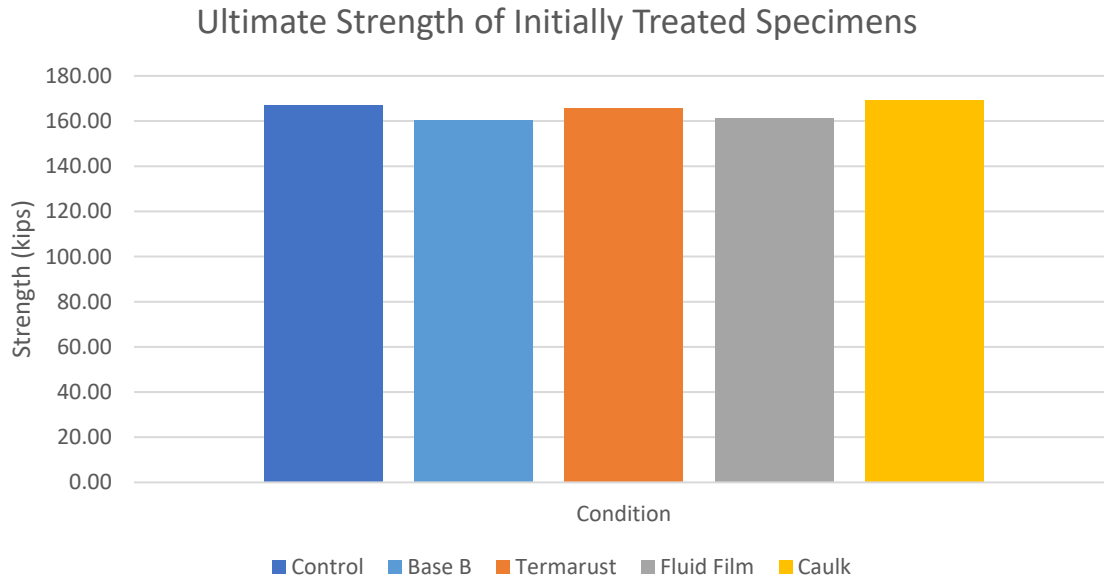


Figure 5.8. Ultimate load of initially treated specimens.

The results for slip resistance demonstrate that specimens exposed to corrosion without any protection on the crevice exhibited higher slip resistance than those without exposure to corrosion (control) and those treated with the mitigating products. These results strengthen the idea that corrosion contributed to the slip resistance of specimens. Specimens that were initially treated did not develop considerable corrosion within the gap region in comparison to the Base B specimens.

In regards to ultimate strength, deterioration of the specimens did not take place from the data point of view. Even though all the strength values for the initially treated specimens were higher than the strength value for Base B specimens, the relative difference is not significant due to the presence of material variability. Based on the cross-sectional area, Base B specimens were already expected to yield lower values of ultimate strength in this group of specimens in Table 5.11. Moreover, cross-sectional loss was not observed around the area where the fractures occurred, as depicted in the photographs in Section 5.1.2. Therefore, the performance of the mitigating products cannot be assessed directly from the ultimate strength results. The final remarks will rely mostly on the visual inspections of the corrosion prevention.

5.2.3 Strength of Repaired Specimens

Table 5.12. Average slippage, ultimate and expected loads of repaired specimens.

Base A and Repaired A Specimens								
Slippage Load			Maximum Load			Average Expected Load		
41.43	kip	Base A	159.80	kip	Base A	151.31	kip	Base A
28.21	kip	A Terma	173.66	kip	A Terma	156.21	kip	A Terma
25.03	kip	A Fluid	165.90	kip	A Fluid	151.90	kip	A Fluid
19.77	kip	A Caulk	165.78	kip	A Caulk	153.51	kip	A Caulk
Base B and Repaired B Specimens								
Slippage Load			Maximum Load			Average Expected Load		
33.65	kip	Base B	160.55	kip	Base B	151.29	kip	Base B
28.63	kip	B Terma	160.85	kip	B Terma	151.13	kip	B Terma
32.01	kip	B Fluid	160.65	kip	B Fluid	150.94	kip	B Fluid
25.64	kip	B Caulk	161.39	kip	B Caulk	151.89	kip	B Caulk

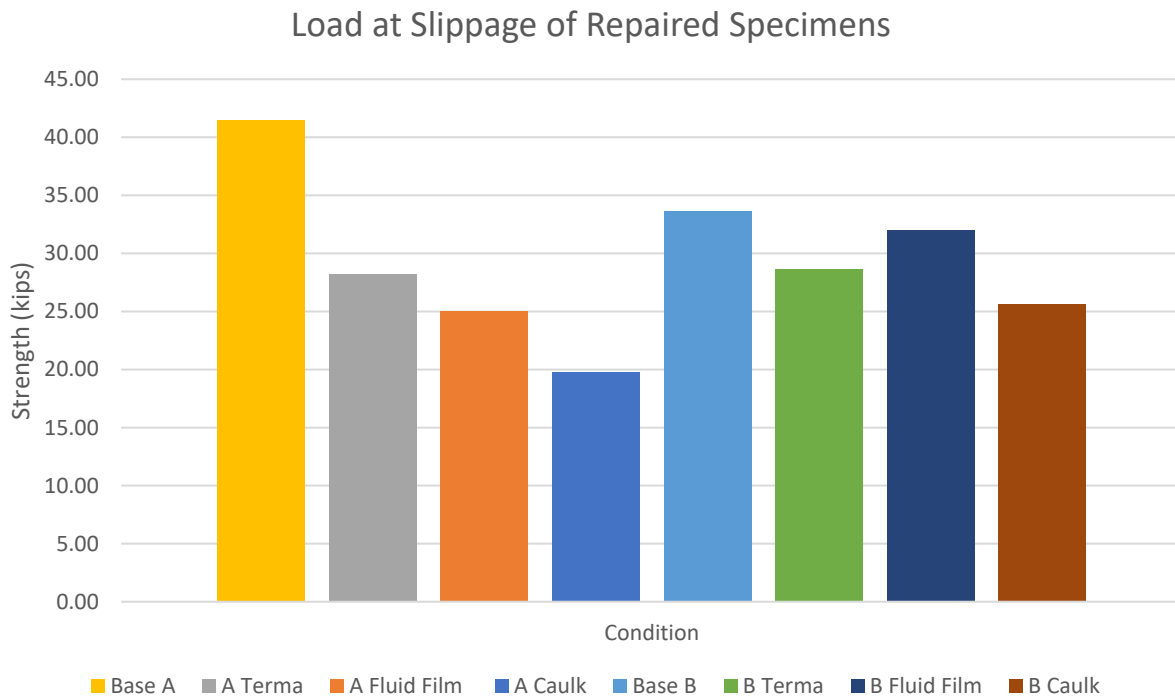


Figure 5.9. Load at slippage of base and repaired A specimens.

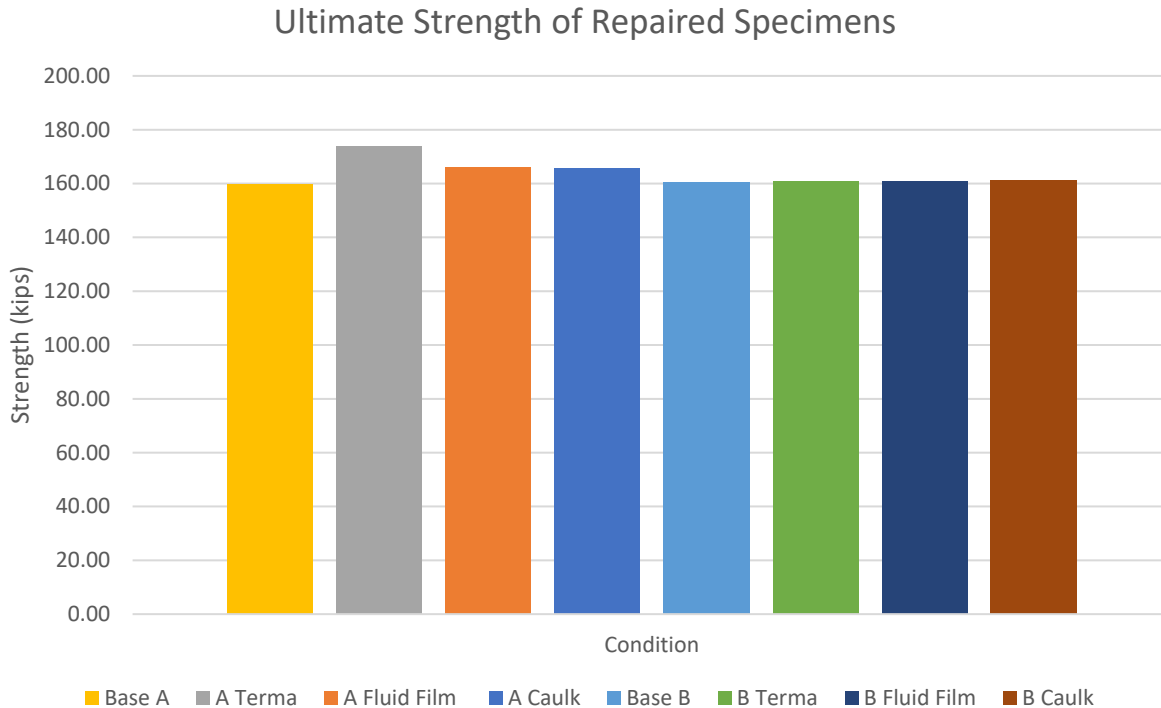


Figure 5.10. Ultimate load of base and repaired specimens.

The slip resistance of the connection decreased after the connections were repaired for both condition A and B. The difference in slip resistance between Base and Repaired A specimens is more remarkable than for condition B specimens. This might be related to the time of exposure after repair. While rust removal was applied in the same manner for both types of specimens, condition B specimens were exposed for a significantly longer time after repair. Condition A specimens were placed in the chambers for a second cycle of misting of 41 days while condition B specimens were placed back in the chambers for a second cycle of misting of 79 days. The difference in time of exposure allows for more formation of rust within the gap. Nonetheless, based on the cross-sectional photographs for repaired condition A and B, there is not much difference in corrosion material formation for these two conditions that is evident in the gap region after the specimens have been fractured and the gap region can be inspected.

With respect to the ultimate strength of the connections, the same conclusion obtained from section 5.2.1 and 5.2.2 is reached in this section. The fact that the repaired specimens did not experience further strength reduction cannot be attributed to the effectiveness of the mitigating products. The

coating system was protecting the area where failure happened, and corrosion did not reach the area where failure occurred. Moreover, corrosion did not develop in the gap region of the splice connection to a significant enough degree that it compromised the controlling connection strength at the net section. Therefore, final remarks will be based on the visual inspections.

6. CONCLUSIONS AND RECOMMENDATIONS

This section provides conclusions based on the results reviewed in the previous chapter. Due the sensitivity of corrosion related laboratory experiments, the conclusions and recommendations provided are based on the scope of this project and the results. These two were affected by the set of environmental conditions that took place in the testing room and strength testing at room temperature. It is also important to highlight that not much research about this specific type of corrosion (crevice corrosion) on this type of structural elements (splice connection) has been performed. Moreover, recommendations will be given to provide guidance for future research on this topic.

6.1 Remarks on Test Results and Field Application Recommendations

General Observations and Conclusions

- For the set of conditions developed in this experiment and the amount of corrosion produced, there is no evidence that the ultimate strength of the connections was affected for any of the different conditions studied (Condition A, Condition B and 10M). This is because rust did not reach the area where the ruptures occurred and did not compromise the gap region to a degree more than the critical net section.
- Corrosion developed within the gap of the specimens was observed to affect the slip resistance of the splice connections due to its “gluing” effect of the middle plates. After removal of rust product during repair, it was observed that the slip resistance decreased.
- Based on visual inspection, the corrosion formation rate was higher for the first three months of exposure followed by a lower apparent corrosion rate thereafter. This could be a characteristic belonging to crevice corrosion, which will require more sophisticated tools for further study.
- Bulging of the splice plates was slightly visible towards the beginning of the ninth month of exposure. The maximum bulging observed was 0.0809 in., which did not affect the structural performance of the connection.
- The ½ in. gap specimens delayed the sealing of the gap with corrosion material since more space was available. If there are no effects on the structural capacity, increasing the gap of

the field splice connections should be considered. Once the gap opening is filled and sealed with corrosion material, the formation of black rust takes place due to lack of oxygen; this situation should be avoided.

Conclusions from the Mitigating Products' Performance

- As an initial treatment, all mitigating products performed effectively in the initial condition test in delaying significant pack rust formation. First, the Fluid Film's performance is somewhat inconclusive based on the visual inspection. The wax worked as a sacrificial layer, but during evaluation it was challenging to differentiate between "sacrificed" wax material and rust since they both had the same coloration. Fluid Film's performance can be categorized as effective because the steel under this wax material did not show signs of significant deterioration.

Second, GE caulk demonstrated enough resistance throughout the misting period. It only allowed small quantities of rusty solution to infiltrate into the crevice. However, these small quantities can represent serious problems in the future if interaction between the metal and a corrosive solution takes place.

Termarust also showed promising results and its use is recommended. The only difficulty of this product was the viscosity of the topcoat. This represented a problem because it was difficult to smoothly apply it over the surface within the gap. Termarust Technologies recommends the use of TRT01 thinner. Therefore, if the viscosity problem is solved, its application is recommended.

- As a repair method, the mitigation strategies exhibited fair to poor performance. First, Fluid Film's performance was similar to the one shown as initial condition. However, the physical characteristics of the "sacrificed" wax changed in contexture and color. This can be an indicator of a chemical reaction taking place due to the remaining pack rust after pressure washing and a lower pH during the time these specimens were placed in the chambers. To obtain a more assertive conclusion, further study of the Fluid Film material is required.

Second, GE caulk was resistant with some discoloration. Despite the durability of the material, caulking should not be employed as a mitigating repair approach since encapsulating corrosive material within the gap promotes the fast formation of black rust. This was the observation for the specimens repaired with caulk in this experiment.

Finally, Termarust performed slightly better than the other two strategies for the condition B specimens. The specimens repaired with this method also faced problems with the viscosity of the Termarust topcoat and its curing. After three days of curing, the material inside the gap was not dried. The recommended thinner should be applied to reduce the curing time and to allow the topcoat to smoothly flow through the gap. Significant corrosion was found in all repaired specimens, but since Termarust demonstrated a slight better performance, its application in the field is recommended.

- Even though the application of these mitigating products was performed on the geometry of a flange splice connection, their implementation can be extended to other members with overlapping elements where the concept of pack rust still applies, and as long as space or air is not being encapsulated within the member. Finally, a summary of the mitigation strategies based upon the observations herein is provided in Table 6.1

Table 6.1. Recommendations and notes on the mitigation strategies.

Treatment	Strategy	Recommended	Notes
Initial	Fluid Film	Yes	
	GE Caulk	Yes	Full sealing of the crevice mouth is required.
	Termarust	Yes	Use thinner to reduce the viscosity of topcoat and to allow smooth application.
Repair	Fluid Film	Yes	Recommended, but additional chemical studies are required.
	GE Caulk	No	
	Termarust	Yes	Use thinner.

6.2 Recommendations for Future Research

The following section provides a series of recommendations based on the observations and outcome of this project. These recommendations have the purpose of providing other researchers better insight of the aspects involving accelerated corrosion testing for this type of structural element.

- First, even though a considerable amount of corrosion developed within the gap of the specimens, corrosion material did not build up between the overlapping splice and middle plates. Therefore, it is recommended to employ a strategy where multiple approaches are used to develop corrosion. For example, in this project, the salt misting test was performed. Since the goal is to develop a significant amount of corrosion, other techniques such as the use of current or a more acidic environment should be considered. Other types of accelerated corrosion tests should also be considered.
- Second, another issue that prevented the development of corrosion between the plates may be the application of the coating system on the sides of the specimen. The area where the fracture happened was protected with the coating system. From the photographs, it can be observed that rust did not reach the area where fracture occurred. Therefore, the coating system should be applied 1.5 to 2 inches after the first line of bolts on the sides of the specimens. In this way, salt solution can infiltrate into the space between the plates from the gap region and from the sides of the specimen.
- The positioning of the specimens in the chambers should be re-examined. The specimens were positioned sideways with the gap running parallel to the vertical axis. Considerable corrosion material was observed at the bottom of the chambers, meaning that the corrosion material was running off from the plates. If the specimens had been placed horizontally (the gap running parallel to the horizontal plane), there would have not been much material loss from the plates, and the chances of getting bulging of the plates may have increased.
- Finally, even though ASTM B117 recommends a pH range of 6.5 to 7.2, an adjustment of pH for this type of test should be considered. A lower pH level exhibits a faster formation of corrosion, and consequently it could be beneficial if the target is to produce greater quantities of corrosion product and bulging of the plates.
- Field testing should be performed on the mitigation strategies studied in order to account for other variables that are difficult to replicate in the lab. For example, exposure to cold

weather, temperature changes and pH changes within the environment should be part of this field testing. Moreover, in the field these strategies would be subjected to cyclic loading, which is an important parameter in bridge design. Field testing will help in clarifying the practicability of these mitigating products.

- Another mitigation strategy consisting of the combined application of Fluid Film and caulk should be considered. These two products have different purposes and their combined application may be beneficial. Caulking restricts the penetration of moisture into the gap, as was observed in the current study. However, 100% efficiency is not guaranteed. Therefore, if some moisture infiltrates into the gap, Fluid Film would be there to avoid the interaction between the solution and the bare steel. It was observed that Fluid Film worked well as a sacrificial layer by absorbing or displacing the salt solution.

APPENDIX A. PH AND TEMPERATURE MEASUREMENTS

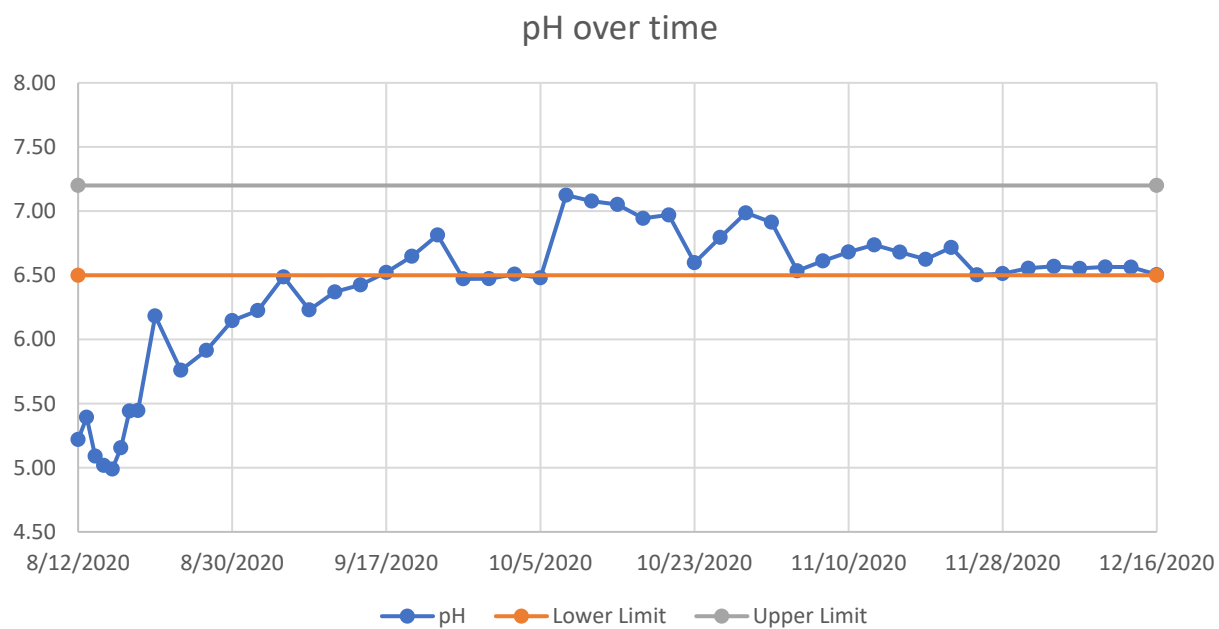


Figure A.1. pH measurements for the first period of misting.

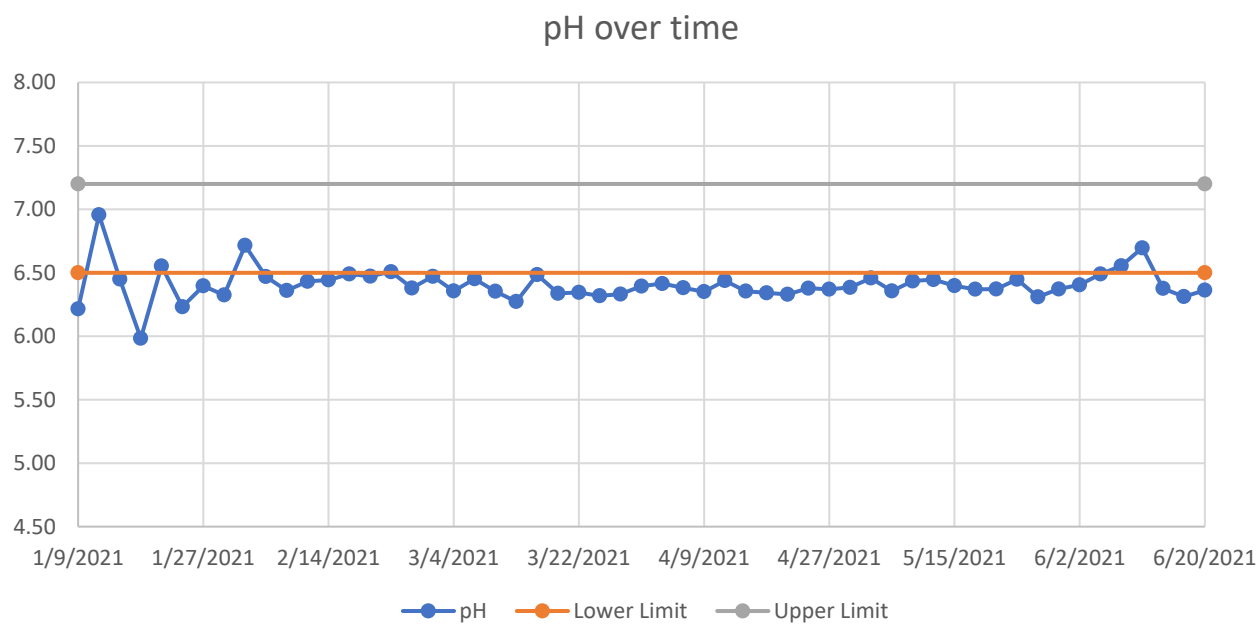


Figure A.2. pH measurements for the second period of misting.

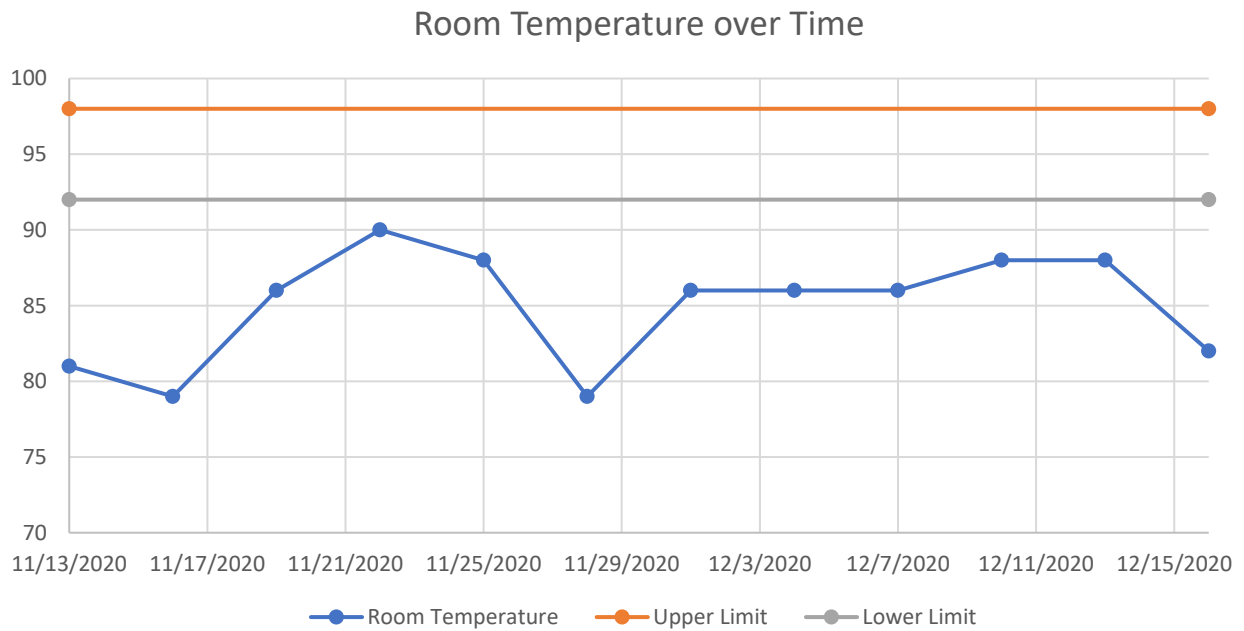


Figure A.3. Temperature measurements for the first period of misting

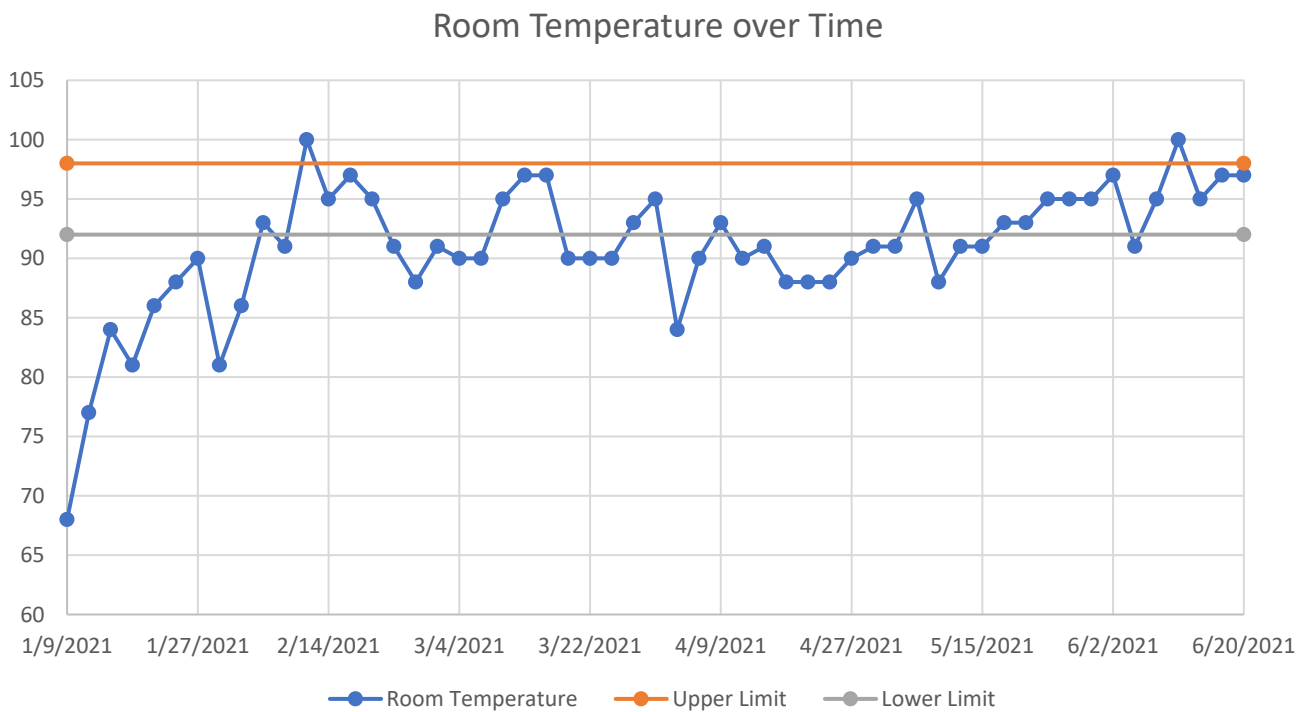


Figure A.4. Temperature measurements for the second period of misting.

APPENDIX B. MATERIALS INFORMATION

Table B.1. Coupon Testing Results

Coupon Testing						
Middle Plates						
Specimen	B1	B2	B3	B4	Average	Range
Test Date	5/14/2021	5/19/2021	5/19/2021	5/19/2021		
Yield Strength (ksi)	52.77	54.68	53.40	56.04	54.22	3.27
Tensile Strength (ksi)	67.31	69.78	70.12	72.34	69.89	5.03
Strain at Break (in/in)	0.2773	0.2656	0.2695	0.2734	0.2715	0.0117
Splice Plates						
Specimen	S1	S2	S3	S4	Average	Range
Test Date	5/21/2021	5/21/2021	5/21/2021	5/21/2021		
Yield Strength (ksi)	56.03	55.75	59.33	56.05	56.79	3.58
Tensile Strength (ksi)	66.85	63.47	66.91	65.60	65.71	3.44
Strain at Break (in/in)	0.2500	0.3000	0.2625	0.2875	0.2750	0.0500

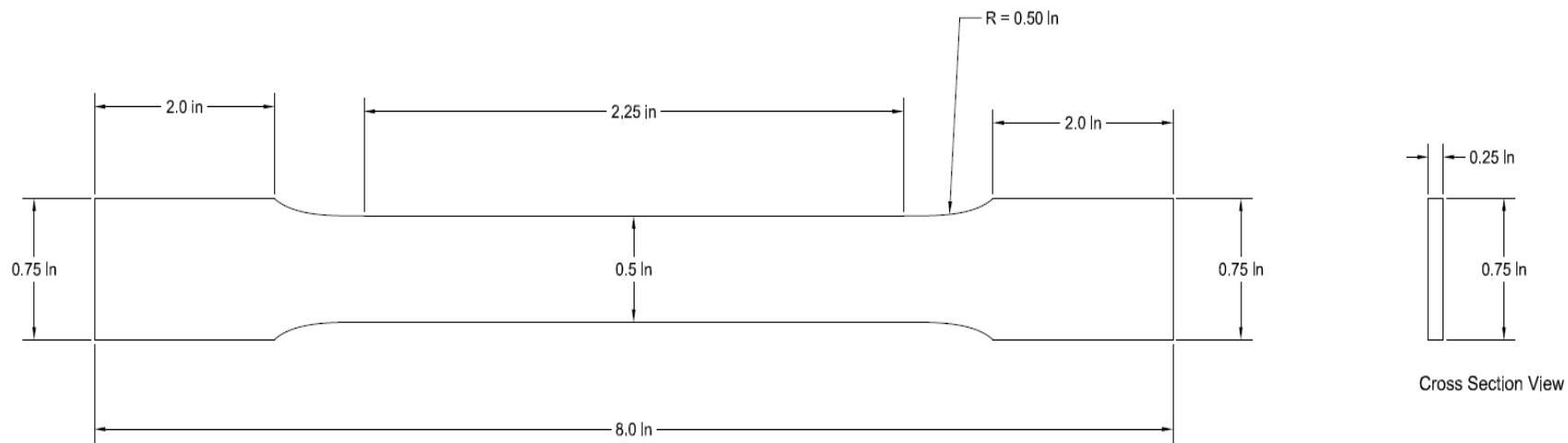


Figure B.1. Coupon geometry for splice plates.

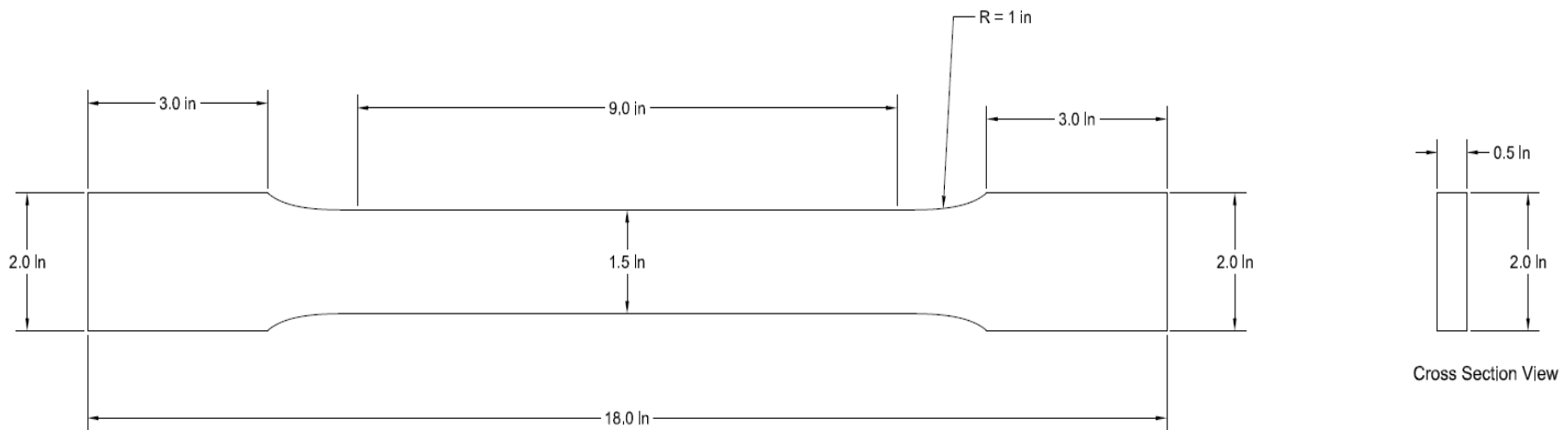


Figure B.2. Coupon geometry for middle plates.

Table B.2. Coating thicknesses

Coating Thicknesses & Plate Thicknesses			
Specimen	Average Coating Thickness (mils)		
	Zinc	Epoxy	Polyurethane
Q-S1-1	3.806	4.498	11.029
Q-S1-2	5.404	4.096	5.630
Q-S1-3	7.163	4.703	4.404
Q-S1-4	3.756	6.279	5.133
Q-S1-5	3.238	7.648	5.372
Q-S1-6	4.645	4.771	6.715
Q-S1-7	4.296	4.493	3.651
Q-S1-8	4.060	4.476	4.989
Q-S1-9	4.024	5.484	5.258
Q-S1-10	5.466	3.484	5.636
Q-B2-11	3.354	5.316	4.796
Q-B2-12	2.653	5.896	5.083
Q-B2-13	3.076	4.791	3.875
Q-B2-14	2.240	6.085	2.458
Q-B2-15	1.984	4.959	3.418
Q-B2-16	2.081	6.315	5.882
Q-B2-17	2.156	9.118	5.419
Q-B2-18	2.015	8.915	5.338
Q-B2-19	2.113	8.563	7.090
Q-B2-20	2.191	8.829	3.995
Q-B2-21	2.056	9.134	6.212
Q-B1-22	1.951	5.994	6.603
Q-B1-23	1.985	7.362	5.276
Q-B1-24	2.001	6.286	6.387
Q-B1-25	2.324	5.133	6.320
Q-B1-26	2.533	5.206	7.361
Q-B1-27	2.503	4.536	8.418
Q-B1-28	2.358	5.279	3.163
Q-B1-29	2.104	5.238	5.699
H-B3-30	2.869	4.052	5.311
H-B3-31	2.441	5.022	4.333
H-B3-32	2.943	5.976	3.283
Q-B4-34	2.888	3.911	4.140
Q-B4-35	2.826	4.256	5.526
Q-B4-36	3.628	3.692	6.157
Average	3.061	5.708	5.410

APPENDIX C. PRODUCT CERTIFICATES


<p>Certificate of Analysis</p> <p style="text-align: center;">Culinox 999</p>	<p>MORTON SALT</p>	 <p>www.makeyourown.buzz</p>																																																									
<p>18-JUN-2019 Manufacturing Site RITTMAN 151 Industrial Ave, Rittman OH, 44270-1593 Jacob DeVries Quality Control 0330/9253015</p>																																																											
<p>Page 1/1</p>																																																											
<p>Manufacturer: Morton Salt, Inc. Morton Order No.: 5101768503 Cust. Order No.: 449748 Delivery /-Item No.: 5204146195 / 000040 Quantity: 98 BAG</p>	<p>Morton Batch No.: RI19164020 Manufact. Date: 13-JUN-2019</p> <p style="padding-top: 20px;">Shipping date: 18-JUN-2019</p>																																																										
<p>General information: This product meets the tolerances for Food Grade Salt as published in the Food Chemical Codex latest edition. It has been manufactured in compliance with all applicable parts of the Good Manufacturing Practice Regulations for foods as set forth in 21 CFR Part 117 and Canadian Food and Drugs Act and Regulations. Product does not contain any of the eleven major food allergens, glutens, or sulfite >10ppm. Product does not contain genetically modified organisms and is not of animal origin. Salt is chemically stable and does not deteriorate over time.</p>																																																											
<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: left;">Parameter</th> <th style="text-align: left;">Result</th> <th style="text-align: left;">Specification</th> </tr> </thead> <tbody> <tr> <td>Sodium Chloride</td> <td>99.99 %</td> <td>>= 99.95 %</td> </tr> <tr> <td>Sulfate</td> <td>0.005 %</td> <td><= 0.030 %</td> </tr> <tr> <td>Calcium & Magnesium as Calcium</td> <td>14 ppm</td> <td><= 60 ppm</td> </tr> <tr> <td>Moisture - Surface</td> <td>0.023 %</td> <td><= 0.100 %</td> </tr> <tr> <td>Insoluble Matter (ppm)</td> <td>46 ppm</td> <td><= 100 ppm</td> </tr> <tr> <td>Iron - Free</td> <td>0.0 ppm</td> <td><= 0.7 ppm</td> </tr> <tr> <td>Copper</td> <td>0.00 ppm</td> <td><= 0.30 ppm</td> </tr> <tr> <td>Arsenic</td> <td><1.0 ppm</td> <td><= 1.0 ppm</td> </tr> <tr> <td>Heavy Metals as Lead</td> <td><2.0 ppm</td> <td><= 2.0 ppm</td> </tr> <tr> <td>Bulk Density (lb/ft³)</td> <td>77.0 lb/ft³</td> <td>65.0 .. 80.0 lb/ft³</td> </tr> <tr> <td>USS #20 (850µm) Retained</td> <td>0 %</td> <td><= 10 %</td> </tr> <tr> <td>USS #30 (600µm) Retained</td> <td>3 %</td> <td>typ. 18 %</td> </tr> <tr> <td>USS #40 (425µm) Retained</td> <td>30 %</td> <td>typ. 42 %</td> </tr> <tr> <td>USS #50 (300µm) Retained</td> <td>42 %</td> <td>typ. 48 %</td> </tr> <tr> <td>USS #70 (212µm) Retained</td> <td>21 %</td> <td>typ. 18 %</td> </tr> <tr> <td>USS #100 (150µm) Retained</td> <td>3 %</td> <td>typ. 3 %</td> </tr> <tr> <td>USS PAN</td> <td>0 %</td> <td>typ. 3 %</td> </tr> <tr> <td>Cumulative Passing USS 70</td> <td>3 %</td> <td><= 25 %</td> </tr> </tbody> </table>			Parameter	Result	Specification	Sodium Chloride	99.99 %	>= 99.95 %	Sulfate	0.005 %	<= 0.030 %	Calcium & Magnesium as Calcium	14 ppm	<= 60 ppm	Moisture - Surface	0.023 %	<= 0.100 %	Insoluble Matter (ppm)	46 ppm	<= 100 ppm	Iron - Free	0.0 ppm	<= 0.7 ppm	Copper	0.00 ppm	<= 0.30 ppm	Arsenic	<1.0 ppm	<= 1.0 ppm	Heavy Metals as Lead	<2.0 ppm	<= 2.0 ppm	Bulk Density (lb/ft ³)	77.0 lb/ft ³	65.0 .. 80.0 lb/ft ³	USS #20 (850µm) Retained	0 %	<= 10 %	USS #30 (600µm) Retained	3 %	typ. 18 %	USS #40 (425µm) Retained	30 %	typ. 42 %	USS #50 (300µm) Retained	42 %	typ. 48 %	USS #70 (212µm) Retained	21 %	typ. 18 %	USS #100 (150µm) Retained	3 %	typ. 3 %	USS PAN	0 %	typ. 3 %	Cumulative Passing USS 70	3 %	<= 25 %
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<p>Electronically released by Jacob DeVries Quality Assurance Technician on 18-JUN-2019</p>																																																											
<p><small>This certificate does not relieve the purchaser from examining the product upon delivery and gives no assurance of suitability of the product for any particular purpose.</small></p>																																																											

Figure C.1. Culinox 999 certificate of analysis.

ArcelorMittal Burns Harbor Plate

QUALITY ASSURANCE REPORT OF TESTS AND ANALYSES

SHIPMENT NO. 804-20376		DATE SHIPPED 00-00-00		CAR OR VEHICLE NO. TRLR		PAGE 1						
ALRO STEEL CORP PO BOX 927 JACKSON MI 49204-0927				ALRO STEEL CORP 5620 CHURCHMAN AVE INDIANAPOLIS IN 46203								
SOLD TO				SHIP TO								
NOTE	SERIAL NUMBER	PAT NO.	HEAT NUMBER	NO. PCS	SIZE AND QUANTITY				YIELD POINT	TENSIL STRENGTH	ELONG.	RED.
					THICKNESS	WIDTH OR DIA.	LENGTH	WEIGHT				
INCHES INCHES INCHES POUNDS PSI PSI IN QUALITY STEEL MELTED & MANUFACTURED IN THE U. S. A. PLATES - ASTM A709-17E1 GR 50 KLD FINE GRAIN PRAC TYPE 2, ASTM A572-15 GR 50 TYPE 2, CH-V A673 FREQ (H) L 15/10 FTLBS AT -20F --- TEST CERTS ARE PREPARED IN ACCORD WITH PROCEDURES OUTLINED IN EN 10204:2004 TYPE 3.1 MFST - REC HRS 11P/4A MFST PPI 0079613- 0001 MFST TEST CERTS ARE PREPARED IN ACCORD WITH PROCEDURES OUTLINED IN EN MFST 10204:2004 TYPE 3.1 - LIFT MAX 18 TON-HTS & SIZES SEP UNLDG OH-PLATE HOOK CO# IN14010813 GH 404-2531 MERCURY IN ANY FORM HAS NOT BEEN USED IN THE PRODUCTION OF THIS ORDER 811E11430 13 1/2 96 240 42471 52400 71100 8 27 54300 72100 8 26 (M55)MFST REF#:07801200												

Q-QUENCH TEMPERATURE T-TEMPERATURE NORMALIZE TEMPERATURE

SERIAL NUMBER	PAT NO.	HEAT NUMBER	HARD BHN	BEND	THICKNESS INCHES	TYPE	SIZE	DIR	CHARPY IMPACT			SHEAR(%)			LAT. EXP MI			
									TEST TEMP F	ENERGY T. LBS.		1	2	3	1	2	3	1
					811E11430	.500	V	FULL	L	-20251	257	277						

Received
Subject to Count and Inspection
MAY 01 2019

Alro Metals/Plastics



RT09500547

HEAT NUMBER	ANALYSIS																MCQUAID GRAIN SIZE
	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Ti	Al	B	Cb	N	Sn	
811E11430	.13	1.22	.009	.004	.303	.022	.02	.03	.006	.059		.038	.0002	.002	.003		

I certify that the above results are a true and correct copy of the actual results contained in records maintained by ArcelorMittal and are in full compliance with the requirements of the specification cited above. This test report cannot be altered and must be transmitted intact with any subsequent third party test reports, if required.

SUPV. QUALITY ASSURANCE ANDREW SMITH ELJ

PM TEST RPT. FPF

Figure C.2. Steel report of tests and analysis.

MILL TEST CERTIFICATE

1700 HOAT RD N.E.
 Tuscaloosa, AL 35404-1000
 800-800-8204
 customerservice@nucor.com

Load Number	Tally	Mill Order Number	PO NO Line NO	Part Number	Certificate Number	Prepared
T168019	00000000755993	N-506179-010	IN13033491 001	07800400	S75599301-1	10/28/2017 10:02
Grade						
Order Description: Hot Roll Plate From Coil 1/4 x 96 x 240 A57250 15ft lbs. @ -20 degrees Quality Plan Description: A57250/IMP-1: ASTM A572-50-15/A709-50/M270-50 H FREQ IMPACTS						
Customer:						
Sold TO: ALRO STEEL CORP Indianapolis IN Ship TO: ALRO METALS SERVICE CENTER CORP. INDIANAPOLIS IN Sent TO:						

Shipped Item	Certified By	Heat/Slab Number	Yield ksi	Tensile ksi	Y/T %	ELONGATION %		Bend OK?	Hard HB	Charpy Impacts (ft-lbs)			Shear %			Test Temp	
						2"	8"			Size in	1	2	3	1	2		3
712303D	S722303FTT	87M6560-04 ***	60.4	71.7	84.2	31.4											
712303D	S7223038LI	87M6560-04 ***								5.0	78	97	75	83.3			-22 F
712303D	S722303FLI	87M6560-04 ***								5.0	77	88	83	82.7			-22 F
712303D	S712303MLI	87M6560-04 ***								5.0	76	74	77	75.7			-22 F
712303D	S722303MTT	87M6560-04 ***	63.0	70.3	89.6	29.1											
712303E	S732303FTT	87M6560-04 ***	60.4	71.7	84.2	31.4											
712303E	S7223038LI	87M6560-04 ***								5.0	78	97	75	83.3			-22 F
712303E	S722303FLI	87M6560-04 ***								5.0	77	88	83	82.7			-22 F
712303E	S712303MLI	87M6560-04 ***								5.0	76	74	77	75.7			-22 F
712303E	S732303MTT	87M6560-04 ***	63.0	70.3	89.6	29.1											
7123068	S732306FTT	A7M4127-01 ***	57.7	68.4	84.4	34.1											
7123068	S7223068LI	A7M4127-01 ***								5.0	76	78	87	80.3			-20 F
7123068	S712306FLI	A7M4127-01 ***								5.0	103	80	85	89.3			-20 F
7123068	S732306MLI	A7M4127-01 ***								5.0	79	96	77	84.0			-20 F
7123068	S732306MTT	A7M4127-01 ***	63.2	70.7	89.4	33.7											

Items: 3 PCS: 27 Weight: 44105 LBS



Mercury has not come in contact with this product during the manufacturing process no manufacturing process. Certified in accordance with EN 10204 3.1. No weld repair has been performed on this product. NUTEMPER TEMPER PASSED plate from coil ISO 9001:2015 Registered, PED Certified

We hereby certify that the product described above passed all of the tests required by the specifications.

Quinn Yu
 Dr. Quinn Yu - Metallurgist

*** indicates Heats melted and Manufactured in the U.S.A.

Figure C.3. Mill test certificate.



Steel Dynamics, Inc.
Flat Roll Group

4500 County Road 59
Butler, IN 46721 USA
Telephone (260) 868-8000
Fax (260) 868-8955

Metallurgical Certification

Cert # 3226015

Ship To	Heidman Steel Proc - T - IN 4400 County Road 59 Butler, IN 46721 United States				Contact Butler RECEIVING P: 260-868-6117			
	Airo Steel Corporation 3100 E. High Street Jackson, MI 49204-0927 United States				Contact Mark Reynolds Purchasing P: 517-788-3343			
Sold To	Length 1,093 ft. / 333 m				Width 48.0000 in. / 1,219 mm			
	Weight 44,210 lbs / 20,053 kg				Gauge 0.2400 in. / 6.10 mm Min			
				Chem Treat		No		
				Oiled		No		

Coil #	198363479	Coil Alias	
Order #	646017	Heat #	41907210
Line Item #	22	PO #	CM13885517 - 22
Part #	07800090		
Material Spec.	ASTM A 1018 HSLAS-F GRADE 50		
Product Desc.	Prime Hot Rolled Band		
Cert Comment			
Surface Treatment			

Ladle Chemical Analysis (%)

C	Mn	P	S	Si	Al	Cu	Ni	Cr	Mo	Sn	N	V	Nb	Ti	B	Ca	Pb	Zr
0.03	0.67	0.006	0.004	0.03	0.032	0.11	0.03	0.05	0.02	0.007	0.008	0.003	0.020	0.001	0.0000	0.002	0.000	0.0009

Mechanical Properties (if applicable)

Tests on Sample	English	Metric
Sample Direction	Transverse	
Tensile Direction	Transverse	
Yield Strength	62.4 KSI	430 MPa
Tensile Strength	66.1 KSI	456 MPa
Percent Elongation	32 %	

Airo Metals/Plastics



RT09617481





Hirosaki Kimura
Hirosaki Kimura
Metallurgist

Shipped from Butler, IN, United States.
Melted, thin slab cast and rolled by proud Americans in Butler, IN, USA.
SDI does not weld or repair Prime Hot Rolled Band products.
All tests were performed according to applicable standards and are correct as contained in the records of the company.

Figure C.4. Metallurgical certification.

APPENDIX D. CAULK TESTING

Table D.1. Caulking products performance over time.

Time of exposure	Caulking Products (Gorilla, Alex Plus, GE)	Comments
0 days		Caulking products are applied at the interface of the plate elements.
7 days		Gorilla and GE are in good shape. Alex Plus shrank a significant amount.
26 days		Gorilla and GE are in good shape. Alex Plus has vanished.
87 days		Gorilla showed some signs of discoloration, and lost adhesion in a corner. GE also lost adhesion in a corner.

APPENDIX E. SAMPLE CALCULATION OF ULTIMATE STRENGTH

Specimen 36 Sample Calculation of Ultimate Strength

Note: To compute these values, the average ultimate strength of the splice plates and the middle plates materials were used.

Properties:	Middle Plates	Splice Plates
	$F_{uaveb} := 69.89 \text{ ksi}$	$F_{uaves} := 65.71 \text{ ksi}$
	$F_{yaveb} := 54.22 \text{ ksi}$	$F_{yaves} := 56.79 \text{ ksi}$
Dimensions:	Middle Plates	Splice Plates
Width:	$w_{b1} := 6.625 \text{ in}$	$w_{s1} := 6.625 \text{ in}$
	$w_{b2} := 6.625 \text{ in}$	$w_{s2} := 6.625 \text{ in}$
Thickness:	$t_{b1} := 0.502 \text{ in}$	$t_{s1} := 0.259 \text{ in}$
	$t_{b2} := 0.501 \text{ in}$	$t_{s2} := 0.259 \text{ in}$
Diameter of bolts:	$d_b := \frac{7}{8} \text{ in}$	

Failure Modes

A) Yielding

$$\text{Middle Plates} \quad P_{b1ave} := F_{yaveb} \cdot (\min(w_{b1}, w_{b2}) \cdot \min(t_{b1}, t_{b2})) = 179.963 \text{ kip}$$

$$\text{Splice Plates} \quad P_{s1ave} := F_{yaves} \cdot (w_{s1} \cdot t_{s1} + w_{s2} \cdot t_{s2}) = 194.889 \text{ kip}$$

$$P_{n1} := \min(P_{b1ave}, P_{s1ave}) = 179.963 \text{ kip}$$

B) Rupture $U := 1$

$$\text{Middle Plates} \quad A_{hole} := 2 \cdot \min(t_{b1}, t_{b2}) \cdot \left(d_b + \frac{1}{16} \text{ in} + \frac{1}{16} \text{ in} \right) = 1.002 \text{ in}^2$$

$$P_{b2ave} := F_{uaveb} \cdot (\min(w_{b1}, w_{b2}) \cdot \min(t_{b1}, t_{b2}) - A_{hole}) \cdot U = 161.944 \text{ kip}$$

Splice Plates $A_{hole} := 2 \cdot (t_{s1} + t_{s2}) \cdot \left(d_b + \frac{1}{16} \text{ in} + \frac{1}{16} \text{ in} \right) = 1.036 \text{ in}^2$

$$P_{s2ave} := F_{uaves} \cdot ((w_{s1} \cdot t_{s1} + w_{s2} \cdot t_{s2}) - A_{hole}) \cdot U = 157.425 \text{ kip}$$

$$P_{n2} := \min(P_{b2ave}, P_{s2ave}) = 157.425 \text{ kip}$$

C) Block Shear

Single line: $U_{bs} := 1$ $L_{pulling} := 5 \text{ in}$ $L_{shear} := 4.5 \text{ in}$

Middle Plates

$$t_1 := \min(t_{b1}, t_{b2}) = 0.501 \text{ in}$$

$$A_{nt} := t_1 \cdot \left(L_{pulling} - 1.5 \cdot \left(d_b + \frac{1}{16} \text{ in} + \frac{1}{16} \text{ in} \right) \right) = 1.754 \text{ in}^2$$

$$c_1 := U_{bs} \cdot F_{uaveb} \cdot A_{nt} = 122.552 \text{ kip}$$

$$A_{nv} := t_1 \cdot \left(L_{shear} - 1.5 \cdot \left(d_b + \frac{1}{16} \text{ in} + \frac{1}{16} \text{ in} \right) \right) = 1.503 \text{ in}^2$$

$$c_2 := 0.6 \cdot F_{uaveb} \cdot A_{nv} = 63.027 \text{ kip}$$

$$A_{gv} := t_1 \cdot L_{shear} = 2.255 \text{ in}^2$$

$$c_3 := 0.6 \cdot F_{yaveb} \cdot A_{gv} = 73.343 \text{ kip}$$

$$R_{b1ave} := c_1 + \min(c_2, c_3) = 185.579 \text{ kip}$$

Splice Plates

$$t_1 := t_{s1} + t_{s2} = 0.518 \text{ in}$$

$$A_{nt} := t_1 \cdot \left(L_{pulling} - 1.5 \cdot \left(d_b + \frac{1}{16} \text{ in} + \frac{1}{16} \text{ in} \right) \right) = 1.813 \text{ in}^2$$

$$c_1 := U_{bs} \cdot F_{uaves} \cdot A_{nt} = 119.132 \text{ kip}$$

$$A_{nv} := t_1 \cdot \left(L_{shear} - 1.5 \cdot \left(d_b + \frac{1}{16} \text{ in} + \frac{1}{16} \text{ in} \right) \right) = 1.554 \text{ in}^2$$

$$c_2 := 0.6 \cdot F_{uaves} \cdot A_{nv} = 61.268 \text{ kip}$$

$$A_{gv} := t_1 \cdot L_{shear} = 2.331 \text{ in}^2$$

$$c_3 := 0.6 \cdot F_{yaves} \cdot A_{gv} = 79.426 \text{ kip}$$

$$R_{slave} := c_1 + \min(c_2, c_3) = 180.4 \text{ kip}$$

$$R_{n1} := \min(R_{slave}, R_{slave}) = 180.4 \text{ kip}$$

Double line: $U_{bs} := 1$ $L_{pulling} := 3.5 \text{ in}$ $L_{shear} := 4.5 \text{ in}$

Middle Plates

$$A_{nt} := t_1 \cdot \left(L_{pulling} - 2 \cdot \left(\frac{d_b + \frac{1}{16} \text{ in} + \frac{1}{16} \text{ in}}{2} \right) \right) = 1.295 \text{ in}^2$$

$$c_1 := U_{bs} \cdot F_{uaveb} \cdot A_{nt} = 90.508 \text{ kip}$$

$$A_{nv} := t_1 \cdot \left(L_{shear} - 1.5 \cdot \left(d_b + \frac{1}{16} \text{ in} + \frac{1}{16} \text{ in} \right) \right) \cdot 2 = 3.108 \text{ in}^2$$

$$c_2 := 0.6 \cdot F_{uaveb} \cdot A_{nv} = 130.331 \text{ kip}$$

$$A_{gv} := t_1 \cdot L_{shear} \cdot 2 = 4.662 \text{ in}^2$$

$$c_3 := 0.6 \cdot F_{yaveb} \cdot A_{gv} = 151.664 \text{ kip}$$

$$R_{b2ave} := c_1 + \min(c_2, c_3) = 220.838 \text{ kip}$$

Splice Plates

$$A_{nt} := t_1 \cdot \left(L_{pulling} - 2 \cdot \left(\frac{d_b + \frac{1}{16} \text{ in} + \frac{1}{16} \text{ in}}{2} \right) \right) = 1.295 \text{ in}^2$$

$$c_1 := U_{bs} \cdot F_{uaves} \cdot A_{nt} = 85.094 \text{ kip}$$

$$A_{nv} := t_1 \cdot \left(L_{shear} - 1.5 \cdot \left(d_b + \frac{1}{16} \text{ in} + \frac{1}{16} \text{ in} \right) \right) \cdot 2 = 3.108 \text{ in}^2$$

$$c_2 := 0.6 \cdot F_{uaves} \cdot A_{nv} = 122.536 \text{ kip}$$

$$A_{gv} := t_1 \cdot L_{shear} \cdot 2 = 4.662 \text{ in}^2$$

$$c_3 := 0.6 F_{yaves} \cdot A_{gv} = 158.853 \text{ kip}$$

$$R_{s2ave} := c_1 + \min(c_2, c_3) = 207.63 \text{ kip}$$

$$R_{n2} := \min(R_{b2ave}, R_{s2ave}) = 207.63 \text{ kip}$$

D) Shear Strength of Bolts

$$F_n := 54 \text{ ksi}$$

$$R_{n3} := F_n \cdot \left(\frac{d_b^2 \cdot \pi}{4} \right) \cdot 4 \cdot 2 = 259.77 \text{ kip}$$

$$R_{n3} = 259.77 \text{ kip}$$

The expected failure mode is fracture.

$$P_{fave} := \min(P_{n1}, P_{n2}, R_{n1}, R_{n2}, R_{n3}) = 157.425 \text{ kip}$$

$$P_{fave} = 157.425 \text{ kip}$$

This is the load at which Specimen 36 is expected to fail (fracture of the net section) based on the average ultimate strength of the steel material.

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