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Pack Rust: Mitigation Strategy Effectiveness

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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. It was found that the proper use of penetrating sealers can be effective in delaying the development of further corrosion, while the use of caulk alone may be problematic as a repair method.</td></tr>
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EXECUTIVE SUMMARY

Introduction

Corrosion is one of most challenging natural phenomena in bridge preservation. Different structural elements in bridges start to show signs of deterioration long before the bridges reach the end of their service life. This damage is caused by environmental conditions and the presence of chemicals, salts, and dirt from natural and human activities. All types of steel and concrete 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 was 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 (Association for Materials Protection and Performance, n.d.). 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). For all bridges, however, approximately 15% are structurally deficient with corrosion being the leading cause of bridge deterioration (Koch et al., 2002).

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 accomplished through the use of coatings systems. In 1997 approximately 5.56 billion liters of organic coating material worth $16.56 billion were used in the United States—for all types of structures—to address general surface corrosion (Roberge, 2008). 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, and deck joints, among others. In this study the effectiveness of different mitigation strategies for pack rust corrosion that occurs between the 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* (Patel & Bowman, 2018), some objectives have been set for the present study. Most of the bridges in Indiana built between 1950 and 1960 are nearing the end of their service life and many are in need of repair. Approximately one third of the steel bridges in Indiana were found to exhibit some degree of pack rust corrosion (Patel & Bowman, 2018). 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. Consequently, the current study evaluates different methodologies and commercial products to mitigate the effects of crevice corrosion in splice connections.

Findings

Accelerated corrosion tests were conducted to evaluate the effectiveness of commercial products used to halt or slow the progression of pack rust. The specimens were subjected to a salt solution misting environment to develop corrosion in the gap region of a splice connection. The commercial products included one caulk sealer (GE Advanced Silicone Sealant) and two different penetrating sealers (Fluid Film and Termarust).

General Observations and Conclusions

- For the set of conditions developed in this experiment and the amount of pack rust corrosion produced, there is no evidence that the ultimate strength of the connections was affected for any of the different conditions studied. The connections were not affected 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.
- The 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 removing the 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 3 months of exposure followed by a lower apparent corrosion rate thereafter. It is uncertain if this is the result of the lower (more acidic) pH level during the initial phase of the testing or if this is a characteristic of crevice corrosion.
- Bulging of the splice plates, caused by the formation of corrosion product, was slightly visible towards the beginning of the ninth month of exposure. The maximum bulging observed was 0.081 inch, which did not affect the structural performance of the connection.
- The 1/2-inch 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 opening of 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 because of the severity of black rust.

Conclusions from the Mitigating Products' Performance

- All mitigating products effectively delayed significant pack rust formation in the initial condition test. First, the Fluid Film formed a wax upon application that worked as a sacrificial layer. From visual 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 good resistance throughout the initial 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 when the caulk is replaced, and resealing occurs.
  - Termarust also showed promising results and its use is recommended. The only difficulty encountered when using 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, but it was not available when the mitigation repair was conducted. Therefore, if the viscosity problem is solved, its application is recommended.

- As a repair method, the mitigation strategies exhibited only fair performance.
  - First, Fluid Film's performance was similar to the one shown as initial condition. However, the physical characteristics of the "sacrificed" wax changed somewhat in texture and color. This can be an indicator of a chemical reaction taking place due to the already existing rust remaining after pressure washing.
  - 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 removal of all corrosion product from a connection in the field is very difficult and encapsulating corrosive material within the gap promotes the rapid formation of black rust caused by the lack of oxygen.
  - Finally, Termarust performed slightly better than the other two strategies. The specimens repaired with this method also faced problems with the viscosity of the Termarust topcoat and its curing. Significant corrosion was found in all repaired specimens, but since Termarust demonstrated a slightly better performance, its application in the field is recommended as a mitigation strategy.
- Even though the application of these mitigating products was performed on the geometry of a flange splice connection, implementation of these products can be extended to other members with overlapping elements that are at risk for pack rust. It is important to ensure that space or air is not being encapsulated and trapped within the member.

Implementation

- For new bridges, the use of a stripe coat is recommended to prolong the service life of splice plate details and improve their resistance to the formation of pack rust. Although all of the strategies (GE caulk, Fluid Film, and Termarust) studied in this experimental research were found to be effective in delaying significant pack rust formation from the initial condition, they are not recommended for new bridges since the life of the treatment strategy is less than the service life typically required for the initial formation of pack rust. An application procedure for stripe coating in new bridges is attached in the appendix section.
- For existing bridges, the application of a penetrating sealer (Termarust or Fluid Film) is recommended to mitigate pack rust. Procedures for pack rust removal and the application of the mitigating repair treatments are attached in the appendix section.

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1. INTRODUCTION

1.1 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. Splice connections are commonly used in steel bridges in Indiana, and they are known to be susceptible to the formation of pack rust in the splice gap after many years of service. 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 B117-19 standard *Standard Practice for Operating Salt Spray (Fog) Apparatus* (ASTM International, 2019). 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* (AASHTO, 2020), and the INDOT standards for structural painting (Sections 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 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 load levels of interest were studied—the load at initial slippage and the ultimate load. This information is useful to evaluate the behavior during service and to assess the strength loss as related to pack rust observed through visual inspection.

Finally, the last task of this project consists of providing a set of detailed guidelines and recommendations for the application of penetrating sealers/caulks in accordance with the procedures of the experiment and the lab results. The implementation of these guidelines in the field are expected to significantly 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) (Davis, 2000).

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 (Davis, 2000). 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 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*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 (Davis, 2000). 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 (Davis, 2000).

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 (Davis, 2000).

2.1.3 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 (Roberge, 2008). First, corrosion attacks that can be recognized by visual inspection are uniform, localized, and galvanic corrosion. Second, attacks that can by 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.

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 inch (or greater) bulging of the plates (Patel & Bowman, 2018). 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 (Roberge, 2008). 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 either the prevention or reduction in growth rate of further pack rust development and, thereby, the prevention or slowing 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 for 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 (Patel & Bowman, 2018). 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 $E_{out} - E_{pass}$ (Patel & Bowman, 2018). 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. Furthermore, other academic sources in combination have been able to explain the development of pack rust in three stages. Figures 2.1, 2.2, and 2.3 illustrate the three stages, and it should be noted that in these figures the crevice, or opening, would be the gap region on both sides of the splice connection.

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 (Roberge, 2008).
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 (Davis, 2000). Thus, since the metal is releasing electrons and

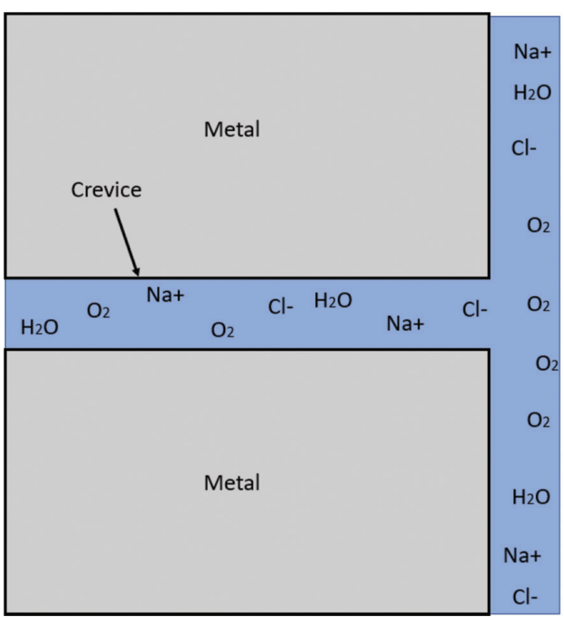


Figure 2.1 First stage of crevice corrosion.

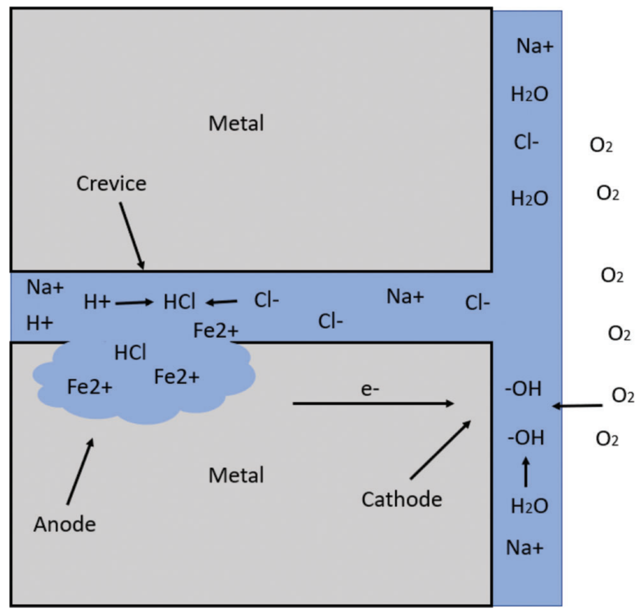


Figure 2.2 Second stage of crevice corrosion.

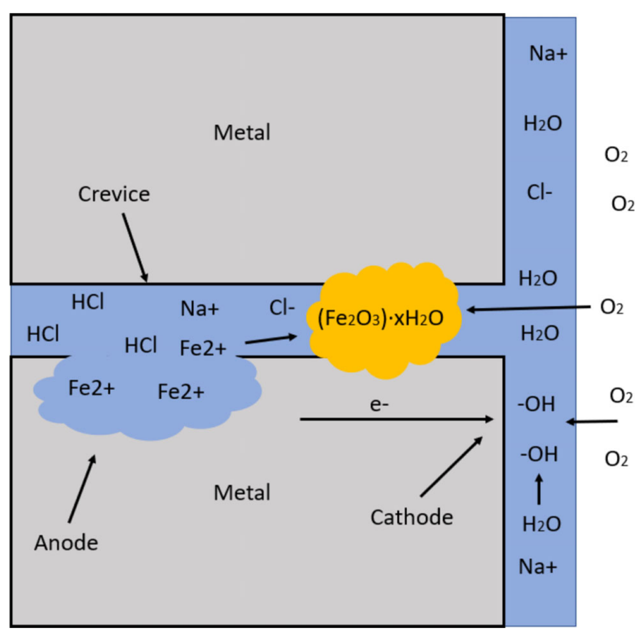


Figure 2.3 Third stage of crevice corrosion.

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).
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.

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 crevice 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 (Roberge, 2008).

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. If the pressures are extreme enough, it can lead to fracture of rivets or bolts, which will result in a loss in capacity of the connection. Moreover, on compressive members, pack rust is capable of introducing eccentricities and deforming built-up members, which can cause local buckling (Kulicki, 1990).

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 threating situations that can be encountered in the field (Roberge, 2008). 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 (Roberge, 2008).

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 2,500 psi and 2,960 psi pressure is required to produce a splice deformation of 1 in for connections with 7/8-inch and 1-inch 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 1 inch (Patel & Bowman, 2018).

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 steel bridges in Indiana have been observed to have pack rust that has developed to some degree. A small percentage of them (3%) have been found to cause extreme bulging such that some of the welds and bolts have fractured (Patel & Bowman, 2018).

2.3 Bolted Flange Splice Connections

The *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2020) 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 (Grubb et al., 2021). The design of bolted connections and bolted splices are covered in AASHTO LRFD 6.13.2 and 6.13.6, respectively. Some of these details and 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 (AASHTO, 2020).

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 (Grubb et al., 2021). 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 (AASHTO, 2020).

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 (AASHTO, 2020). 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 (Davis, 2000). 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 (Davis, 2000).

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°F–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 (Davis, 2000).

3. LITERATURE REVIEW

3.1 Strategies Implemented by Other DOTs

The Departments of Transportation across the U.S are using various mitigation strategies 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) (Patel & Bowman, 2018). 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 for 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 Preventative / Mitigation Approaches Used by Other DOTs.

Over time four main preventative/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 in 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 2018, caulking is one of the methods utilized by INDOT to deal with pack rust (Patel & Bowman, 2018).

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: (1) neutralize the acidic environment inside the crevice, and (2) 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, Delaware and Missouri require 100% solid rust sealers and calcium sulfonate rust sealers, respectively (Patel & Bowman, 2018).

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. As such, the use of a stripe coating is intended to prevent the formation of pack rust. 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 in the coating (Machen, 2017). 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 (Patel & Bowman, 2018).

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 (Patel & Bowman, 2018).

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* (NYSDOT, 2013). 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. Item 564.2101 0011 specifies the use of the following materials.

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-inch 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*

(NYSDOT, 2012) This item was implemented in a proposed bridge maintenance project for 10 bridges in Orange and Westchester Counties in New York (NYSDOT, 2019). 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, descalers, 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* (NYSDOT, 2013). 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 (MnDOT, 2019). 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, and so on, are stripe coated (MnDOT, 2019). The application of epoxy penetrating sealer is based upon judgement of the engineer (Sondag & Burgess, 2018).

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 (Sondag & Burgess, 2018).

3.1.2.3 Illinois's cleaning and painting procedure for existing steel structures. The treatment of general corrosion for Illinois is specified in the *Guide Bridge Special Provisions* (IDOT, 2022). 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 (IDOT, 2022).

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 1,000 psi and a maximum pressure of 5,000 psi using potable water along with other requirements of SSPC-SP WJ-4 *Light Cleaning* (SSPC, 2017). 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 (IDOT, 2022).

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 (IDOT, 2022).

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 Illinois establishes two requirements for the epoxy penetrating sealers that are used in repair projects: (1) sealers must be clear in texture and (2) sealers must 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.

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 *Structures of their Engineering Standard Specifications* under Chapter 8, Section 811, "Painting and Protective Coatings" (LADOTD, 2018). 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 5,000 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 (LADOTD, 2018).

Recoating consists of the application of different protective products, that combined, contribute to mitigating corrosion over the affected area. First, a full

TABLE 3.1
Painting systems for existing steel structures in Illinois (IDOT, 2022)

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

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 cervices 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 unpigmented 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 (LADOTD, 2018).

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 1/2-inch width (LADOTD, 2018).

3.1.2.5 Bach steel pack rust removal technique. Bach Ornamental and Structural Steel Inc. is a contractor in the Michigan that rehabilitates wrought iron and steel structures that have deteriorated or 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 qualified contractor in several midwestern states. They have performed riveting and rehabilitation work on historical bridges. They have also executed projects in a number of western states (Bach Steel, 2021).

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 (N. Holth, personal communication, May 4, 2020). 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 inch. 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-inch-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 inch 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 (N. Holth, personal communication, May 4, 2020).

As previously mentioned, Bach Steel has worked on restoration of bridges in Indiana such as the Shelby

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 (5,000 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 (5,000 psi min), solvent cleaning	Yes, unpigmented 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

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 (Bach Steel, 2021).

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: Cleaning and Coating Existing Structural Steel* of the Standard Specification. A sealant from the MDOT Qualifying Product List was used to caulk the gaps of the repaired areas and prevent moisture penetration (N. Holth, personal communication, May 4, 2020).

Additional details were provided by Bach Steel through an email interview (N. Holth, personal communication, May 4, 2020). 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 inch, 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."

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 since a previous study by (Patel & Bowman, 2018) found that pack rust occurred frequently in such connections.

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 (Fluid Film, n.d.).

Fluid Film can be applied using a brush, roller, or airless paint sprayer. For airless sprayers, a pressure of 2,000 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 Table 3.3.

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 (Fluid Film, n.d.).

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 many years (Fluid Film, n.d.).

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-polmerized 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 (see Tables 3.4 and 3.5 for more information). Opposite to Fluid Film, Termarust has years of history in the bridge

TABLE 3.3
Properties of Fluid Film

Appearance	**Clear**
Viscosity	16,800–21,600 cps
Flashing point	405°F minimum
VOC	Less than 25% for aerosol; less than 1% for non-aerosol/bulk
Specific conductivity	9 ohm/cm at 1 mHz
Specific gravity	0.875–8.885
Effect on paint	No effect
Re-paintability	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

TABLE 3.4
Properties of TR 2200HS HRCSA penetrant sealer (Termarust Technologies, 2021)

Appearance	**Amber**
% Total solids	100%
Flashing point	248°F
VOC	0%
Specific gravity	1.0305 ± 0.03

TABLE 3.5
Properties of TR 2100 HRCSA topcoat (Termarust Technologies, n.d.a)

Appearance	**Varies Depending on Client's Requests**
Odor	Normal for the materials permitted (ASTM D1296)
% Total solids	59.5%–67.5%
Flashing point	108°F
VOC	2.0–2.42 pounds per gallon
Specific gravity	1.05–1.19
Effect on paint	No effect
ASTM B117 salt spray testing	Passes 4,00–5,000 hours (208 days)

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 (Termarust Technologies, n.d.a).

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 (Termarust Technologies, 2011). 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 5,000 psi and a 6-inch standoff distance and applying the HRCSA coating system. Termarust presented a report of this bridge, 5 1/2 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 (Termarust Technologies, 2011).

Before application of the products, a surface preparation is required (Termarust Technologies, n.d.b.). First, the pack rust is removed by pressure washing the rust material at a minimum of 40,000 cleaning units with a zero-degree rotating tip. Cleaning units is equivalent to multiplying the flow rate (GPM) times the pressure (psi). In accordance with Termarust, 7,000 psi pressure washing is the most effective to remove pack rust, dirt and contaminants. Nonetheless, pressure washing can be performed at a minimum of 5,000 psi with cold water (as in the Pennsylvania Turnpike Bridge) or at 4,000 psi with hot water (140°F) at a standoff distance of 4 inches (W. Senick, personal communication, 1 May, 2020). 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 (W. Senick, personal communication, 1 May, 2020). (Termarust Technologies).

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 high-volume, low pressure (HVLP), low-volume, low pressure (LVLP), conventional or airless spray over the use of a brush (Termarust Technologies, n.d.c). 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 (Termarust Technologies, n.d.b). More information regarding the surface preparation and application can be found in their painting specifications and technical data (Termarust Technologies, n.d.b.).

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 (General Electric, n.d.).

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 1 to 2 hours prior to the application of the caulking product. Backer rods are recommended when gaps are larger than 1/2 inch in width or 1/2 inch by 1/2 inch in area. Since moisture and ambient temperature affect the curing rate, it is recommended to apply this sealant at a temperature above 32°F (General Electric, n.d.). Table 3.6 presents the properties of the GE Advanced Silicone sealant.

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 (Wall & Ceiling Conference, 2016). Therefore, based on this review, some new caulking material requirements should be incorporated

TABLE 3.6
Properties of GE Advanced Silicone 2 sealant

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

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[1]		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		
Gorilla 100% Silicone Sealant–Clear[1]		Do not apply on metals sensitive to corrosion including brass and galvanized metals
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[1]		
DAP 3.0 High Performance Gutter and Flashing Sealant	Advanced hybrid polymer	

[1]This product has been tested in this research.

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 (Chemical Concepts Blog, 2018). These acids can contribute to corrosion of metal substrates. Silicone caulks can be one of the following 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.

Table 3.7 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.

Additionally, Table 3.8 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

Characteristics/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 +-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 the following different conditions: (1) control (no exposure to salt misting) (2) base specimens, which are exposed for a determined period of time (3) initially treated specimens, which are protected with the mitigating products since the beginning (4) 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 Setup 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 B117-19. The room was isolated with 2-in isolation foam sheets on the exterior wall and any opening that could lead to heat loss (see Figure 4.1). At the beginning, two 5,100 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 (see Figure 4.2).

4.1.1 Lexan Boxes

Three Lexan boxes were used to store the steel specimens during the accelerated corrosion test (see Figure 4.3). 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 1/2-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, as shown in Figure 4.4.

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 (A&C Plastics, Inc., n.d.). 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.

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 (Patel & Bowman, 2018). The dimensions of

Figure 4.1 Initial setup of the testing room.

Figure 4.2 Modified setup of the testing room.

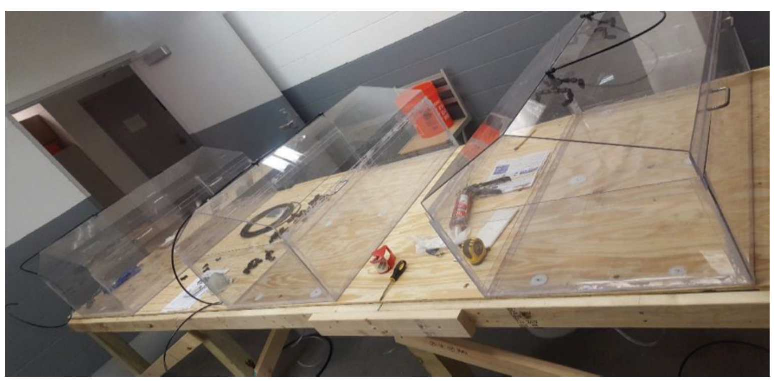


Figure 4.3 Lexan boxes.

the connected plates are 6.5 inches wide by 18 inches long by 1/2 inch thick, while the dimensions of the connecting plates are 6.5 inches wide by 12.25 inches long by 1/4 inch thick. Other components such as bolts, holes, nuts, and washers meet the geometric requirements per AASHTO LRFD Section 6.13.2.3 (AASHTO, 2020). The bolts were sized such that the plates failed before the bolts. The size of the bolts was determined to be 7/8 inches which is greater than the 5/8-inch minimum diameter required by the standards. Two different types of specimens were fabricated: (1) specimens with a 1/4-inch gap between the connected plates and (1) specimens with 1/2-inch gap between connected plates. The project focuses more on the 1/4-inch gap specimens (32 units fabricated) since this is the gap size most commonly used by INDOT. The other 1/2-inch gap specimens (three units fabricated) are used to study the gap size as a parameter and compare with the other specimens.

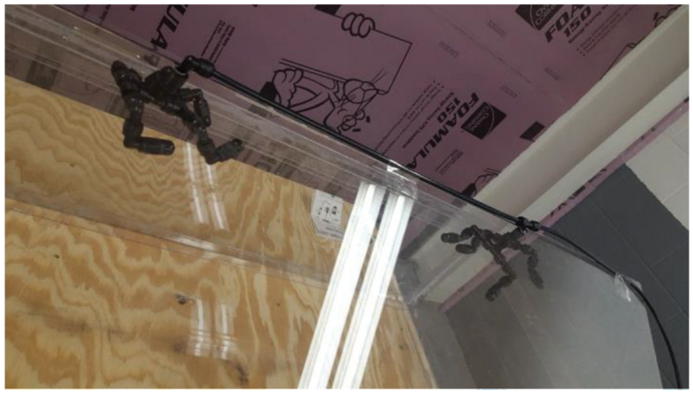


Figure 4.4 Roof of Lexan boxes holding the atomizers.

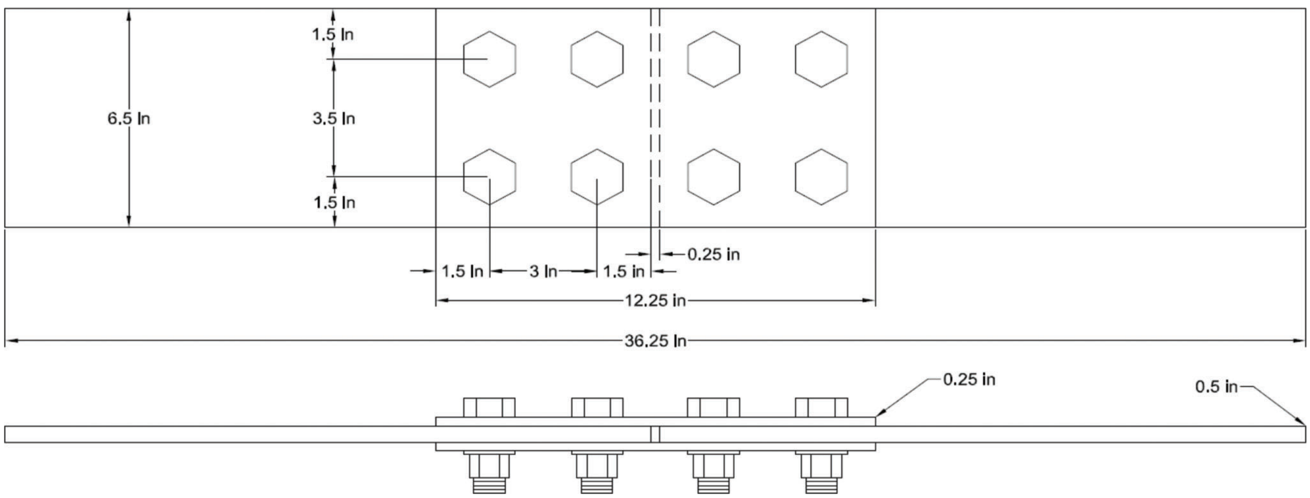


Figure 4.5 Dimensions of the 1/4-inch gap splice connection specimen.

The geometric detailing is shown in Figure 4.5 and Figure 4.6. The diameter of standard holes was determined to be 15/16 inch since 7/8-inch bolts were used in this project. The center-to-center distance between bolts is 3 inches for both the 1/4-inch and the 1/2-inch gap specimens. Finally, the minimum edge distance was 1.5 inches and 1.375 inches, respectively, for the 1/4-inch and the 1/2-inch gap specimens. Both types of specimens met the minimum distance requirements per the standards (AASHTO, 2020). A cross sectional and profile view is shown for the middle plates in Figure 4.7 and the splice plates in Figure 4.8.

Bolts, nuts and washers meet the requirements and recommendations of ASTM F3125/3125M, A563, and F436/F436M, respectively (ASTM International, 2022a,b,c). The following elements were used in the specimens.

1. 7/8 inch by 2.25-inch ASTM 3125 GradeA325 plain finish steel structural bolts.
2. 7/8-inch ASTM A194 2-H plain finish heavy hex nuts.
3. 7/8-inch ASTM F436 Type 1 plain steel structural flat washers.

A specimen was assembled in the shop to check for fit-up and assembly as shown in Figure 4.9. Note that no coatings were applied for this simple fit-up specimen. For the actual specimens a primer coat was applied to the plates prior to assembly.

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 a 1/8 inch. 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 (ASTM International, 2021b).

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

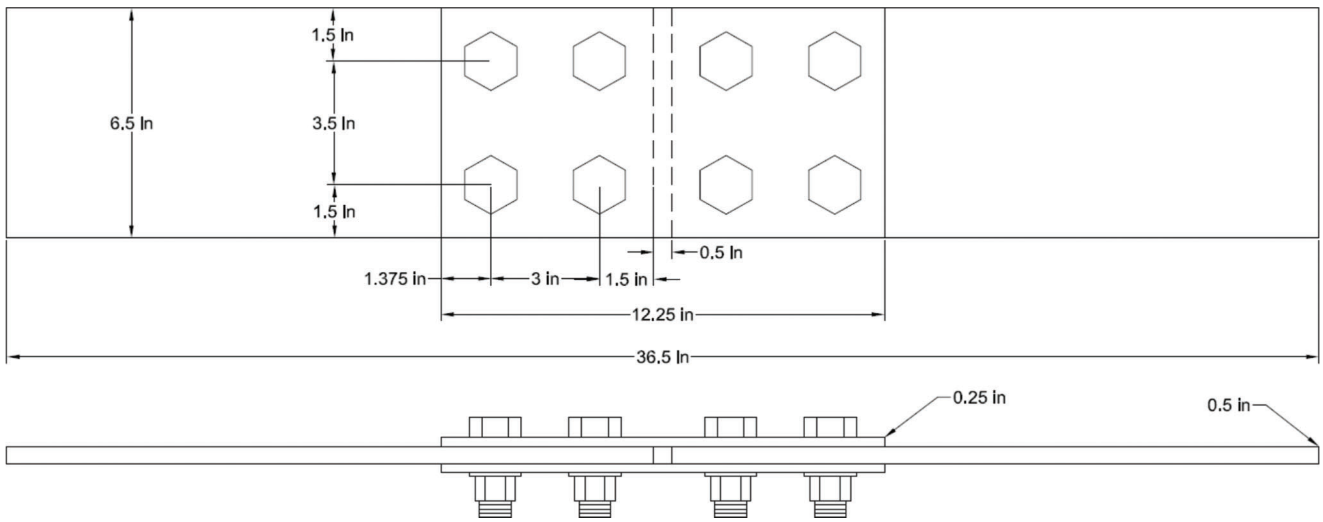


Figure 4.6 Dimensions of the 1/2-inch gap splice connection specimen.

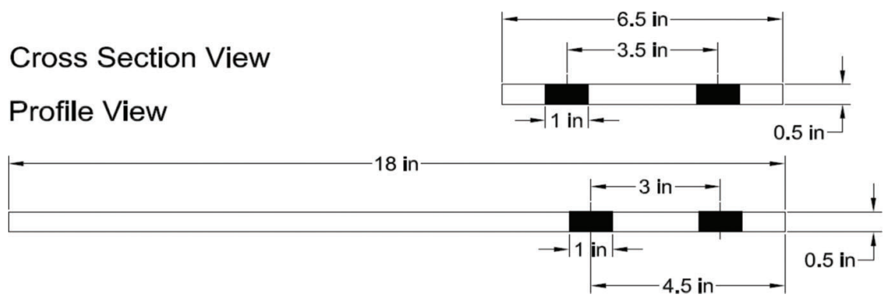


Figure 4.7 Typical cross section and profile of middle plates.

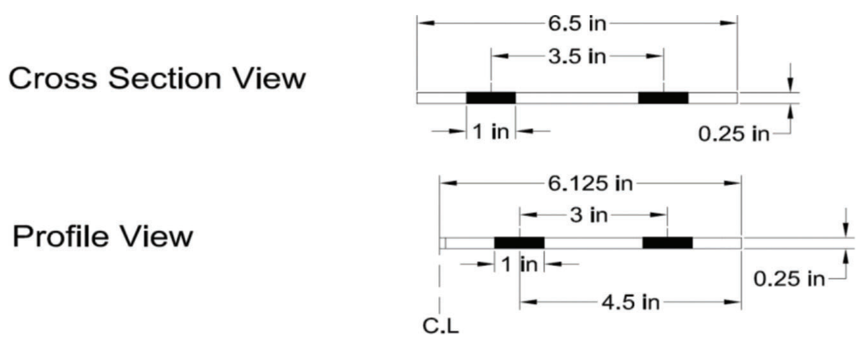


Figure 4.8 Typical cross section and profile of splice plates.

and tensile strength of the middle and splice plates are used to compute the average expected strength of the connection specimens.

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 (Inspection 4 Industry LLC, n.d.). 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 3,800 psi. They were placed in a vertical position to let the water run downwards and avoid puddles of water. Figure 4.10 shows a number of middle plates and splice plates being pressure washed. The pressure wand was at a distance of 6–12 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.

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-inch by 2.25-inch ASTM 3125 GradeA325 Plain Finish Steel Structural Bolts, and 7/8-inch 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 1/3 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 (Research Council on Structural Connections, 2014).

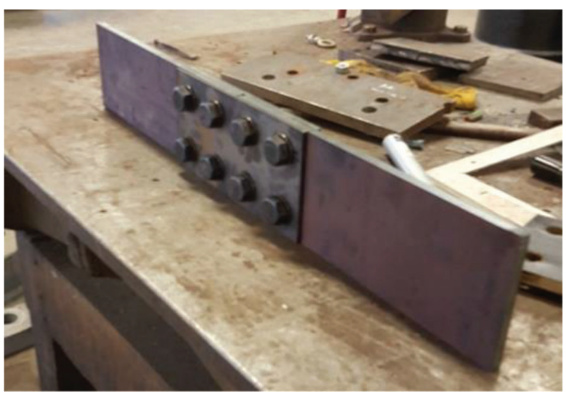


Figure 4.9 Uncoated specimen.

4.2.4 Painting of the Steel Specimens (INDOT Three-Coat System)

The INDOT three-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 with the *INDOT Standards Division 900–Material Details* ("Section 909–Paint and Liquid Epoxy") (INDOT, 2019b). 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. "Section 619–Steel Bridge Painting" in *Division 600–Incidental Construction* under the explains the different procedures that should be followed and under what set of standards (INDOT, 2019a). In this project, two of these procedures were performed—(1) solvent cleaning the steel plates (SSPC-SP 1) and (2) 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 three-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 topcoats 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 4.10 Plate's dirt removal with a 3,800-psi pressure washer.

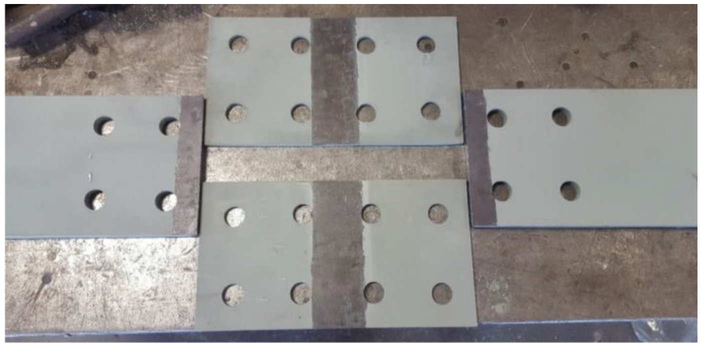


Figure 4.11 Portion of the specimen being isolated for accelerated corrosion.

Figure 4.12 Application of epoxy layer.

Figure 4.13 Application of polyurethane layer.

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, 3 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, 4 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 1 day before measuring the dry film thickness A photograph of the specimens with the epoxy intermediate coat after application is shown in Figure 4.12.
4. Finally, approximately 3 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. A photograph of the specimens with the polyurethane topcoat layer after application is shown in Figure 4.13.

Figure 4.14 shows the final product after the application of the coating system. Moreover, the area

Figure 4.14 Final coated specimen.

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

outside the gap was only painted with zinc primer as shown in Figure 4.15. Removal of the tape, which was in place after specimen assembly to prevent any of the epoxy or polyurethane applications from coating the inside of the gap, resulted in some stripping off of the initial zinc primer coating. This region was touched up so that it only contained zinc primer. Table B.2 shows the coating thickness information for each one of the specimens.

4.3 Salt Spray Test for Accelerated Corrosion (ASTM B117-19)

This section describes the procedure used to simulate the atmospheric conditions in the field that induce corrosion. In accordance with 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 B117-19 *Standard Practice for Operating Salt Spray (Fog) Apparatus* (ASTM International, 2019). 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 (ASTM International, 2018). 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 (ASTM International, 2018). 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 3 days with a SX823-B Portable Multiparameter meter from Apera Instruments (see Figure 4.16). 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

Figure 4.16 SX823-B portable multiparameter meter.

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) (Davis, 2000). 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 (Davis, 2000). 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 (Roberge, 2008).

4.3.2 Conditions of the Testing Room

ASTM B117-19 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-inch-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 3 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 (Moran Yanez, 2016). 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 3 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 9 days. The amount of solution prepared every 9 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 3 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: (1) August 12, 2020, to December 16, 2020, (127 days) and (2) January 9, 2021, to June 21, 2021, (164 days). The misting of the specimens was halted during a shutdown of the laboratory for 3 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 region 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 (Patel & Bowman, 2018). The specimens were exposed to misting for 111 days, and then repaired with the mitigating products. Before applying the mitigating products, the surface immediately outside the gap region was cleaned up with wire brushing to remove surface corrosion and a layer of Rust-Oleum was applied to the area near the crevice's mouth. Rust-Oleum was selected for recoating the outside surface since no more Zinc primer was available. It was believed that this product substitution was not critical since the corrosion inside the gap region was the testing promoting the pack rust, and not the surface corrosion outside the gap. 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 1/4-inch bulging of the plates is observed (Patel & Bowman, 2018). These specimens were repaired in the same manner as Condition A specimens. All specimens regardless of their assigned condition were flipped after 3 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 1/4-inch 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 1/4-inch 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 ways.

1. First letter = Q (1/4-inch gap) or H (1/2-inch gap).
2. Second letter = S (primer applied with spray) B (primer applied with brush).
3. First number = day of work on which primer was applied.
4. Second number = number of the specimen.

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

1. Control = initial condition with no exposure and corrosion deterioration.
2. Initial = initially treated specimen was exposed for 172 days.
3. Condition A = time of exposure was 111 days.
4. Condition B = time of exposure was 175 days (for Base B, 172 days).
5. 10 M = time of exposure was 284 days (approximately 10 months) with no repair.

Three extra 1/2-inch gap specimens were fabricated to monitor and compare the corrosion development with the 1/4-inch 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.

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 (Patel & Bowman, 2018). Condition A tries to replicate rating 4 of pack rust in which excessive rust bleeding can be observed. Ratings 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 1/4 inch. Rating 3

TABLE 4.1
Distribution of the 1/4-inch 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
	10 M	2

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 (in.) 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	10 M	8/12/2020	6/14/2021	284	0.081
Q-B2-19	1	2	10 M	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

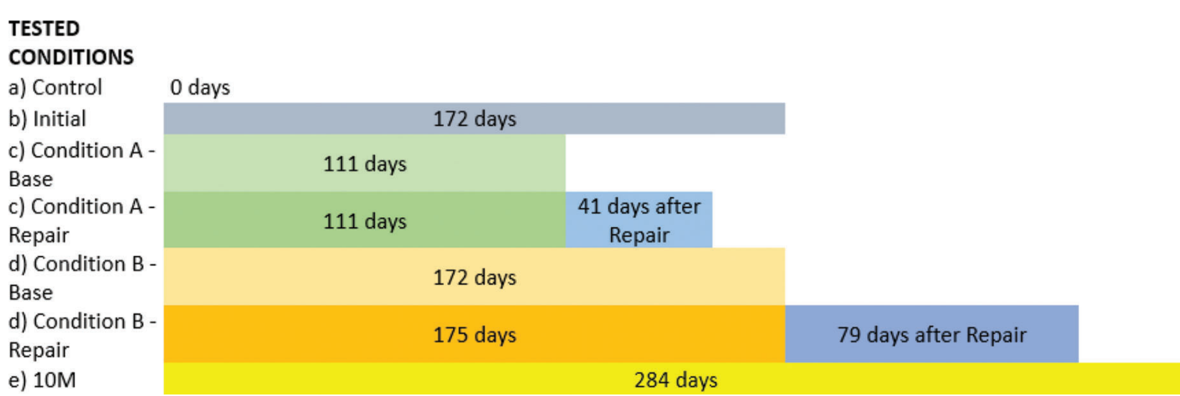


Figure 4.17 Conditions tested.

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 5,000 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 (see Figures 4.18 and 4.19). 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 water and Chlor*Rid 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.

1. *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-inch-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. Application of the product in girders in the field are discussed in Appendix F.
2. *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). The 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

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.

Figure 4.20 Fluid Film application for initial and repair condition.

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. See Figure 4.21. The application of the product in girders in the field is discussed in Appendix F.

3. *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 1/4 inch. Figure 4.22 illustrates the specimen surface after application of the GE Silicone caulk in the flange gap region.

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.

The application of all mitigation products extended approximately 1.5–2 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 sideway 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 3 days in a warm environment. However, 3 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. It should be noted that Termarust Technologies recommends the use of TRT01 thinner. However, the thinner was not available when the mitigation repair was implemented, and it is likely that the topcoat thickness was excessive. 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 Table 4.3. The recommended dry film thickness for Fluid Film application is 5 mils (Fluid Film, n.d.). 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 (Termarust Technologies, 2011).

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 understand any reductions in structural capacity. 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

Figure 4.21 Termarust application for initial and repair condition.

Figure 4.22 Caulk application for initial and repair conditions.

TABLE 4.3
Thicknesses of Fluid Film and Termarust products

Thicknesses of Applied Products (mils)							
			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

Figure 4.23 MTS machine used for strength testing.

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 (see Figure 4.23). 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: (1) load at slippage and (2) 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.

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 (ASTM International, 2021a). 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 inches and 8 inches, 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 with 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: (1) the formation of surface corrosion around the mouth of the gap and (2) 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 to 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 inches 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.

5.1.1 Control and Base Specimens

5.1.1.1 Analysis of base specimens. A steady formation of rust bleeding was observed at the interface of the plates during the first 3 months. As the specimens approached 1 month of misting, the formation of small corrosion "bumps" was visible. These bumps increased in size and number rapidly. After 7 weeks (1.75 months approximately), the visibility through the gap of the specimens was compromised. At 3 months, significant deformation of the mouth was observed on both ends

TABLE 5.1
Bulging measurements of the Condition B and 10 M specimens

		Bulging of the Specimens			
		Time of Exposure			
Specimen	**Assigned Condition**	**146 Days Bulging (in)**	**172 Days Bulging (in)**	**257 Days Bulging (in)**	**290 Days 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	10 M	0.0575	0.0575	0.0731	0.0809
Q-B2-19	10 M	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

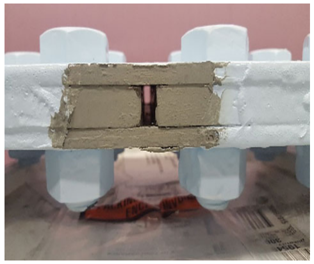
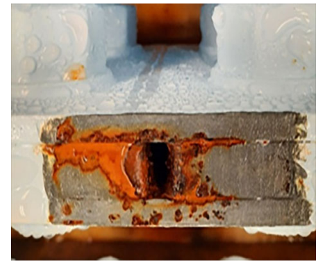
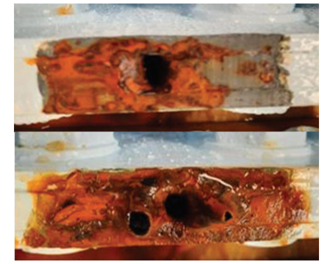
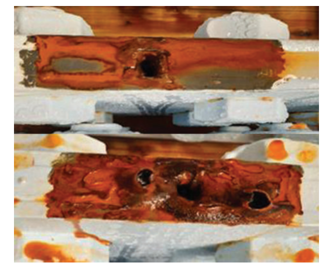
of the gap. The shape of the mouth was deformed from a rectangular shape to an irregular shape. After 3 months, all specimens were flipped on the side. The bottom end of the gap showed more aggravated surface corrosion and deformation of the mouth compared to the top end of the gap. This can be attributed 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 visible corrosion indicators 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 inches and 0.0752 inches were measured, respectively). Specimen 23 exhibited a higher measured value of bowing (0.0823 inches), 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 inches.

Table 5.2 shows the development of corrosion on the base and 10 M 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 ($FeO(OH)H2O$) is the orange/yellow type of rust and it is produced as a result of high moisture content (Antunes et al., 2014; Armor Protective Packaging, 2019). On the other hand, iron (II) oxide ($Fe3O4$) is a black colored corrosion product, also known as magnetite, and it is produced due to an environment with limited oxygen (Chico et al., 2015; Roberge, 2008). 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.

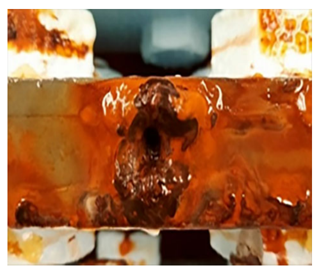
Specimens that reached Condition B (7, 8, 9, 10) showed a similar pattern in the rust formation along the cross section when compared to Condition A (5, 6). These six specimens were placed in the chambers during

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				
10 M: 18, 19. Specimen 19 shown in the 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.

(Continued)

TABLE 5.2
(*Continued*)

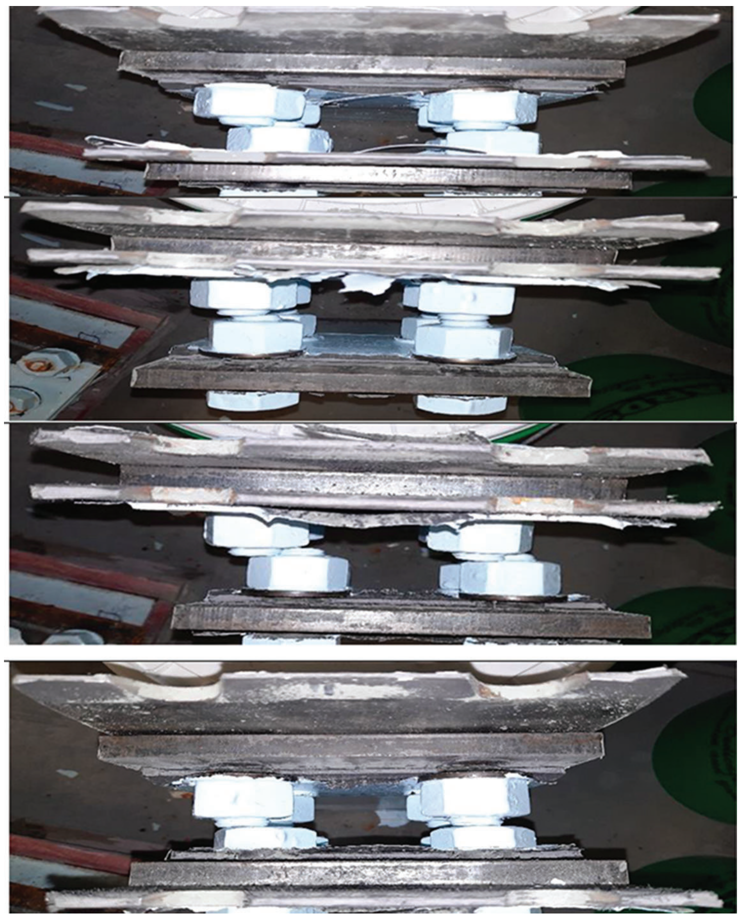
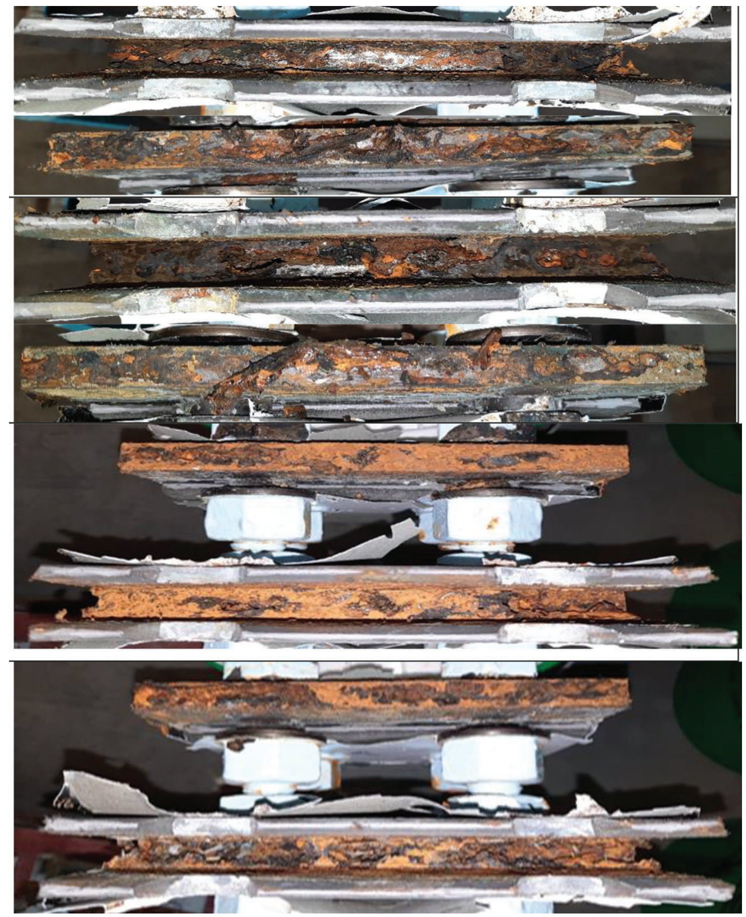
Condition/Specimens	Time of Exposure: 111 Days/Testing Day	120 Days	165 Days	172 Days/Testing Day
A Base: 1, 2, 5, 6. Specimen 5 shown in the pictures				
B Base: 7, 8, 9, 10. Specimen 8 shown in the pictures				
10 M: 18, 19. Specimen 19 shown in the pictures				
Remarks	Built up material was present 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.

(Continued)

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			
10 M: 18, 19. Specimen 19 shown in the 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
Corrosion 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)**
	

(Continued)

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)**
	

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 10 M 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).

5.1.1.2 Analysis of 1/2-inch base specimens. Specimens 30, 31, and 32 were 1/2-inch gap specimens exposed for a period of time to reach Condition A. These specimens can be compared with the specimens with a 1/4-inch gap. In a similar way, a steady formation of rust was observed between the interface of the overlapping plates for the first 3 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 1/4-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 1/4-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.

5.1.2 Initially Treated Specimens

5.1.2.1 Analysis of initially treated specimens. By the end of the first 3 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 30, 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.

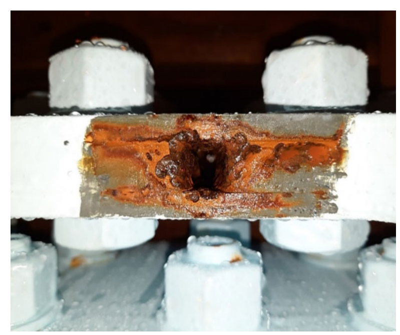
5.1.3 Repaired Specimens

5.1.3.1 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 (see Figure 5.1). 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

TABLE 5.4
Corrosion development for 1/2-inch gap specimens

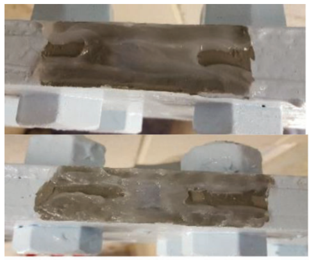
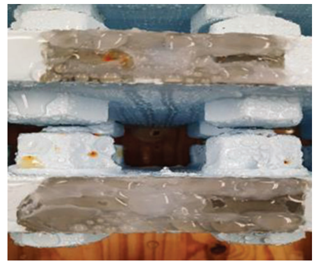
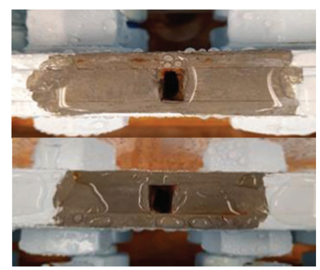
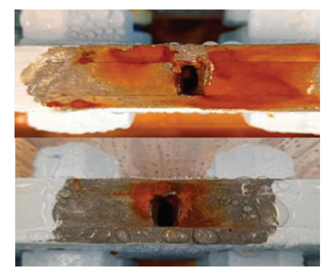
Time of Exposure	Specimen 32
14 Days	
1 Month	
2 Months	

(Continued)

TABLE 5.4
(Continued)

Time of Exposure	Specimen 32
3 Months	
4 Months	

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.

(Continued)

TABLE 5.5
(*Continued*)

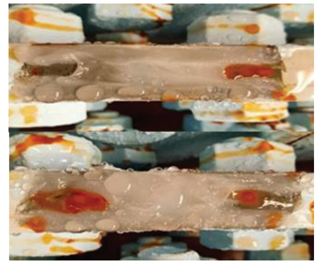
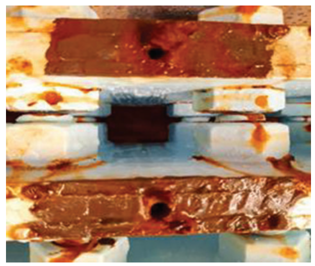
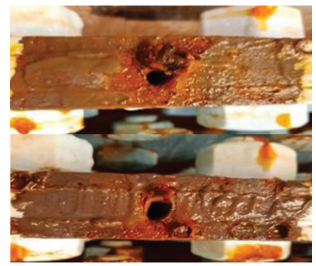
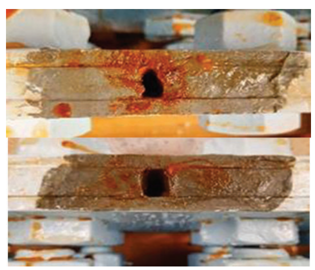
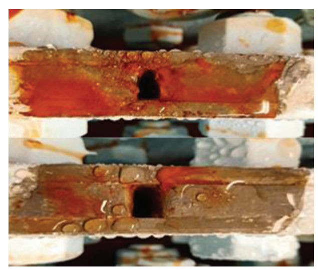
Condition/ Specimens	Time of Exposure			
	90 Days (Splices Flipped)	**120 Days**	**165 Days**	**172 Days/Testing Day**
Caulk: 17 and 24 (Top)				
Termarust: 25 and 26 (Top)				
Fluid Film: 27 and 29 (Top)				
Remarks	Specimens have been flipped. Black rust dots are observed around the caulk. Termarust 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 signficantly 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
Corrosion formation in the cross section of initially treated specimens

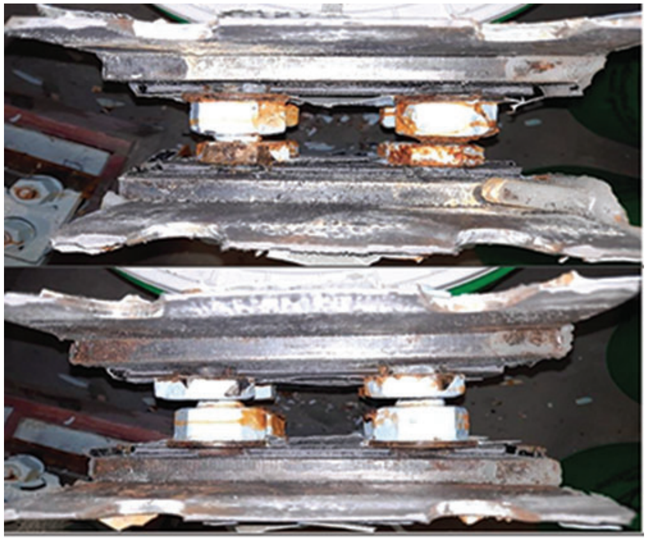
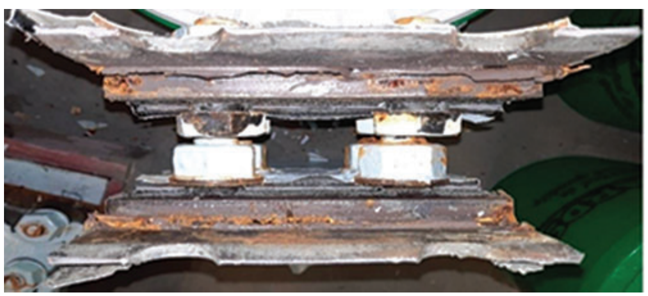
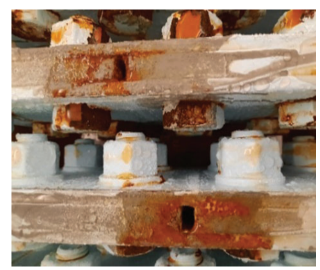
Condition B/Time of Exposure: 172 Days	
GE Silicone Caulk Specimens 17, 24 (Downwards)	**Fluid Film Specimens 27, 29 (Downwards)**
	
Termarust Specimens 25, 26 (Left to Right)	
	

TABLE 5.7
Comparison between mitigation strategies for specimens repaired for Condition A and Condition B

	Time of Exposure			
Condition/Specimens	**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.

(Continued)

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 degration. 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.

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

Figure 5.2 Discoloration of caulked specimen.

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 (see Figure 5.2). 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 (see Figure 5.3). 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 3 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.

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.

5.2 Strength Test Results and Quantitative Analysis

The tension strength test had two main objectives: (1) determine the strength reduction in the specimens due to corrosion development, and (2) determine the strength reduction in the specimens after repair with the mitigation strategies and additional exposure. Two points along the strength curve are of interest: slip

TABLE 5.8
Corrosion formation in the cross section of specimens repaired for Condition A and Condition 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)	
	

(Continued)

TABLE 5.8
(*Continued*)

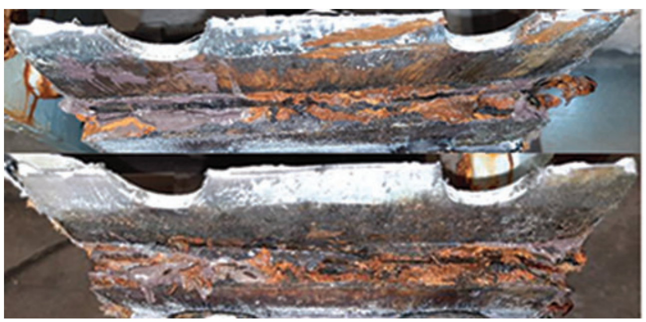
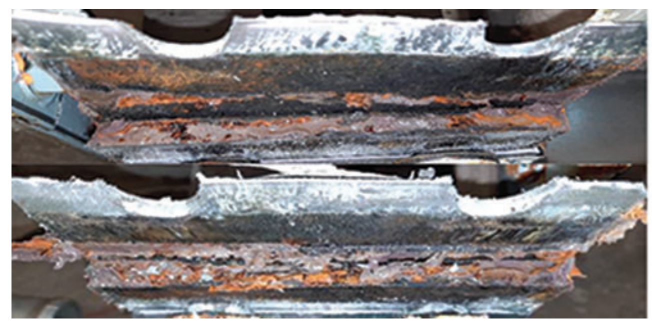
Repaired Condition B/Time of Exposure: 257 Days (82 Days After Repair)	
GE Silicone Caulk Specimens 20, 21 (Downwards)	**Fluid Film Specimens 4, 23 (Downwards)**
	
Termarust Specimens 22, 28 (Left to Right)	
	

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

TABLE 5.9
Experimental and theoretical strength values for all specimens

			Strength Measurements (kips)		
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	10 M	26.85	172.75	152.47
Q-B2-19	6/14/2021	10 M	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

resistance and the ultimate load. Table 5.9 shows the results of testing.

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 10 M 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.

Table 5.9 shows 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 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.

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 10 M 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.

In regard to ultimate strength, deterioration of the specimens did not take place from the data point of view (see Figure 5.5). 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.

5.2.1 Strength of Control and Base Specimens

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 10 M specimens exhibited 3% higher strength than the control specimens. It is important to spotlight that only two 10 M 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 10 M specimens average

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	10 M	172.23	kip	10 M	154.22	kip	10 M

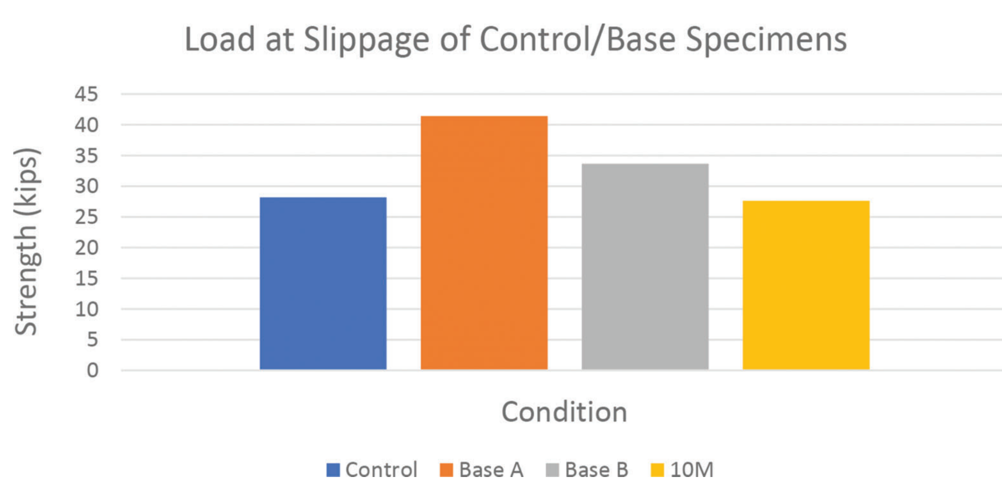


Figure 5.4 Load at slippage of control and base corroded specimens.

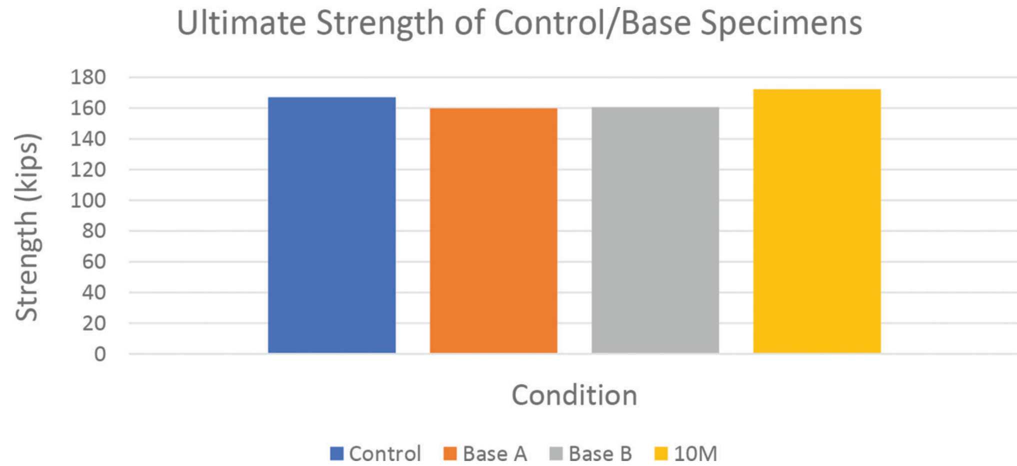


Figure 5.5 Ultimate load of control and base corroded specimens.

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

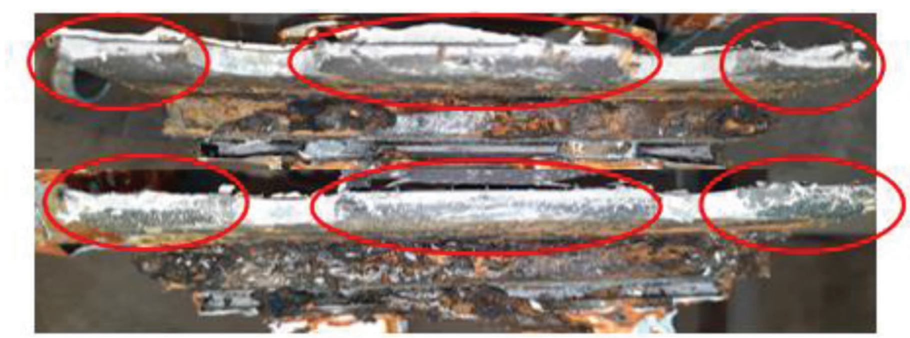


Figure 5.6 Specimen 19 cross-sectional area exposed to 284 days of corrosion.

expected load was higher than the rest of the specimens. Given 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.

5.2.2 Strength 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 (see Figure 5.7). These results strengthen the idea that corrosion

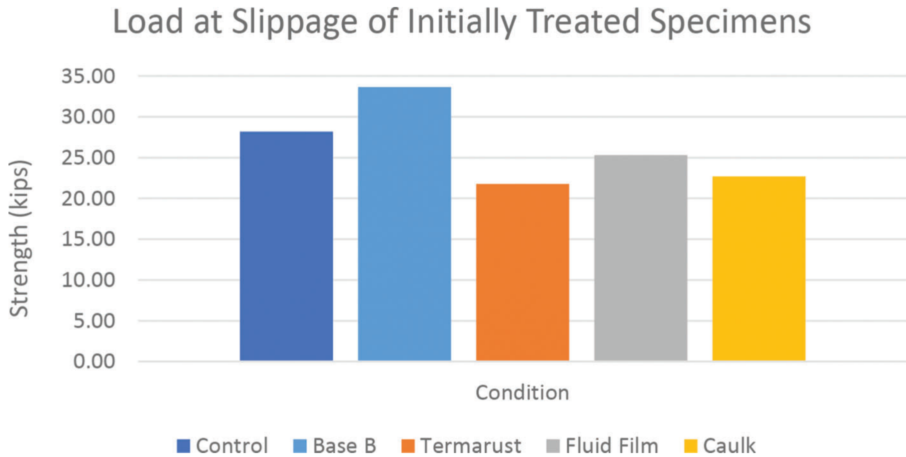


Figure 5.7 Load at slippage of initially treated specimens.

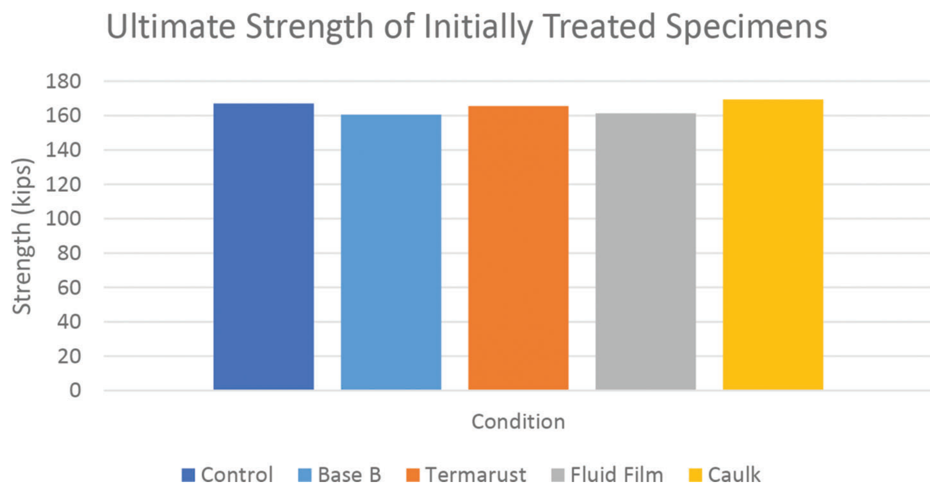


Figure 5.8 Ultimate load of initially treated specimens.

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. However, in spite of the differences noted for slip resistance, there was little difference noted in the ultimate strength of the initially treated specimens, as can be observed in Figure 5.8.

5.2.3 Strength of Repaired Specimens

The slip resistance of the connection decreased after the connections were repaired for both Condition A and B (see values in Table 5.12). The difference in slip resistance between Base and Repaired A specimens is more remarkable than for Condition B specimens (see Figure 5.9). 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 Conditions 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 Sections 5.2.1 and 5.2.2 is reached in this section. The fact that the repaired specimens did not experience further strength reduction, as is evident in Figure 5.10, 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.

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

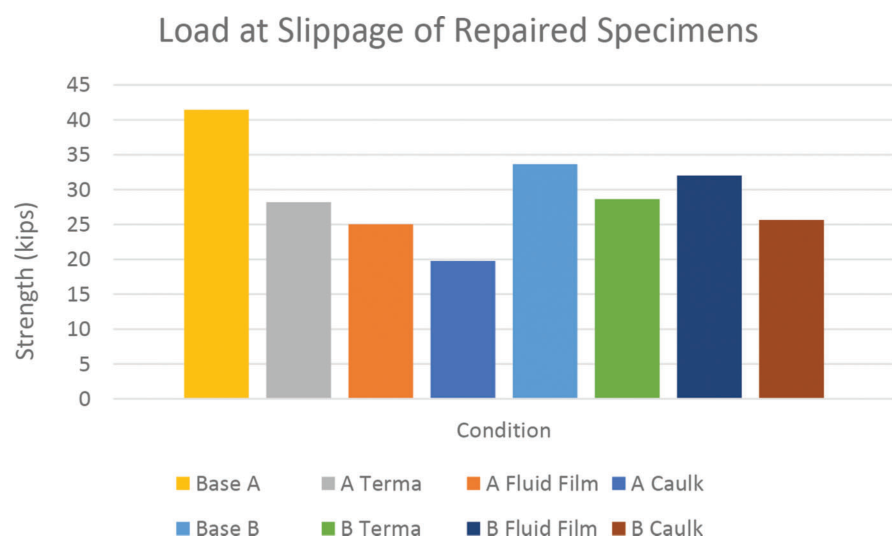


Figure 5.9 Load at slippage of base and repaired A specimens.

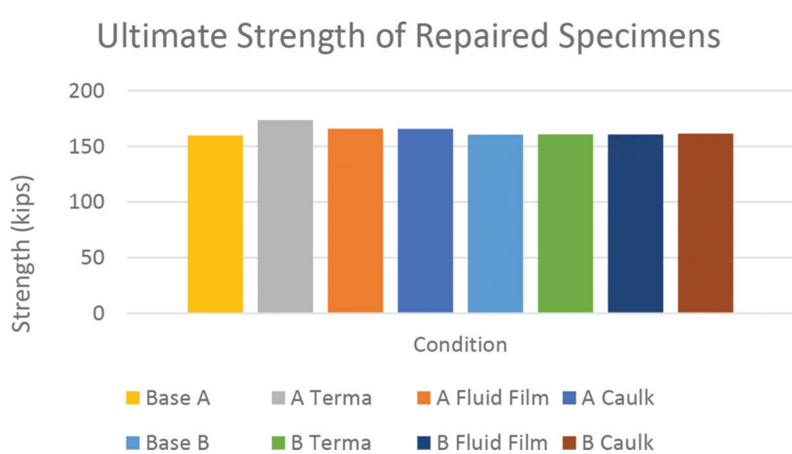


Figure 5.10 Ultimate load of base and repaired specimens.

Therefore, final remarks will be based on the visual inspections.

5.3 Deterioration Curves for Steel Members with Pack Rust

Deterioration curves are a graphic depiction of the structural condition of a bridge member or element as the bridge ages. The structural condition is often tied to the 9 to 0 NBI condition evaluation, where 9 represents a new or superior condition and 0 represents failure and closure of the bridge. The structure is often scheduled for major repair or replacement when it reaches a "poor" condition rating of 4 (Sinha et al., 2009); however, programming repairs often occur well before a rating of 4 is reached.

Sinha et al. (2009) used NBI data from Indiana to determine the condition rating corresponding to steel girder and beam bridges. It was shown that the service life for steel bridges in Indiana is 80 years, as measured by the time that it takes for the structural condition to deteriorate from a new (9) to a poor (4) condition (see Figure 5.11).

Work actions for many structural conditions can be performed at particular times to improve the structural condition and cause the condition rating to jump up to a better condition. Such a change in the condition rating could correspond to a deck replacement for a bridge deck that had suffered delamination or reinforcement corrosion damage, or perhaps a straightening and/or strengthening repair for of a steel girder flange that had been impacted and subsequently distorted.

In the case of pack rust developed at steel girder connections, it was desired to know what the deterioration curve would look like as pack rust developed. One of the reasons that the strength of the splice plate connection was evaluated in this study was to understand how the strength decreased as pack rust developed over time and got progressively worse. Accelerated corrosion testing was used to develop pack rust for simulated splice plate girder connections. In the subsequent structural testing conducted in this study, however, the pack rust that developed did not provide enough of a decrease in the structural capacity of the connection to dominate the splice plate behavior. The joint still failed at the net section, which was removed some distance from the splice plate gap region where the pack rust was forming. For the pack rust levels generated in the accelerated corrosion testing, which is estimated to simulate 20 to 40 years of service life, there was no noticeable decrease in the overall strength of the connection due to pack rust. This is not to say that pack rust never causes a deterioration in the strength, but in the case studied herein the pack rust deterioration in the gap region was not enough the dominate the behavior and result in a failure at the corroded section; the net reduced section where the bolts were placed instead dominated. However, significant pack rust that causes bulging of the splice plates or loss of bolt head or bolt shank cross section could certainly result in a decrease in structural capacity of the joint.

Consequently, in spite of the lack in strength decrease observed in the testing herein, it is still recommended that significant pack rust that develops in structural joints be mitigated to the extent possible so that no additional pack rust can develop. In such a case, the pack rust mitigation would cause a horizontal shift in the deterioration curve (see Figure 5.12). This simply means that the mitigation is effective in not allowing any further deterioration of the structural detail due to pack rust development for the effective life of the mitigation work action. The mitigation work action would last between 5 to 10 years before an additional mitigation would be needed to prevent further pack rust development and deterioration.

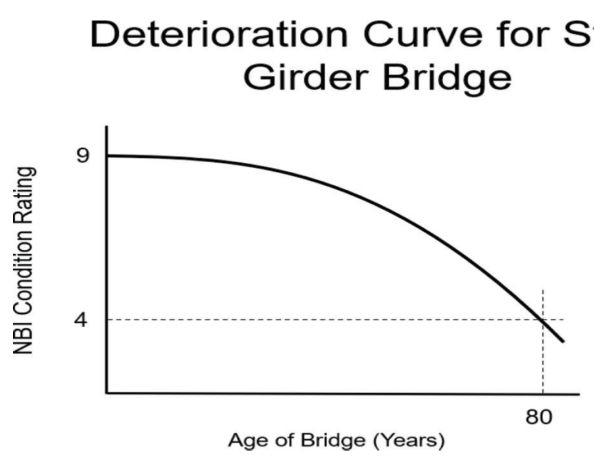


Figure 5.11 Deterioration curve for steel bridge beam and girder members (Sinha et al., 2009).

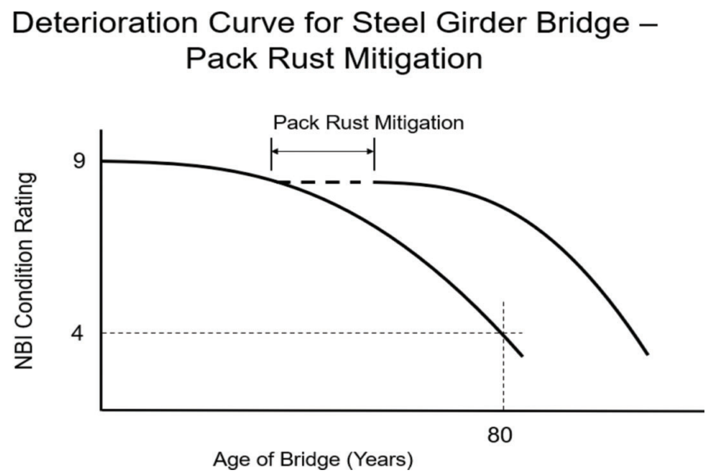


Figure 5.12 Steel bridge girder deterioration curve adjusted for pack rust mitigation.

6. CONCLUSIONS, RECOMMENDATIONS AND INDOT STRATEGIC GOALS

This section provides conclusions based on the results reviewed in the previous chapter. Due to 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. 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.

The research in this study impacts the INDOT Strategic Goals related to *safety* and *asset sustainability*. It is believed that the development of pack rust in steel bridge connections, like bolted or riveted moment splice connections, could become problematic and negatively impact the load capacity of a bridge structure. It was found that particular strategies can be employed to mitigate or delay the initiation, progression and spread of pack rust and thereby prolong the service life of a steel bridge structure. Implementation of these measures will thereby improve the safety of steel bridges and protect the steel bridge inventory, which is a valuable asset.

6.1 Remarks on Test Results and Field Application Recommendations

6.1.1 General Observations and Conclusions

- For the set of conditions developed in this experiment and the amount of pack rust 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 10 M). This is because the pack rust did not influence the area where the connection fracture occurred and also did not compromise the strength of the connection in the gap region.
- Corrosion developed within the gap of the specimens affected the slip resistance of the splice connections due to its "gluing" effect on the middle plates. After removal of rust product during repair, it was observed that the slip resistance decreased. This reinforces the previous statement.
- Based on visual inspection, the corrosion formation rate was higher for the first 3 months of exposure followed by a lower apparent corrosion rate thereafter. This could be the result of the lower (more acidic) pH level during the initial phase of the testing, or it could be a characteristic belonging to crevice corrosion, which will require more sophisticated tools for further study.
- Bulging of the plates was slightly visible towards the beginning of the ninth month of exposure. The maximum bulging observed was 0.0809 inches, which did not affect the structural performance of the splice connection.
- The 1/2-inch 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 is filled and sealed, the formation of black rust takes place due to lack of oxygen.
- The formation of black rust is believed to be undesirable and should be avoided if possible. Black rust often forms due to the lack of oxygen. During the corrosion process acidification can occur in the deep portions of a crevice as a result of chloride and sulfide ions reacting with positively charge iron regions. This location acts as an anode and through corrosion cell action promotes the formation of pack rust at the cathode near the crevice opening where there is plentiful oxygen and water. The pack rust growth can seal the crevice opening and choke off the supply of oxygen, which results in black rust (magnetite) inside the crevice.

6.1.2 Conclusions from the Mitigating Products' Performance

- As an initial treatment, all mitigating products performed effectively in the initial condition test. First, the

Fluid Film's performance is inconclusive based on the visual inspection. The wax worked as a sacrificial layer, but during visual evaluation it was challenging to differentiate between "sacrificed" wax material and rust since they both had the same coloration. However, 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 only fair performance. First, Fluid Film's performance was at first similar to that shown in the initial condition test. 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 already existing rust (remaining after pressure washing) and lower pH. 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 approach since encapsulating corrosive material within the gap promotes the fast formation of black rust. The development of black rust was observed for the specimens repaired with caulk in this experiment.

  Finally, Termarust performed slightly better than the other two strategies (at least 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 3 days of curing, the material inside the gap was not dried. The recommended thinner—which was not available during the testing repair operation—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 slightly 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 should be able to 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, recommendations for treatment implementation in the field are twofold: (1) treatments for new steel bridge structures and (2) treatments for those steel bridge structures that have been in service and have developed pack rust. A summary of the recommended mitigation strategies is provided in Table 6.1.

  - For new steel bridge structures, it is recommended that a stripe coat be applied to the splice plates in the gap region and also to the ends of the girders being spliced. The stripe coat will provide extra protection to delay the formation of pack rust inside the gap region of the splice plate connection. The stripe coat should be at least 2-in wide and add 3–4 mils of zinc primer on top of the initial layer of zinc primer. Note that the stripe coat is to be applied before the splice connection is assembled in the field and the epoxy intermediate coat and the polyurethane topcoat have been applied.
  - For existing steel bridge structures that have developed notable pack rust, it is recommended that either the Fluid Film or Termarust treatments (or other equivalent penetrating sealers) be injected into the gap region after the pack rust in the splice plate gap region has been removed to the extent possible. Following one of these treatments, caulk should not be used to seal the gap opening. Moreover, it should be noted that the treatment should be effective for a number of years, but it will eventually need to be reapplied after corrosion product is first noticed to have redeveloped in the splice plate gap region.

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

TABLE 6.1
Recommendations and notes on the mitigation strategies

Treatment	Strategy	Recommended	Notes
Initial	Stripe coat	Yes	Add a zinc primer stripe 2-in wide in gap region to provide additional corrosion protection
Repair	Fluid Film	Yes	Recommended, but additional chemical studies are required
	GE caulk	No	–
	Termarust	Yes	Recommended, but use thinner to reduce the viscosity of the topcoat and allow smooth application

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 further explored. 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 were placed horizontally (the gap running parallel to the horizontal plane), there would have not been much material loss from the plates, and the possibility of developing bulging of the plates may have increased. However, increased chamber sizes are needed for testing specimens in a horizontal configuration.
- 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.
- Use of the recommended mitigation strategies should be implemented on a number of splice connection details in the field. These connections should be intentionally tracked for observation to note their performance under field conditions. Many field conditions are difficult to replicate in the laboratory testing and may affect the results. For example, exposure to cold weather, sunlight exposure, temperature changes and pH changes within the actual bridge environment may influence the performance of the treatment mitigation strategies. Field performance 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 for trial implementation on a few bridges in the field. 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.

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APPENDICES

Appendix A. pH and Temperature Measurements

Appendix B. Material Information

Appendix C. Product Certificates

Appendix D. Caulk Testing

Appendix E. Failure Mode Sample Calculation

Appendix F. Specifications for Pack Rust Treatment

APPENDIX A. PH AND TEMPERATURE MEASUREMENTS

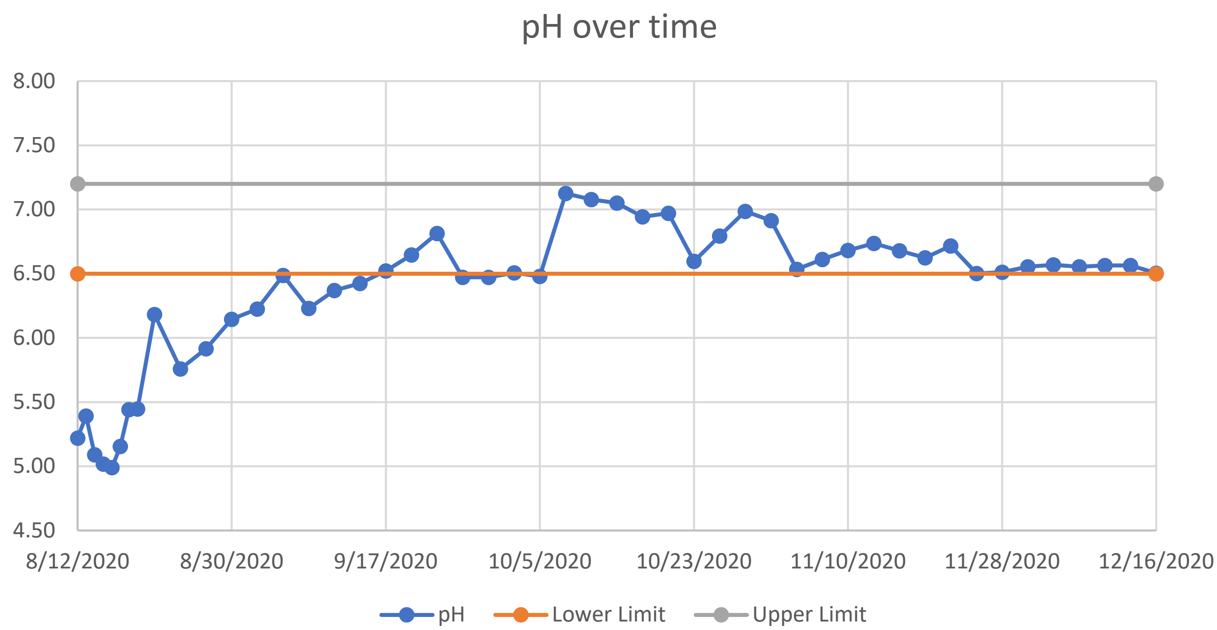

Figure A.1 pH measurements for the first period of misting.

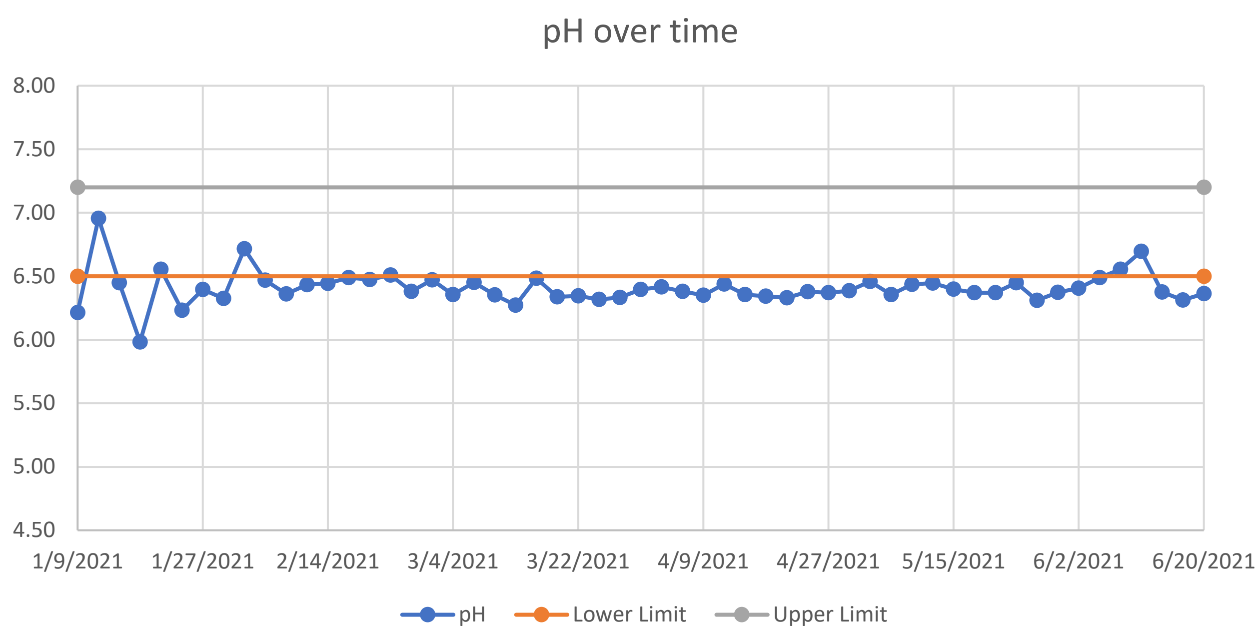

Figure A.2 pH measurements for the second period of misting.

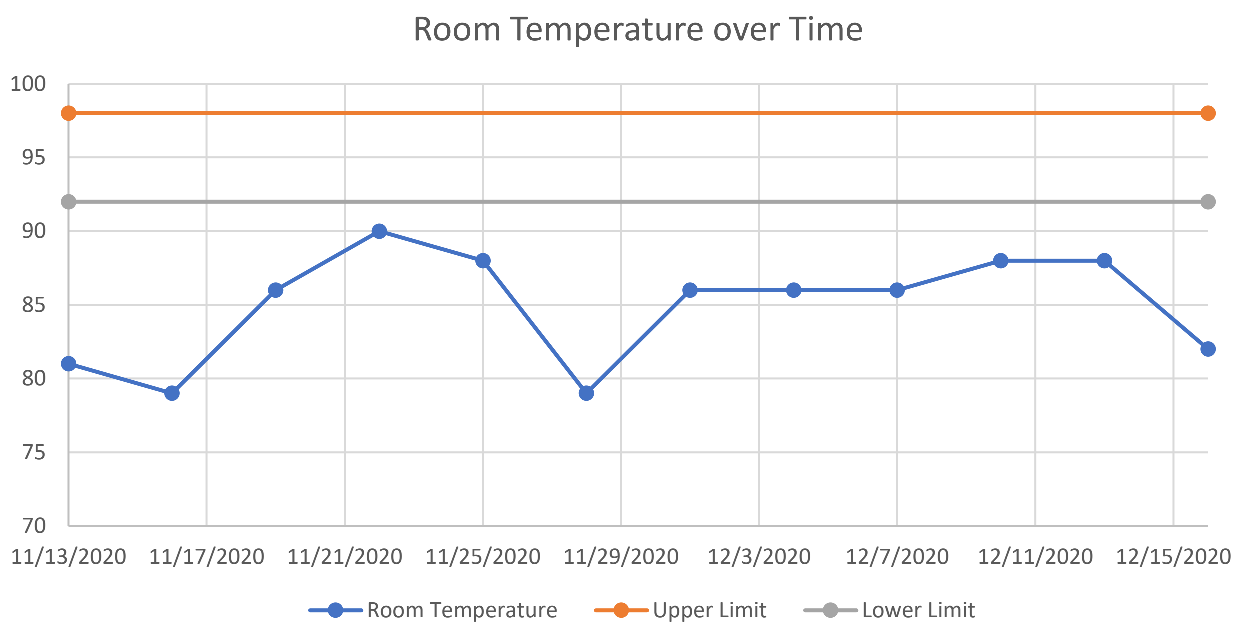

Figure A.3 Temperature measurements for the first period of misting

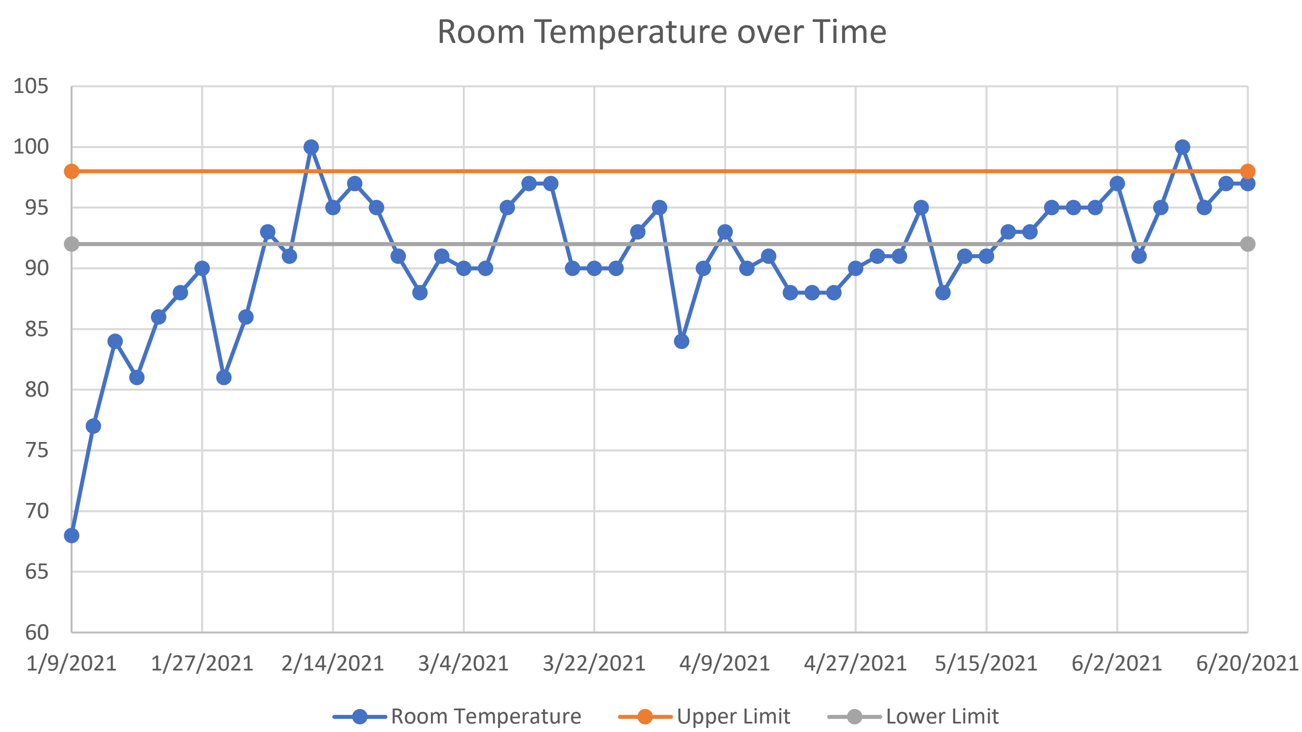

Figure A.4 Temperature measurements for the second period of misting.

APPENDIX B. MATERIAL 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

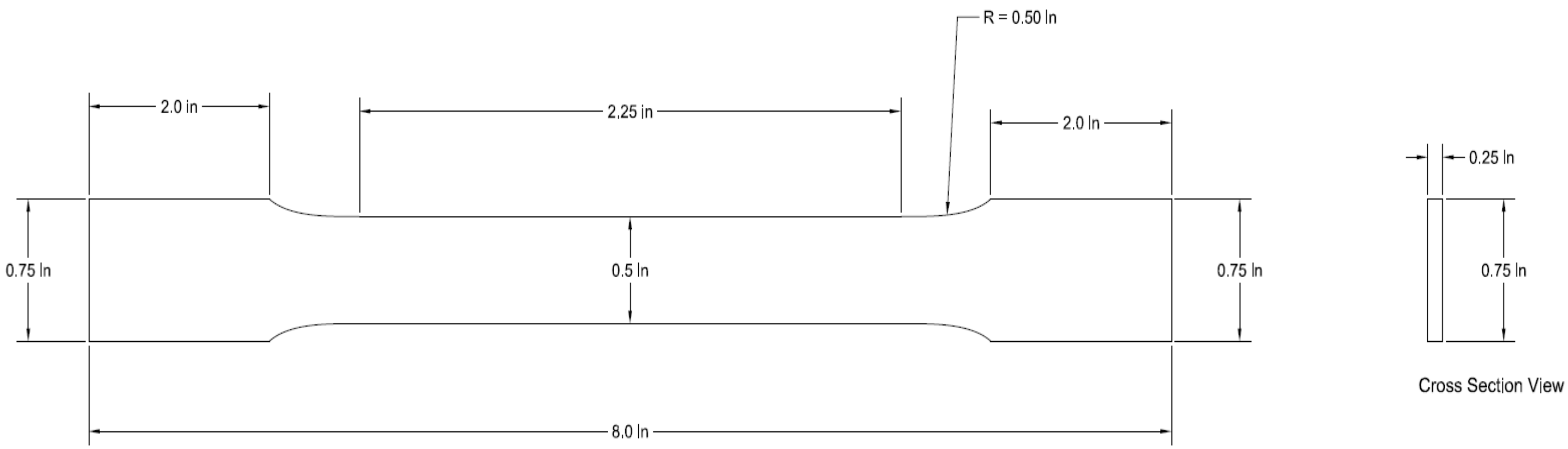

Figure B.1 Coupon geometry for splice plates.

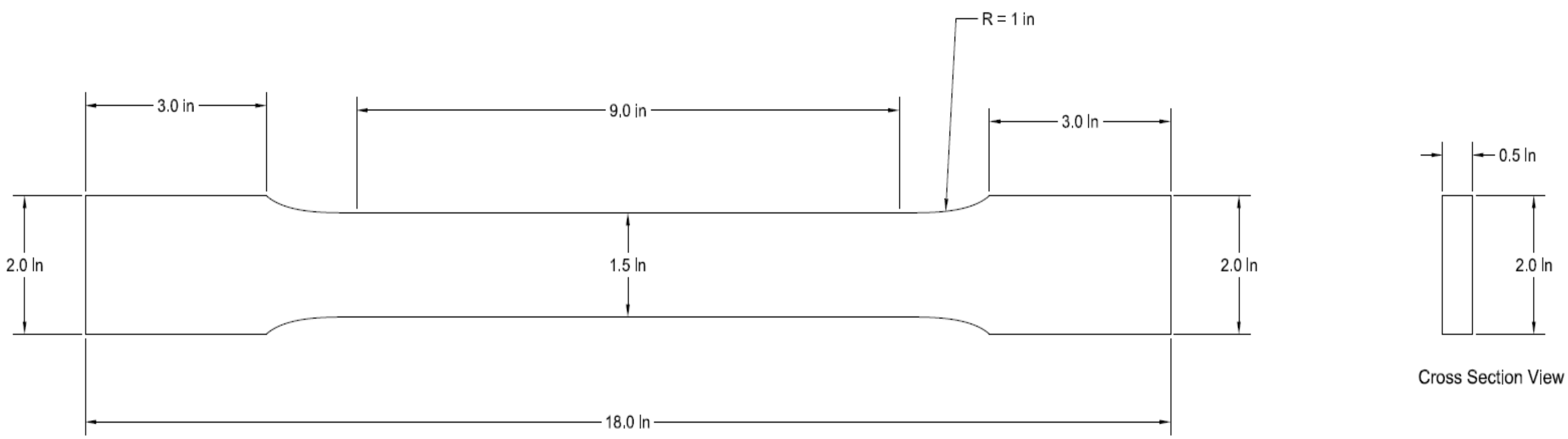

Figure B.2 Coupon geometry for middle plates.

Table B.2 Coating thicknesses

Coating Thicknesses & Plate Thicknesses			
	Average Coating Thickness (mils)		
Specimen	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

MORTON SALT

Certificate of Analysis

Culinox 999

18-JUN-2019
Manufacturing Site
RITTMAN
151 Industrial Ave, Rittman
OH, 44270-1593
Jacob DeVries
Quality Control
0330/9253015

Page 1/1

Manufacturer:	Morton Salt, Inc.	Morton Batch No.:	RI19164020
Morton Order No.:	5101768503	Manufact. Date:	13-JUN-2019
Cust. Order No.:	449748		
Delivery /-Item No:	5204146195 / 000040		
Quantity:	98 BAG	Shipping date:	18-JUN-2019

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.

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/ft3)	77.0 lb/ft3	65.0 .. 80.0 lb/ft3
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 %

Shipping Plant: 151 Industrial Ave , Rittman, OH, 44270-1593

Electronically released by Jacob DeVries Quality Assurance Technician on 18-JUN-2019

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.

Figure C.1 Culinox 999 certificate of analysis.

ArcelorMittal Burns Harbor Plate

QUALITY ASSURANCE

REPORT OF TESTS AND ANALYSES

SHIPMENT NO.	DATE SHIPPED	CAR OR VEHICLE NO.	PAGE
804-20376	00-00-00	TRLR	1

SOLD TO	SHIP TO
ALRO STEEL CORP PO BOX 927 JACKSON MI 49204-0927	ALRO STEEL CORP 5620 CHURCHMAN AVE INDIANAPOLIS IN 46203

NOTE	SERIAL NUMBER	PAT NO.	HEAT NUMBER	NO. PCS	THICKNESS INCHES	WIDTH OR DIA. INCHES	LENGTH INCHES	WEIGHT POUNDS	YIELD POINT PSI	TENSIL STRENGTH PSI	ELONG. IN	RED.
			811E11430	13	1/2	96	240	42471	52400	71100	8	27
									54300	72100	8	26

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

(M55)MFST REF#:07801200

Q-QUENCH TEMPERATURE | T-TEMPER TEMPERATURE | NORMALIZE TEMPERATURE

SERIAL NUMBER	PAT NO.	HEAT NUMBER	HARD BHN	BEND	THICKNESS INCHES	TYPE	SIZE	DIR	TEST TEMP F	ENERGY T. LBS. 1	2	3	SHEAR(%) 1	2	3	LAT. EXP MI 1	2	3
		811E11430			.500	V	FULL	L	-20	251	257	277						

Received
Subject to Count and Inspection
MAY 01 2019
Alro Steel Corporation
Indianapolis

Alro Metals/Plastics
RT09500547

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

CHEMICAL ANALYSIS

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.

NUCOR

NUCOR STEEL TUSCALOOSA, INC.

MILL TEST CERTIFICATE

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

Page:2 of 2

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 % 2"	ELONGATION % 8"	Bend OK?	Hard HB	Charpy Impacts (ft-lbs) Size mm	Charpy 1	Charpy 2	Charpy 3	Charpy Avg	Shear % 1	Shear % 2	Shear % 3	Shear % Avg	Test Temp
7J2303D	S7J2303FTT	B7W6560-04 ***	60.4	71.7	84.2	31.4													
7J2303D	S7J2303BLI	B7W6560-04 ***								5.0	78	97	75	83.3					-22 F
7J2303D	S7J2303FLI	B7W6560-04 ***								5.0	77	88	83	82.7					-22 F
7J2303D	S7J2303MLI	B7W6560-04 ***								5.0	76	74	77	75.7					-22 F
7J2303D	S7J2303MTT	B7W6560-04 ***	63.0	70.3	89.6	29.1													
7J2303E	S7J2303FTT	B7W6560-04 ***	60.4	71.7	84.2	31.4													
7J2303E	S7J2303BLI	B7W6560-04 ***								5.0	78	97	75	83.3					-22 F
7J2303E	S7J2303FLI	B7W6560-04 ***								5.0	77	88	83	82.7					-22 F
7J2303E	S7J2303MLI	B7W6560-04 ***								5.0	76	74	77	75.7					-22 F
7J2303E	S7J2303MTT	B7W6560-04 ***	63.0	70.3	89.6	29.1													
7J2306B	S7J2306FTT	A7W4127-01 ***	57.7	68.4	84.4	34.1													
7J2306B	S7J2306BLI	A7W4127-01 ***								5.0	76	78	87	80.3					-20 F
7J2306B	S7J2306FLI	A7W4127-01 ***								5.0	103	80	85	89.3					-20 F
7J2306B	S7J2306MLI	A7W4127-01 ***								5.0	79	96	77	84.0					-20 F
7J2306B	S7J2306MTT	A7W4127-01 ***	63.2	70.7	89.4	33.7													

Items: 3 PCS: 27 Weight: 44105 LBS

ALRO STEEL/METAL
RT07407091

Mercury has not come in contact with this product during the manufacturing process nor manufacturing process. Certified in accordance with EN 10204 3.1. No weld repair has been performed on ... Manufactured to a fully killed fine grain practice. NUTEMPER TEMPER PASSED plate from coil
ISO 9001:2015 Registered, PED Certified

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

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

Dr. Quiln Yu - Metallurgist

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	Heidtman Steel Proc - T - IN 4400 County Road 59 Butler, IN 46721 United States	**Contact** Butler RECEIVING P: 260-868-6117
Sold To	Alro Steel Corporation 3100 E. High Street Jackson, MI 49204-0927 United States	**Contact** Mark Reynolds *Purchasing* P: 517-788-3343

Length	1,093 ft. / 333 m	**Width**	48.0000 in. / 1,219 mm	**Chem Treat**	No
Weight	44,210 lbs / 20,053 kg	**Gauge**	0.2400 in. / 6.10 mm | Min	**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	0.008	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 %	

Alro Metals/Plastics
RT09617481

Hiroshi 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.

Retrieve on : 2/26/2019 1:39:39 PM *Steel Dynamics Rev. Level 1.12 [1560]* **Page 1 of 1**

Figure C.4 Metallurgical certification.

APPENDIX D. CAULK TESTING

Table D.1 Caulking products conditions 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. FAILURE MODE SAMPLE CALCULATION

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
	$F_{uaveb} := 69.89\ ksi$	$F_{uaves} := 65.71\ ksi$
	$F_{yaveb} := 54.22\ ksi$	$F_{yaves} := 56.79\ ksi$
Dimensions:	Middle Plates	Splice Plates
Width:	$w_{b1} := 6.625\ in$	$w_{s1} := 6.625\ in$
	$w_{b2} := 6.625\ in$	$w_{s2} := 6.625\ in$
Thickness:	$t_{b1} := 0.502\ in$	$t_{s1} := 0.259\ in$
	$t_{b2} := 0.501\ in$	$t_{s2} := 0.259\ in$

Diameter of bolts: $d_b := \frac{7}{8}\ in$

Failure Modes

A) Yielding

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

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

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

B) Rupture $U := 1$

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

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

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

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

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

C) Block Shear

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

Middle Plates

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

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

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

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

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

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

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

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

Splice Plates

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

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

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

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

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

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

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

$$R_{s1ave} := c_1 + min\left(c_2, c_3\right) = 180.4\ \mathbf{kip}$$

$$R_{n1} := min\left(R_{b1ave}, R_{s1ave}\right) = 180.4\ \mathbf{kip}$$

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

Middle Plates

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

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

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

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

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

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

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

Splice Plates

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

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

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

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

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

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

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

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

D) Shear Strength of Bolts $F_n := 54\ ksi$

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

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

The expected failure mode is fracture.

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

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

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.

APPENDIX F. SPECIFICATIONS FOR PACK RUST TREATMENT

SPECIFICATION FOR STRIPE COATING TREATMENT OF SPLICE PLATE CONNECTIONS IN NEW BRIDGES

Application of Stipe Coat for Splice Plate Moments Connections (New Bridges)

1. Apply a stripe coat (a) in the middle portion of the splice plates on the side that is located on the inside in the gap opening region, and (b) to all ends of the girders being spliced together.
2. The stripe coat should be at least 2-in wide and add 3–4 mils of zinc primer on top of the initial layer of zinc primer. Care should be taken to ensure that the stripe coat is not too thick.
3. The stripe coat for the splice plates is applied prior to the plates being connected together with the girder. The stripe coat should extend across the entire width of the plate and provide extra coating protection for the splice plate connection gap opening on the inside of the connection.
4. The stripe coat for the girder ends should be deposited around the entire girder periphery so that when the girder ends are attached to the flange and web splices any gap regions have an extra layer of protection.
5. Note that the stripe coat is applied before the splice connection is assembled in the field. After the splice connection has been assembled, then the epoxy intermediate coat and the polyurethane top coat may be applied as per standard practice.

SPECIFICATION FOR PACK RUST REMOVAL AND APPLICATION OF MITIGATING TREATMENT IN EXISTING BRIDGES

Pack Rust Removal (Existing Bridges)

1. Contaminants, dirt, organic material, nests, grime and loose material should be removed. Old paint and grease should be removed in accordance with SSPC-SP1 "Solvent Cleaning."
2. In order to remove the loose, thick and porous rust; and improve the overall quality of the pack rust removal process, apply one, or a combination, of the following procedures per the SSPC standards.
    - Hand tool cleaning (SSPC-SP2)
    - Power tool cleaning (SSPC-SP3)
    - High pressure water cleaning (SSPC-WJ4), with a 5,000-psi cold water pressure washer or higher-pressure washer. Road salts should be removed by using a chloride remover together with the water spray. (The use of Chlor*Rid, or an equivalent cleaning agent, is recommended. The water should be mixed with Chlor*Rid at a ratio of 1 unit of Chlor*Rid to 100 units of water by volume.) The standoff distance should be between 4 and 8 inches.
3. For optimum performance check to see if the soluble salt has been removed from the surface. Kits are available to test for soluble salt contents (ISO 8502-6/9). Recommended acceptable levels of non-visible contaminants (in micro grams per square centimeter) are Chloride NVC3 3 ug/cm^2, Sulfate NVS10 10 ug/cm^2, Nitrate NVN10 10 ug/cm^2.
4. Dry the area surrounding the crevice with rags.
5. Dry the area inside the crevice by applying compressed air at 100 psi until water has been completely removed.
6. After pack rust removal, some of the surface coating on the splice plates and the girder flange plates will be lost immediately adjacent to the splice plate gap opening. This area will need to be repainted with the corresponding coating system immediately if possible. Otherwise, protect the steel from highway runoff for a maximum of 24 hours. Finally, the pack rust mitigation product can be applied.

Pack Rust Mitigating Product Application

1. For treatment of the splice plate gap region, insert the wand or syringe used for injection of the penetrating sealer mitigation product into the gap of the connection and apply the product as you slowly move the wand outwards. Repeat the process from the other end of the gap. The objective is to treat as much of the internal length of the splice plate gap region as possible.
2. Treat the surface near the splice plate gap opening as per the mitigation product used.
3. Application suggestions for the two penetrating sealers that were tested are provided in the supplemental recommendations. Other penetrating sealer products are available commercially and may also be suitable.

SUPPLEMENTAL RECOMMENDATIONS FOR SPECIFIC PACK RUST MITGATING PRODUCTS

Fluid Film

1. Following the instructions of the product, insert the wand of the spray can into the gap of the connection and apply the product as you slowly move the wand outwards. Repeat the process from the other end of the gap.
2. Spray the area near the mouth of the crevice to obtain a dry-film thickness of 4 to 5 mils. Extend the application at least 3 inches from the centerline of the gap along the interface of the plates.
3.

Termarust

1. Apply TR 2200 penetrating sealer into the crevice or joints in a pressurized manner, and over the area around the mouth of the crevice. Termarust recommends the use of high-volume, low-pressure (HVLP), low-volume, low-pressure (LVLP), conventional or airless spray over the use of a brush. The application of the Termarust products should be performed above 35.6°F.
2. In order to inject the penetrating sealer into the gap of a splice connection, a syringe with a tip smaller than the width of the gap can be used.
3. Apply TR 2100 topcoat with a brush immediately after the penetrating sealer around the mouth of the crevice. The minimum dry-film thickness is 10 mils. A minimum dry-film thickness of 20 mils is recommended for areas that have suffered high levels of pack rust.
4. To apply the topcoat into the gap, thin the topcoat with TRT01 thinner, and then apply it using a spray gun. The surfaces within the gap need to be completely coated.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

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