Corrosion of Hydraulic Steel Structures and Preventive Measures

Jackson Daniel Hinton

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Corrosion of hydraulic steel structures and preventive measures

By

Jackson Daniel Hinton

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Corrosion of hydraulic steel structures and preventive measures

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Hydraulic steel structures (HSS) are key components of U.S. Army Corps of Engineers infrastructure and are subject to corrosive environments, unpredictable loadings, and extreme conditions. Corrosion can take many forms and can cause costly damage to HSS due to inadequate design of protective measures. There are numerous forms of corrosion that have a negative effect on HSS, as well as material properties that need consideration when designing HSS preventive measures. Understanding corrosion and providing proper preventive measures is crucial for HSS. Proper maintenance and repair of these protection systems also play a significant part in corrosion control of HSS.

Key words: hydraulic steel structures, corrosion, preventive measures
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Chapter I
Introduction

Part of the U.S. Army Corps of Engineers (USACE) mission is to provide engineering services for the nation’s inland and coastal waterway systems. This requires the construction and maintenance of navigation channels and harbors, while providing regulated water levels on inland waterways. Within the approximate 12,000 miles of the U.S. commercial inland navigation channels that are maintained by USACE, there are 191 active lock sites with 237 operable navigation lock chambers, and over 50 percent of those locks are above 50 years old. [1] In order for USACE to provide safe, reliable, efficient, and environmentally sustainable movement of vessels on these channels, it must recognize the significance of preventing the deterioration of its infrastructure and key components.

Some of the key components of USACE infrastructure include hydraulic steel structures (HSS). According to USACE regulations, HSS are structures comprised of steel that control or regulate water and are typically part of a larger navigation, hydropower, or flood control project. [2] This would encompass steel structures such as what is seen in Table 1.1. This table consists of a list of HSS items located in the Arkansas, Louisiana, and Mississippi areas that were inspected by the author over the past nine years. All of the field data collected for the research for this article was from these HSS items, and used to exemplify the effects of the different types of corrosion
associated with HSS. These inspections were also used to compare the different types of preventive measures applied or situations that would require a preventive measure.

Table 1.1  Hydraulic Steel Structure Types

<p>| |</p>
<table>
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<tbody>
<tr>
<td>Lock gates</td>
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<tr>
<td>Dam spillway gates</td>
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<tr>
<td>Tainter gates</td>
</tr>
<tr>
<td>Tainter valves</td>
</tr>
<tr>
<td>Bulkheads and stoplogs</td>
</tr>
<tr>
<td>Vertical lift gates</td>
</tr>
<tr>
<td>Components of hydroelectric and pumping plants</td>
</tr>
<tr>
<td>Lock wall accessories</td>
</tr>
<tr>
<td>Flood protection gates</td>
</tr>
<tr>
<td>Lifting beams (used to install other HSS)</td>
</tr>
<tr>
<td>Outlet works gates</td>
</tr>
</tbody>
</table>

Different types of hydraulic steel structures.
CHAPTER II
HYDRAULIC STEEL STRUCTURES DESIGN

USACE HSS are typically designed for a 100 year service life. [3] The HSS that were inspected and used for examples and comparison range from 30 – 60 years old. When designing a new HSS or repairing an existing one, the engineer has to ensure that essential design requirements are satisfied so that the HSS will meet or exceed its design life. Some design considerations include strength, serviceability, fatigue and fracture, corrosion, and wear. Sufficient analyses including sizing of members, connection detailing, determining compatibility with adjacent features, and providing for corrosion resistance all must be performed and checked to ensure a safe, functional, and reliable design. [2]

Designing for resistance to distress and performing routine inspections for signs of distress in HSS within USACE is a significant aspect of mission support. Some forms of distress include fatigue damage and fracture, but corrosion is the primary form of distress and is the most readily apparent. [2] Because of this, it is important to maintain routine inspections and make expeditious repairs so that the design life of the HSS is not jeopardized.
In general, HSS should be inspected at least every 25 years, however fractural critical members (FCM) of HSS are required to be inspected every five years. There are several factors that can influence the scheduling of the inspections, such as expense of dewatering, the potential of loss of life due to failure, previous inspection findings, and damage during operation. [2] It has proven to be more efficient in most cases to inspect the entire gate on the same routine cycle as the FCM while the gate is dewatered, accessible, and out of service. Inspection times vary depending on the type of structure. For instance, stoplogs are inspected while in storage and not being used, or prior to their next use, while, miter gates are dewatered during low water and during times that would least impact commercial river traffic. HSS inspections require a minimum of two inspectors, due to safety reasons and to ensure a thorough inspection. The average inspection can last from a couple of hours to a several days, depending on various factors such as access to the HSS, the condition of the HSS, the size of the HSS, and weather. When inspecting HSS and preparing a report, there are no specific grades for condition of the HSS. Typically the inspectors will provide specific issues found during the inspection, but will also provide general conditions such as “good”, “fair”, and “poor” similar to what is done for bridge inspections. Depending on the severity of the issues found, such as cracks in FCM, severe corrosion, or damage that hinders proper operation of the HSS, repairs will be made immediately or budgeted for in an upcoming fiscal year.

Corrosion on a steel structure can seriously weaken or impair its operation and expected design life. Therefore, the effect of corrosion on the strength, stability, and serviceability of HSS must be considered in new design and evaluated after inspection. Corrosion may have an effect on bending, shear, and bearing of the HSS steel members.
The major degrading effects of corrosion on HSS structural members are the loss of cross section, buildup of corrosion at connection points, and pits that induce a notching effect or micro cuts into the metal surfaces.

Reduction in section area in a member causes a reduction in the strength and loss of structural stiffness, leading to increased stress levels and even deformation [4] without any change in loading. The buildup of corrosion is most damaging at connections, which can cause a prying action, also known as corrosion packout or pack rust. [5] Stress concentrations that are induced by pits or micro cuts can significantly increase the stresses at this point, which can lead to fatigue cracks or fracture.
Corrosion is the degradation of a material due to a reaction with its environment. Some forms of corrosion are purely electrochemical reactions while other forms result from mechanical factors. Generally, HSS are susceptible to three forms of corrosion which include general atmospheric corrosion, localized corrosion, and mechanically assisted corrosion. [5]

General atmospheric corrosion is defined as a corrosive attack that results in a thin uniform spread over a wide area, as seen in Figure 3.1. It is very commonly found to occur in the typical ambient environment of HSS. General atmospheric corrosion was found during most of the inspections completed on HSS items that were used for this examination. Since HSS are used to control water, the amount of steel that is exposed to an ambient environment fluctuates, such as Tainter gates and miter gates. In the case of the stoplogs that are stored in ambient environments, such as on a barge or in a storage yard until their use is required, general atmospheric corrosion is very common, as seen in Photos 2 and 3. However, this type of corrosion is not likely to cause significant structural degradation.
Figure 3.1  General Atmospheric Corrosion of the Upper Part of a Tainter Gate on the Ouachita River in Louisiana.
Figure 3.2   General Atmospheric Corrosion on a Stored Dam Stoplog on the Red River in Louisiana.
More harmful to HSS than general atmospheric is localized corrosion, and there are five types. These types include crevice corrosion, pitting corrosion, galvanic corrosion, stray current corrosion, and filiform corrosion [5], all of which have been commonly found during inspections.

Crevice corrosion occurs in narrow openings that are between two contact surfaces. Most of the HSS inventory inspected are welded structures, so bolted connections are minimal. However, crevice corrosion was prevalent in bolted connections such as a dam stoplog that has a seal bar clamping the rubber J-bulb seal to the skin plate,
as seen Figure 3.4. There are numerous HSS in this inventory that are strictly riveted and in these structures, it is not uncommon to find crevice corrosion between plate connections. It can also occur between a steel component and a nonmetal one (e.g., under rubber seals, paint layers, debris, sediment build up, or organisms trapped on the HSS members). Crevice corrosion can lead to blistering of the paint which leads to failure of the paint system, and further increases corrosion. [5] Since environment cannot be controlled, all these factors are taken into consideration during designs and repairs.

Figure 3.4 Crevice Corrosion on a Dam Stoplog Seal Bar and Skin Plate.
Pitting corrosion typically occurs on bare metal surfaces as well as under paint systems. If the pitting occurs under the paint, it can result in the formation of a blister and failure of the paint system in that area. Localized pitting can produce stress concentrations, or stress risers that disrupt the stress distribution, creating a fracture initiation point and reduce the fatigue life. [5] Pitting corrosion is another form of corrosion that is very commonly found among HSS and a good example can be seen in Figure 3.5. This photo shows pitting in a vertical lift gate located in an intake tower in central Arkansas. This particular pitting is very common in this area and is found on most HSS in the intake towers in central Arkansas. It initially starts with a pinhole or holiday in the paint system. It then forms a rust nodule, and when that nodule is removed, the structure is left with a pit as seen in Figure 3.5. Pitting can occur on a steel member or in a weld. Pitting is also commonly found on the webs and flanges of horizontal beams in structures. This is mostly due to trapped water from inadequate drain hole size, clogged drain holes, missing drain holes, or improper storage, as in the case of stoplogs being stored at an angle and exposed to rain. When severe pitting has occurred, it is up to the engineer to structurally analyze the effects and risk of failure from newly introduced stress risers.
Galvanic corrosion can occur on HSS where steel members with dissimilar metals are in contact, and in some cases studies have shown it can even occur in the use of carbon-fiber-reinforced plastics (CFRP) and steel connections. [6] A galvanic series can be used to determine the electrochemical potential between the dissimilar metals. Figure 3.6 is an example of a galvanic series as it pertains to HSS. The metals in bold text in Figure 3.6 represent the most common metals found in HSS in the inspected inventory. ASTM G82-98, Development and Use of a Galvanic Series for Predicting Galvanic Corrosion Performance, should be used when developing a galvanic series. [7]
One consistent type of galvanic corrosion among the HSS inspected was, stainless steel studs welded to carbon steel members of gates, such as Tainter gates, for the mounting of sacrificial anodes in a cathodic protection system. Most sacrificial anodes on HSS consist of magnesium blocks that have carbon steel mounting brackets. If stainless steel studs are used, it leads to the accelerated deterioration of the mounting brackets. This causes the anode to lose its electrical connection, rendering the anode useless. Not only is the anode lost, but the stainless steel stud now causes galvanic corrosion with the carbon steel member of the gate, as seen in Figure 3.7.
A good comparison can be seen in some Tainter gates on the Red River in Louisiana. These Tainter gates have carbon steel studs for the mounting of the sacrificial anodes. As seen in Figure 3.8, the anode is corroding as designed and there is virtually no corrosion to the carbon steel gate. It is uncertain if this is the original anode, but this anode has been installed for a long time. The brackets have corroded, but have not lost the electrical connection between the gate and the anode bracket.
While for maintenance purposes it is quicker and easier to have stainless steel nuts and studs when replacing sacrificial anodes, it is much easier and less expensive to replace a corroded carbon stud than to cut out and replace a corroded area on a steel beam or plate of an HSS. Also, for most HSS it is very expensive and difficult to routinely dewater to monitor and replace anodes that are falling off or getting knocked off by debris. As shown, it is more likely to have more issues with galvanic corrosion with stainless steel studs than carbon steel studs.
It is very common for HSS to have carbon steel members and seal bars, but have stainless steel bolts in an attempt to ease the maintenance requirements. Seals are often damaged from debris and use. It makes it much easier to remove the seal bar to replace the seal if the bolts and nuts are stainless steel and have no corrosion, as opposed to carbon steel nuts and bolts that are typically corroded. However, this can cause a significant increase in corrosion for the carbon steel gate as seen in Figure 3.9, if not installed with proper preventive measures as discussed later.

Figure 3.9 Corroded Carbon Steel Seal Bar from Galvanic Reaction with Stainless Steel Bolts and Nuts.
Another good example of galvanic corrosion with the HSS inspected can be seen in Figure 3.10. This photo is of a roller gate that is constructed of carbon steel but has stainless steel rollers. The left photo shows the rollers in place prior to removal for a rehabilitation project. The right photo shows the carbon steel mount (after sandblast) that the stainless steel rollers were in constant contact with.

![Figure 3.10](image.png)

Figure 3.10  Galvanic Corrosion of Vertical Lift Gate that has Stainless Steel Rollers and is Located in a Dam Intake Tower in Mississippi.

Stray current corrosion may occur when sources of direct current are attached to the HSS, or unintended electrical fields from cathodic protection systems are generated. This can come from sources of direct current such as impressed current cathodic protection systems that are not properly monitored. [5] The stray current causes the steel connected to it to have paint failure and corrosion of the steel. Filiform corrosion occurs due to thin paint systems. It has the appearance of fine filaments emanating from one or more sources in random directions. [5]
Less commonly found corrosion types within the inspected HSS inventory included the three mechanically assisted corrosions: erosion corrosion, cavitation corrosion, and fretting corrosion. All are caused by external factors continually coming in contact with the material surface, removing the paint system and member section.

Table 3.2 clearly illustrates the 3 different forms of corrosion that HSS are susceptible to and the different types that fall under each form.

Table 3.2   Forms of Corrosion that HSS are Susceptible to.

<table>
<thead>
<tr>
<th>General Form</th>
<th>Specific Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. General atmospheric corrosion</td>
<td>Crevice corrosion</td>
</tr>
<tr>
<td></td>
<td>Pitting corrosion</td>
</tr>
<tr>
<td></td>
<td>Galvanic corrosion</td>
</tr>
<tr>
<td></td>
<td>Stray current corrosion</td>
</tr>
<tr>
<td></td>
<td>Filiform corrosion</td>
</tr>
<tr>
<td>2. Localized corrosion</td>
<td>Erosion corrosion</td>
</tr>
<tr>
<td></td>
<td>Cavitation corrosion</td>
</tr>
<tr>
<td>3. Mechanically assisted corrosion</td>
<td>Fretting corrosion</td>
</tr>
</tbody>
</table>

There are numerous factors that can influence HSS corrosion such as design details, material properties, maintenance and operation, environment, coating systems,
and cathodic protection systems. [5] Out of all of these factors, the environment is the only one that cannot be controlled to prevent corrosion of HSS.

Corrosion of steel increases significantly when the relative humidity is greater than 40 percent, which is very common in the South. Corrosion is also aggravated by alternately wet and dry cycles with longer periods of wetness tending to increase the effect. [5] All of the HSS inspected see wet and dry cycles, but the amount of cycles can vary significantly depending on the use and storage of the HSS.
CHAPTER IV
PREVENTIVE MEASURES

The primary preventive measures for corrosion on HSS are paint and cathodic protection systems properly designed to work together. The effectiveness of a protective coating system is highly dependent on proper treatment of the steel surface prior to the coating application. Additionally, inconsistencies in the paint system can lead to local coating failure, which could result in corrosion under the paint. Areas of HSS that are difficult to coat adequately such as sharp corners, edges, crevices, weld terminations, copes, rivets, and bolts are typically more susceptible to corrosion. [5]

Repairing previously corroded members with section loss and pitting is challenging because these members are difficult to adequately coat. Section loss on the edges of corroded members can create knife edging. This thin edge causes improper paint film thickness and can compromise the new paint system. Knife edging is typically found on stiffeners, and the bottom of triangular stiffeners of the Steele Bayou Vertical Lift Gates (Figure 4.1) and the diaphragm stiffeners between horizontal beams also found on the same HSS are examples (see Figure 4.2). Knife edging is not only limited to this type of HSS, but is prevalent in older HSS (30-60 years) and HSS that have continuous water control use, as far as passing or holding back large volumes of water. The large volumes of water lead to large amounts of debris impacts and innumerable wet and dry
cycles. Also, the HSS with knife edging mostly consisted of HSS that are very expensive
to dewater and repair/repaint, or very difficult to access. HSS items such as Tainter
gates, miter gates, and Tainter valves fall in this category and knife edging was typically
found during inspections.

Figure 4.1  Knife Edging on the Bottom Horizontal Beam Stiffeners on Steele Bayou
Vertical Lift Gate Located in Mississippi.
A method used to paint in crevices, welds, edges, and other difficult areas is called striping. It is typically done with a brush prior to the paint spray application, but can be done with other tools as well. The intent of this method is to provide the proper mil thickness of the paint coating in hard-to-reach areas that may not be adequately covered by a conventional spray method. Providing detailed job specifications that are applicable to the material being painted and the actual paint system will aid in achieving
a high quality paint system. Strict quality control and quality assurance methods ensures
the paint system is applied according to specifications. The use of standards published by
SSPC (Society of Protective Coatings) or NACE (National Association of Corrosion
Engineers) safeguard quality paint systems. The coating system applied to repair plates
or components must be compatible with the protective system of adjacent steel. [5]

Cathodic protection is a technique used to prevent or reduce the rate of corrosion
in HSS or other metal surfaces. A properly designed cathodic protection system creates a
galvanic reaction where the HSS is the cathode and that the sacrificial anode will corrode
first in the electrochemical connection. Typically an electrolyte such as water is required
to promote this galvanic corrosion. [8] Approximately 50% of the HSS inventory
inspected contains some type of cathodic protection. Stoplogs or bulkheads are the main
inventory that typically do not have cathodic protection systems due to the nature of their
use and storage.

HSS that are coated but do not have cathodic protection can form holidays,
der discontinuities in the coating, that result in corrosion. On the other hand, if an HSS has
cathodic protection but does not have a coating, the operational costs to maintain that
structure would be excessively high and inefficient. Combining both paint and cathodic
protection systems has shown to be the most economical and effective measure to prevent
corrosion on HSS within the inventory used for this research. [9] There are some
instances where the designer may determine that there is not enough benefit to utilize
cathodic protection for the added expense at fabrication and for maintenance during the
service life of the HSS. As in the case of a stoplog or bulkhead strictly used for
dewatering that is in storage a majority of the time. Also, there are some cases where a
designer may not fully understand or be aware of the benefits to having cathodic protection in conjunction with the paint system. Using EM 1110-2-2704, Cathodic Protection Systems for Civil Works Structures, in conjunction with NACE Recommended Practice RP0169-2002, will provide the most effective techniques for protecting HSS from corrosion.

For the intended outcome of the designed corrosion preventive system to be fully accomplished, the cathodic protection system must be compatible with the coating selected. A majority of the protective coatings used in HSS are compatible with cathodic protection systems, but there can be adverse effects to the coating if used together improperly. Determining compatibility will lead to the determination of which one is the primary means of protection. [9] NACE International Publication 6A100, Coatings in Conjunction with Cathodic Protection, should be referenced when determining compatibility of paint and cathodic protection systems.

4.1 HSS COATINGS

Quality control during application of paint is significant when it comes to coatings. Typically a coating will have an expected life span that may or may not be specified by the manufacturer. And for a coating to fulfill the specified life span, strict quality control must be maintained prior to and during the coating application process. Failure to maintain strict quality control during the coating application will jeopardize the life span of the coating. [10]

There are several types of coatings that are used on HSS by USACE that include polyurethane, coal tar epoxy, epoxy, and vinyl. [10] The vinyl paint system was prevalent with the HSS inspections used for this paper. This paint system is found to be
highly effective in resisting abrasive debris and corrosion. However, it has been noted by various maintenance personnel that once the paint system is damaged and breached, it is very difficult to repair, unlike the other paint systems. Vinyl is a very difficult paint system to apply even in a controlled shop environment by qualified personnel. Also, the vinyl paint system is heavily restricted in use as well as production due to the materials required to create the paint system and the volatile organic compounds (VOCs) emitted during the painting process.

Another painting method that has been implemented on HSS in other areas of USACE, not within the inspected inventory, is the duplex system. This system consists of dual protection with a zinc coating and a paint coating. First, a metallic zinc coating is applied to the steel and acts as a sacrificial layer for corrosion protection. The zinc can be applied in three ways: by a zinc-rich primer paint, by metalizing (hot zinc is sprayed onto the surface), or by galvanizing (steel is immersed in a molten zinc bath). Second, a paint coating is applied to the zinc-coated surfaces for additional protection and for an aesthetic finish. It is harder to achieve a good paint adhesion on a metallic zinc-coated steel surface than the traditional zinc primer coated bare steel surface. [11] This coating system is typically very expensive.

4.2 CATHODIC PROTECTION

It is standard practice for USACE to use cathodic protection systems in combination with protective coatings to alleviate corrosion of HSS. As mentioned previously, protective coatings by themselves are not completely corrosion resistant. Holidays will become increasingly permeable over time. Currently there are two types of cathodic protection systems used for HSS which include sacrificial anodes or impressed
current anodes. Sometimes a hybrid system that includes both can be installed on HSS.

The sacrificial anode system, also known as galvanic cathodic protection system, uses sacrificial anodes typically consisting of magnesium- or zinc-based alloys. These anodes are anodic in relation to the ferrous structure they are attached to, causing them to corrode at an accelerated rate compared to the structure. There is no external power source required for this type of system, meaning little maintenance is required. This system is designed to be consumed and the anodes must be routinely inspected and replaced. The inspection and replacement schedule could vary greatly, such as annually to every five years, depending on environmental factors and access. This requires the designer to place anodes in accessible areas. This system is recommended to be used on a well-coated structure that does not see significant amounts of damaging wear [12], from large debris impacts. This type of cathodic protection was commonly found on Tainter gates and vertical lift gates during the inspections.

The other type of cathodic protection system uses impressed current. This system consists of anodes that are made of durable materials that can resist electrochemical wear or dissolution. This system requires a power source to provide the impressed current. The impressed current system is a more complex design and requires more maintenance than the sacrificial anode. This system can be highly effective on poorly coated HSS due to the ability to adjust the protective current delivered over the life of the structure. [12] This type of cathodic protection system was commonly found on miter gates, where it is very expensive to dewater and would be difficult to access sacrificial anodes for inspecting and replacement.
High voltage impressed current systems can rapidly accelerate the deterioration of a paint system if the protection system is improperly maintained and operated. This applies to the systems that contain impressed currents which can be increased above the designed voltage threshold. This condition is called overvoltage and typically occurs on systems that are not continuously monitored [10], or where operators are not properly trained.

A good example of an impressed current system that is either inoperable or not properly maintained can be seen in Figure 4.3. This photo shows a miter gate in a lock on the Red River in Louisiana that has severe paint failure, corrosion, and section loss. It is very common for these types of cathodic protection systems to be damaged from debris in the river or boat/barge traffic in the lock chamber itself, as in the case of this system. Also, it is not uncommon for the knowledge of the particular impressed current system to be lost with the aging infrastructure and constant operational personnel change. This can lead to the improper maintenance and operation of the system, or even deter maintenance personnel from attempting to repair the system.
Figure 4.3  Corrosion of a Miter Gate on the Red River in Louisiana Due to Paint System and Impressed Current System Failure.
DESIGN CONSIDERSTIONS

When designing HSS there are several items that should be taken into consideration. In some instances it is necessary to have dissimilar metals in contact that are significantly far apart in a galvanic series as seen in Figure 3.6. In this case it is best to provide an electric insulator such as a nylon washer, dielectric grease, a thick paint coating system, etc., between the two metals and avoid large ratios of cathode to anode area. Both metal surfaces should be painted as well. [5] The most common coupling of dissimilar metals in HSS is stainless steel and carbon steel. If this coupling is not properly insulated and painted, galvanic corrosion will occur and accelerate corrosion of the carbon steel once it is initiated. [13]

Another design consideration to account for is structural detailing. In general, continuous welded connections are more resistant to corrosion than bolted connections due to the weld sealing the adjacent surfaces. Small volumes of water can be trapped under fasteners and between plies that are not sealed in bolted connections, causing crevice corrosion. Most of the HSS that were inspected are continuously welded structures, however, there are some structures that were found to have intermittent welding. Those with the intermittent welding did not show signs of crevice corrosion due to the proper sealer, such as paint mil thickness or caulking, at the joint.
When repairs are required, they should be detailed to compensate for conditions that contribute to corrosion. Components should be detailed so that all exposed portions of the repair can be painted properly. Sharp corners or edges should be ground off flat or rounded to allow paint to adhere properly. Horizontal plates should have drain holes to prevent the entrapment of water. The drain holes should be located at the lowest position with the size generally in the range of 1 in. to 3 in. in diameter. The cut edges of the drain holes should be smooth and free of notches. All weld imperfections such as slag, weld splatter, or any other deposits of the steel should be ground off. [5]

Even though HSS may be exposed to the same environment type, thickness loss of the structural steel can vary significantly. Increased thickness of a member should be added to steel members of HSS in certain situations such as where the calculated load nears the capacity of the axially loaded members and maximum moment areas of flexural members for load resistance factor rating (LRFD), or where the calculated stress nears the allowable stress when LRFD is not applicable and allowable stress design (ASD) is required. [14] Typically HSS are designed using LRFD, however, there are instances in current guidance that require ASD since LRFD methods have not yet been developed. Also, some HSS members are difficult to access for maintenance and it is known that members will incur some corrosion and section loss over the design life of the HSS. Therefore, minimum and increased thicknesses are required during design. The minimum steel thickness of any member is 3/8 inch. For members that are difficult to access, the thickness is increased a minimum of 1/8 inch beyond what is required from the design. [3]
Corrosion-fatigue, the reduction in the fatigue life of a steel member, should also be taken into consideration during the design phase. This consists of a combination of pitting, crevice, and stress corrosion. [4]. HSS that see fluctuating loads and are subjected to a corrosive environment should look at strain-life fatigue-corrosion models relevant to the material and environment. [15]
There are two prime examples of HSS that show the difference between proper and improper corrosion resistance design. These HSS are the Muddy Bayou Drainage Structure vertical lift gates, Figure 6.1, and the Little Sunflower vertical lift gates, Figure 6.2. There are two gates at each structure. Both sets of gates were put into service in 1977. The structures are approximately 20 miles apart in central Mississippi. Muddy Bayou Drainage Structure was put into service as an aquatic restoration structure used to regulate water levels for the Eagle Lake area, with minimal flood control. Little Sunflower Drainage Structure is part of the Yazoo Backwater Project that serves the purpose of protecting areas that are affected by the Mississippi River and its backwaters.
Figure 6.1  Muddy Bayou Drainage Structure Vertical Lift Gate Removed from the Slot for Maintenance.
These vertical lift gates have equivalent environmental factors due to their close proximity and shared drainage areas. The average humidity in Mississippi is above 50%, making it an ideal location for corrosion of HSS. These gates are operated regularly to control water levels, therefore the gates see a significant amount of wet and dry cycles over the entire gate. The drainage area of these two structures is comprised of agricultural land and wooded land. This will have an effect on the pH level of the drainage water depending on exactly what chemicals are involved. Typically corrosion occurs at low pH (highly acidic conditions) or at high pH (highly alkaline conditions) levels. [5]
Both the Muddy Bayou and Little Sunflower vertical lift gates are constructed with 36 ksi mild carbon steel that was painted with a 4 to 5 coat vinyl paint system. The main difference in the gates at each structure is that the Muddy Bayou vertical lift gates were fabricated with a sacrificial cathodic protection system, while the Little Sunflower vertical lift gates were fabricated with no cathodic protection system. Based on available design documentation, the only reasoning stated as to why no cathodic protection was used for Little Sunflower gates is because it was determined unnecessary to add cathodic protection to the Little Sunflower vertical lift gates since they were anticipated to be completely free of water on the riverside (skin plate side) of the gates for approximately 20 percent of the time and would be completely submerged only 20 percent of the time in service. Now, the gates at Little Sunflower are completely submerged approximately 24 percent of the time and the gates are completely out of the water only approximately 5 percent of the time. It appears the Little Sunflower gates have seen more use, which led to more wet and dry cycles than originally anticipated by designers. However, minimal cathodic protection should have been installed during original fabrication, which is evident as seen later in this case study.

As seen in Figure 6.3, the sacrificial anodes are working properly for Muddy Bayou vertical lift gates by deteriorating faster than the steel gate. The anode used for the cathodic protection system of Muddy Bayou consists of an 8”x8”x2” magnesium anode. Sacrificial anodes made of magnesium are good for HSS such as Muddy Bayou, based on the distance that magnesium and mild steel are from each other on the galvanic series seen in Figure 3.6, and that magnesium is less noble than mild steel.
Both sets of gates have had minimal maintenance over their life span. Little Sunflower vertical lift gates were repainted around 1998. The surface prep and painting were both done in the field. Surface prep for this painting consisted of cleaning the whole gate with a pressure washer and providing more local surface preparation with a wire brush and grinding wheel in some areas. The paint system used was an aluminum oxide red metal primer. At least two coats were applied with an airless sprayer. The Muddy Bayou gates were removed in 1995 to replace the rubber seals. The only steel that was found to be corroded were the steel bars that hold the rubber seals in place (see Figure 6.4). These bars were isolated from the cathodic protection system, and the steel
bars consisted of mild steel while the bolts are stainless steel. These factors allowed for accelerated corrosion. The steel bars were replaced with new painted bars. Also, a wire brush was used to clean other minor areas of corrosion on steel members and touch-up paint was applied. The gates were recently painted and some sacrificial anodes were replaced subsequent to the inspection that the photos for this study were taken.

Figure 6.4   Typical Corroded Seal Bar on Muddy Bayou Gates.

Little Sunflower has suffered significantly more corrosion due to the improper corrosion control measures taken during original design, fabrication, and maintenance, even though minimal maintenance was provided. Also, improper surface preparation and paint application during the repainting of the gates, plus the aluminum oxide red metal
primer used as the paint system, had a significant effect on the rate of corrosion and section loss. Figures 6.5 – 6.7 illustrate the severity of the corrosion on these gates. Figure 6.5 shows a bay at mid height of one of the Little Sunflower gates. At this location there is a joint between the upper and lower halves of each gate with a rubber seal that runs horizontally. The two halves are connected by a bolted connection at each vertical stiffener, as seen in Figure 6.5. Note the paint system failure, general corrosion, and pitting of the plates and the section loss in the stiffeners and flanges. It is apparent where the red primer paint was placed over the original grey paint in some areas. Figure 6.6 shows severe section loss of flanges and the vertical stiffeners, along with general corrosion of the plates. This particular photo was taken near the bottom of the gate and is typical of the bottom halves of each gate at Little Sunflower.

Figure 6.5  Severe Corrosion and Section Loss of Little Sunflower Vertical Lift Gate.
For the Little Sunflower gates, the corrosion was more severe at the bottom of the gate. This raised concern due to the loading and purpose of the gates. Due to hydrostatic loading, there are higher pressures near the bottom. Figure 6.7 shows the section loss in the triangular stiffeners of the bottom of the gate. This is due to a combination of paint system failure, no cathodic protection, debris impacts, and erosion corrosion. As previously stated, these gates are used for water control and can see significant flow under the gate when it is raised in various positions, increasing the potential for erosion corrosion.
A fitness-for-purpose analysis of the Little Sunflower gates in their current condition was performed. The gates were modeled by the USACE Engineer Research and Development Center (ERDC), Information Technology Laboratory using ABAQUS finite element software. The fitness-for-purpose analysis allowed for the determination of critical flaw sizes at various locations in the structure. The condition of the gate that was input for the model was determined by what was noted in the most recent inspection report. Characteristics such as deterioration, section loss, damage to members, and weld defects were applied to the current condition model. The model illustrated how the stresses in the stiffeners increased significantly where section loss due to corrosion is present, as seen in Photos 18 and 19. The results from the finite element based stress analysis showed that the corrosion on the gates induced an increase of 2+ ksi in local
stresses, creating unwanted stress concentrations at the horizontal beam to skin plate connections, and minimized the factor of safety. Using Von Mises stresses, the analysis showed an actual/allowable ratio close to 1, where anything over 1 indicates stresses beyond the allowable, and even below 1 for maximum principal stresses on some elements. Other results from the fitness-for-purpose analysis showed allowable sizes for defects such as edge cracks and holes that could be used during subsequent inspections to determine the maximum acceptable flaw sizes. [16]

Based on the results from the inspection and analysis, new vertical lift gates were designed and fabricated for Little Sunflower Drainage Structure (see Figure 6.8 and Figure 6.9). Corrosion preventive measures such as sacrificial anodes for cathodic protection, epoxy paint coating, galvanic corrosion resistant connections, and proper quality control and assurance were incorporated in the design and fabrication. The total cost to fabricate the new gates, remove the old gates, and install the new gates was approximately $1 million. The installation required careful planning and special equipment to avoid removing the operating machinery above each gate.
Figure 6.8   New Vertical Lift Gate for Little Sunflower Prior to Shipment to Site.
Figure 6.9 Top Half of New Vertical Lift Gate During Installation.
CHAPTER VII
CONCLUSION

To ensure an HSS will last its intended design life, it is imperative that proper corrosion prevention measures are taken into consideration during the design, implemented properly during fabrication, and maintained throughout its life. A properly designed HSS, with its paint system and cathodic protection system, will prevent costly corrosion damages that are avoidable when all the previously discussed aspects are taken into consideration. It is critical to ensure that all the designed aspects of an HSS are fabricated properly and with quality. Proper maintenance and repair are essential to preventing and controlling corrosion of HSS. To ensure proper maintenance and repair, these structures should be periodically inspected for corrosion or damage and cleaned of debris and sediment buildup. Any areas of deteriorated paint coatings should be cleaned by wire brush, sand blasting, etc., then repainted according to industry standards such as SSPC and NACE. Steel members that have severe corrosion or corrosion outside of design tolerances should be repaired or replaced to American Welding Society (AWS) welding code D1.1 or D1.5, depending on the role of the steel member. Missing, damaged, or severely corroded cathodic protection should be replaced. Impressed current cathodic protection systems should be tested periodically to verify correct voltage as to
not cause accelerated deterioration of both the paint system and steel members, leading to costly repairs to USACE infrastructure.

*The views in this thesis are those of the author and do not necessarily represent those of USACE.

All photos included in this thesis were taken by the author.
REFERENCES


