Duluth-Superior Harbor Freshwater Corrosion Update

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Abstract

In the early 2000's, it was discovered that the steel sheet piling in the Duluth-Superior Harbor (DSH) was corroding at a rate much greater than observed in other Great Lakes fresh water harbors and ports. Much of the port's over 13 miles of steel sheet pile walls are heavily pitted, with several facilities having severe perforations entirely through the steel sheets. Holes as large as 10 inches or more in diameter have now been discovered. Once the Duluth-Superior accelerated corrosion had been discovered and reported, other Great Lakes ports and harbors also started to observe steel corrosion issues in some structures, although not as severe as in the DSH.

Since the fall of 2004, a multi-partner project steering committee has provided a detailed, systematic focus for the needed research and mitigation recommendations to determine the cause and extent of the corrosion, as well as explore potential methods for the repair of existing damaged steel sheets. Funding was secured for several focused studies to answer why the accelerated corrosion is occurring, and determine potential options to slow or eliminate corrosion on existing and new steel structures.

This paper will 1) update the extent of accelerated fresh water corrosion observed in both the DSH and other Great Lakes harbors, 2) discuss the results of completed and on-going studies to determine the cause(s) of the accelerated harbor corrosion, and 3) explore methods being tested for steel structure mitigation and protection.

Preliminary test results indicate that iron-oxidizing bacteria are present on the corroded structures, and testing continues to determine whether these or other bacteria may be causing the accelerated corrosion. Protective coating trials have shown promising results for protecting steel structures. Testing continues to explore how different coatings withstand the severe ice impact and abrasion observed in the DSH and other cold region environments during winter conditions. Several of the alternative corrosion control product tests have also shown promising results for extending the usable lives of existing structures.

Background of Duluth-Superior Harbor Corrosion

The Duluth, Minnesota and Superior, Wisconsin shared harbor is located on Lake Superior and fed fresh water by the St. Louis and Nemadji Rivers. In 1998, it was discovered that many marine structures in the DSH were experiencing significant corrosion and pitting levels higher than typically experienced in fresh water harbors. Figure 1 shows severe corrosion levels characteristic on harbor structures.

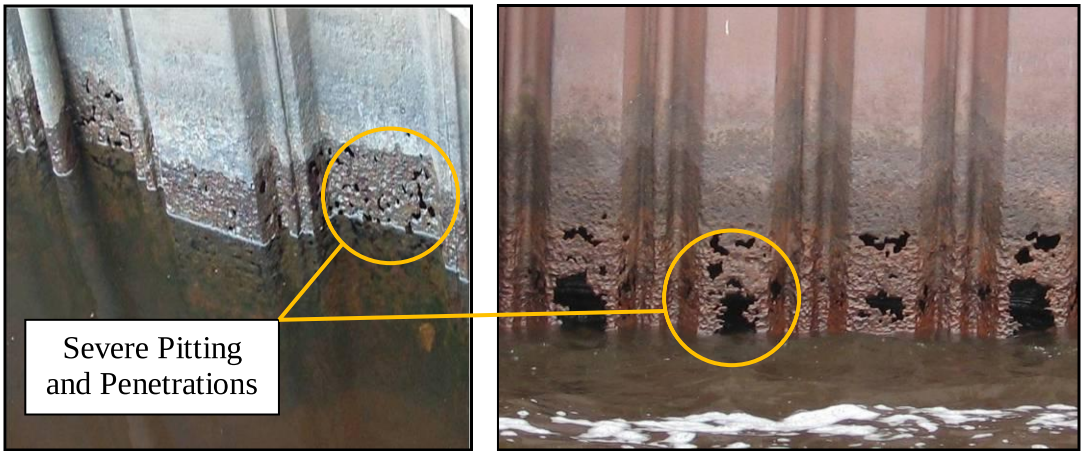

Figure 1. Typical Corrosion Found on DSH Sheet Pile Structures

In fall of 2004, a panel of corrosion experts was brought to the DSH with the financial support of numerous federal, state, local, and private agencies to view the accelerated corrosion and recommend further action items. The panel made recommendations on both short and long term investigations necessary to:

1. Document the extent of harbor steel corrosion, especially on critical structures.
2. Determine corrosion rates and establish a corrosion rate monitoring program.
3. Identify the cause of the accelerated corrosion.
4. Develop standard replacement designs using coatings and cathodic protection.
5. Test or develop alternative protective or repair systems for existing or new structures.
6. Initiate a corrosion characterization survey of other Great Lakes port facilities.

Following the panel's recommendations, many studies have been initiated with most carrying on through today. A summary of the team's findings regarding the extent, causes of, and solutions to the accelerated corrosion are found in the following sections.

Extent and Rate of Accelerated Corrosion

Investigations initiated by the study team have found that advanced pitting is found on all unprotected steel structures in the DSH. The corrosion is especially pronounced in areas around 0.5 to 3.3 meters (1 to 10 ft) below water surface levels. Depths greater than 3.3 meters show little to no corrosion. Table 1 shows a summary of the average corrosion rates and pitting found at different depths.

Table 1. Corrosion Rate and Pitting Summary

Distance Below MLW	Average Yearly Corrosion Rates	Pitting Levels
0.0 to 0.2 Meters (0.0 to 0.5 Feet)	Minor 0.01 - 0.04 mm/y (0.4 – 1.6 mils /y)	Low Concentration Small Uniform Pits
0.2 to 1.2 Meters (0.5 to 4 Feet)	Significant 0.04 – 0.10 mm/y (1.6 – 3.9 mils /y)	High Concentration, Large Diameter Deep Pitting and Perforations
1.2 to 3 Meters (4 to 10 Feet)	Less Severe 0.02 – 0.07 mm/y (0.8 – 2.8 mils /y)	High Concentration, Medium to Small Pitting
>3 Meters (> 10 Feet)	Minor 0.01 - 0.04 mm/year (0.4 – 1.6 mils /y)	Small Concentrated Pitting Resembling Etching

The corrosion rates listed in Table 1 summarize a compilation of many underwater investigations and measurements taken on structures throughout the harbor, and are similar to rates typically found in *salt water* environments. Data collected also suggests that the corrosion rates in the harbor abruptly increased in the mid-1970’s due to reasons not yet understood.

Steel structures constructed prior to the mid-1970’s exhibit similar corrosion levels regardless of their age, while structures installed after the mid-1970’s show degrees of corrosion proportional to their period of immersion in the harbor.

To measure and monitor current corrosion rates in the harbor, a series of test samples were installed at several DSH sites in 2006 and 2008. At each location, eight 10mm (3/8 in) thick uncoated steel coupons with measured weights and dimensions were installed at a depth of 1.2 meters (4 feet). A coupon is removed from each site every 6 months, cleaned, and measured to determine its physical losses and pitting depths. Examples of sample appearance before cleaning (left image) and after (right image) are shown in Figure 2.

Figure 2. Uncoated Test Coupon Before and After Cleaning

Results of the testing to date show uniform corrosion rates between 0.043 mm to 0.095 mm (1.7 to 3.7 mils) loss per year which is consistent with the long term degradation rates shown in Table 1.

To determine the current average corrosion rates throughout the harbor, Linear Polarization Resistance (LPR) measurements were taken at a series of sites in 2006. The LPR testing equipment monitors the current flowing between electrically charged electrodes and calculates the instantaneous corrosion rates found in the water. The results from the study matched the long term corrosion rate of other harbor studies, indicating that the equipment will be useful in monitoring instantaneous rates in the future.

It is important to note that *average* thickness of unprotected steel structures will deteriorate at these values, but *pitting rates* will be approximately 7.5 times higher. These higher pitting rates need to be taken into consideration when estimating the expected remaining useful life of unprotected steel.

Observations have also shown that severely corroded areas are usually accompanied by orange tubercle growths on the surface of the steel. Figure 3 shows the appearance of the tubercles before (left figure) and after (right figure) cleaning in a lab environment.

Figure 3. Tubercle Growths Associated With Corrosion

Cause of Accelerated Corrosion

While the exact origin of the accelerated corrosion has not yet been positively identified, many potential sources have been ruled out through the team's investigations, and the likely cause has been identified.

Analysis shows that the date of original manufacture and the metallurgy of steel structures do not appear to be significant factors in corrosion levels. Water quality measurements have shown that temperature, pH, dissolved chloride and oxygen, and conductivity levels in the DSH are typical of other fresh water harbors with normal corrosion rates; and that water chemistry does not appear to be a direct cause.

The DSH is relatively unique as a large high voltage (250 kV) DC power transmission line terminates in the vicinity of the harbor. The initial 2004 corrosion panel listed stray current from the line as one of the potential causes of the acceleration as this phenomenon has been shown to cause increased corrosion at other locations.

This source was ruled out during a 2008 test where the voltage on the line was manipulated by the line's operator in order to induce current into the ground. Simultaneously, electrical current and voltage potentials between test probes placed in the harbor water were monitored at several sites. No correlation was found between the power line voltage changes and harbor water current and voltage levels, eliminating stray DC current as a contributor to the corrosion acceleration.

Analysis by the University of Minnesota Duluth and the Naval Research Laboratory of the test coupons installed in the harbor in 2006 to 2008 show that a probable principle corrosion acceleration mechanism is Microbiologically Influenced Corrosion (MIC). MIC is a general term for corrosion resulting from the presence and activities of micro-organisms on and near steel structures, and is not normally found in fresh water harbors.

In-situ biological samples are collected from the test coupons removed from the harbor and are then tested for DNA structure, cultured, and analyzed using electron microscope technology. Figure 4 shows examples of micro-organisms found on tubercle growths (left image) and steel test coupons (right image) as observed through an electron microscope.

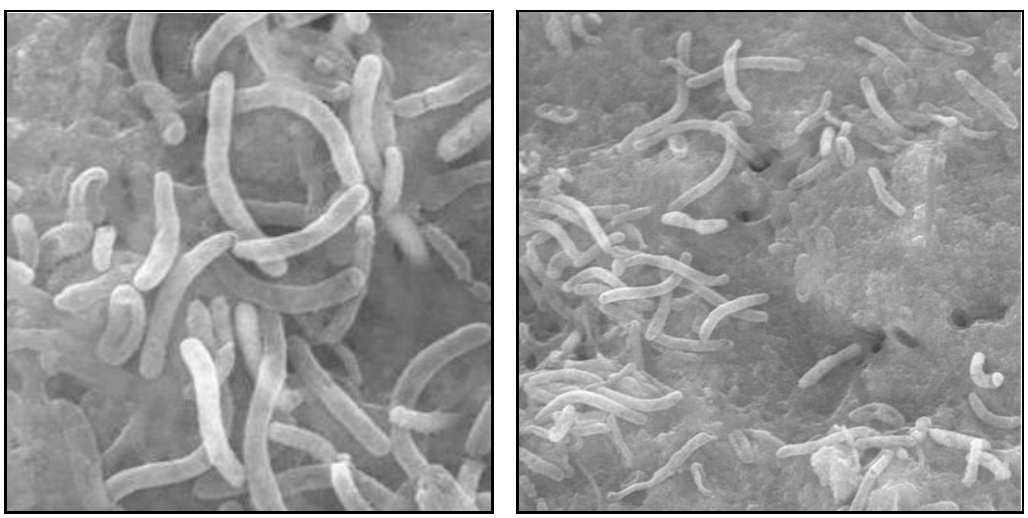

Figure 4. Micro-Organisms Viewed Through Electron Microscope

Presence of these micro-organisms results in small physical or chemical differences in the metals or surrounding environment which has been shown to cause pitting, crevice corrosion, differential aeration cells, metal concentration cells, selective de-alloying, increased erosion, and increased galvanic corrosion.

Coupons will continue to be removed periodically from the test sample sites and undergo further analysis. Testing is being carried out to confirm which forms of MIC or other bacteria may be causing or directly influencing the accelerated corrosion and to potentially develop solutions that inhibit the sources.

Protection & Remediation System Testing

Corrosion in the harbor is occurring at a rate that will require replacement or reconstruction at many facilities within 10 years as well as greatly reducing the expected life of new steel structures installed in the DSH. Therefore, an element of the team's analysis has been to test alternative systems designed to protect new and existing steel structures from corrosion and/or reinforce existing structures and extend their useful life.

<u>Coating System Evaluation</u>

Several coating trials have been initiated to evaluate the ability of different coating systems to prevent the unique corrosion found in the harbor as well as stand up to the ice forces experienced during the winter months.

In the spring of 2007, test coupons similar to the uncoated steel samples described previously were covered with various coatings from six different manufacturers, and installed at a number of sites throughout the harbor. Scribes were made to bare metal on each of the coupons to simulate damage from ice or vessel impact.

In late 2008, the coupons were removed from each of the test sites and inspected. Visual observations were documented on all samples, and some coupons were analyzed for corrosion loss and biological growth testing. Analysis showed no signs of loss of adhesion anywhere including near the scribed areas. A typical coated test sample removed for inspection is shown in Figure 5.

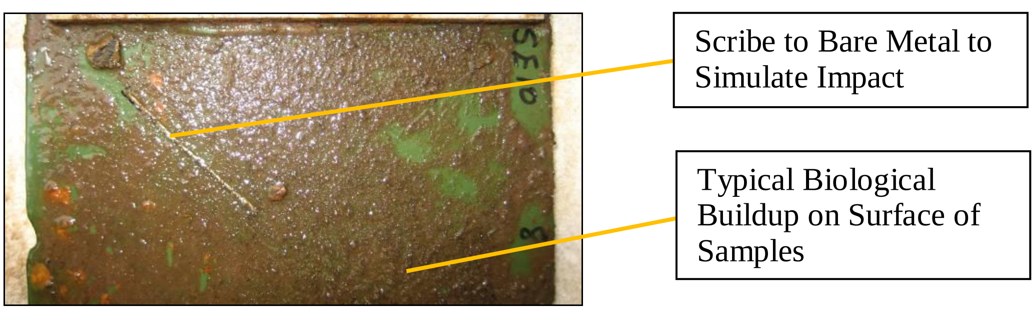

Figure 5. Coated Test Coupon

In the fall of 2008, a test was begun to evaluate different coating abilities to hold up to actual DSH ice abrasion and impact. Freeze ice thicknesses in the harbor range from 0.5 to 1.2 meters (1.5 to 4.0 ft), with an additional 0.5 to 1.5 meters (1.5 to 5.0 ft) of stack and pack ice typically found along harbor walls. The abrasion effects on coatings from ice expansion and contraction are significant, but even greater damage can be caused from ice impact – especially in the late fall, early winter, and spring when shipping is active in the ice covered waters.

The impact test installed a total of 18 total samples, each coated with one of 9 different coatings. Shown in the left image of Figure 6, the 1 meter (3 ft) long samples were fabricated from steel channels, sandblasted, coated, and mounted on a pier along a high shipping traffic channel in the harbor. The samples were installed in the heaviest ice impact and corrosion zones, with their top edges just above MLW (Mean Low Water datum) as shown in the right image of Figure 6. The test samples will be inspected yearly and coating thicknesses, adhesion, and overall conditions will be recorded.

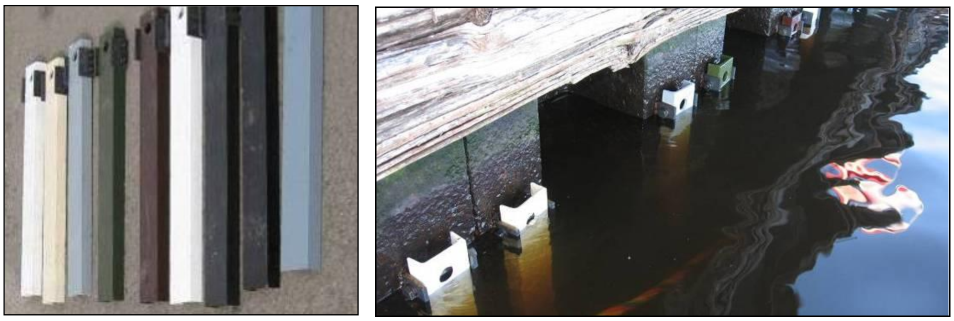

Figure 6. Ice Abrasion Samples Before and After Installation

In addition, six sites in the DSH already with full scale coating systems in place (including one with over 1200 ft of coating and another with over 850 feet of coating) are being monitored yearly beginning in 2008 to determine each coating's effectiveness against corrosion and its resistance to wear and impact from ice. The average of ten coating thickness readings, adhesion, and overall conditions at each site will be recorded. 2008 results revealed that all of the coatings were in good condition except for one coal tar epoxy example which had completely disappeared after being applied over twenty years ago.

In August of 2009, a full scale test was initiated to evaluate the ability of different coatings to protect existing corroded steel sheet piling from further corrosion as well as withstand ice forces. Eight different and unique coatings with good impact resistance and rapid cure times were installed adjacently on a sheet pile wall near a high ship traffic area in the harbor. Approximately 170 square feet of each coating were installed from a portable cofferdam after sandblasting the metal to SSPC-10. The coated surfaces extended from about 0.7 meter (2 feet) above to 3.3 meter (10 ft) below the harbor water line. An example coating application is shown in Figure 7.

Figure 7. Side By Side Full Scale Corroded Sheet Pile Coating Trial Examples

Each coating will be evaluated for ease of installation, cost, corrosion prevention, ability to resist ice abrasion and impact, as well as bonding adhesion to the base metal. Testing and evaluations will be performed initially and on a yearly basis to ascertain each product's thickness losses, adhesion, and overall condition and performance in harbor conditions. Results of the all sample and full scale corrosion, abrasion and impact monitoring will be published for use in the DSH and other fresh cold water regions.

<u>Alternative Repair Methods</u>

In order to test or develop alternative protective or repair systems for steel structures in lieu of standalone coating systems, three different full scale alternative corrosion protective systems were installed between 2005 and 2008 and are being monitored. Existing steel piles adjacent to a main channel in the harbor were chosen as the high ship traffic will expose each to the highest level of ice impact found in the harbor. All systems were installed to protect an area from 1 meter (3 ft) above to 3 meters (9 ft) below MLW, protecting the heaviest ice impact and corrosion zone.

The systems installed were chosen for their low installation costs, proven abilities to protect against corrosion in less rugged environments, low coefficients of friction, ease of installation, and durability against ice impact and abrasion.

The first system is comprised of an H shaped fiberglass jacket installed around an existing steel H-Pile. The jacket is fabricated in two halves which are held together by tongue and groove closures. Dimensions of the fiberglass jacket were customized to create a 25 mm (1 in) void between it and the steel. Epoxy grout is pumped into this space, forming bonds with the steel and fiberglass and preventing further corrosion. This system also has an added advantage as it provides some structural benefits in addition to corrosion protection.

A second system similar to that described above was installed on an adjacent H-Pile, with the difference being that the cover is rectangular rather than H shaped. While this system is more flexible as its dimensions do not match specific H shapes being protected, installation costs become less attractive as more epoxy grout is required.

The final system is designed to protect cylindrical steel pipe pile. The outer jacket cover of this system is fabricated from high density polyethylene (HDPE). Petrolatum paste is used to fill any large pits on the steel surface and create a seal to prevent direct contact between water and steel and resulting corrosion. The jacket is installed and joined with bolts which are tightened to force out any water and air, and protect the inner corrosion inhibiting components from damage by external forces. Pictures of the H-Shaped (left figure), rectangular (middle figure) and pipe (right figure) protective systems are shown in Figure 8.

Figure 8. H-Shaped, Rectangular, and Pipe Pile Protective Systems

The project team inspected the three pile protection systems in the spring of 2009 and all systems survived the winter of 2008-2009 severe ice conditions without damage and remain sound. The team will continue with systematic yearly observations of each system's ability to withstand ice impact and abrasion forces and publish results for use by harbor and other cold region port facility owners and managers.

<u>Cathodic Protection</u>

In the fall of 2008, the team began a cathodic protection system (CPS) trial to evaluate the effectiveness of these systems in the harbor as compared to other fresh water installations, and to assist in calculations for future full scale CPSs.

Sacrificial magnesium anodes were attached to two steel pipe samples with known measurements and weights and submerged in the harbor; one uncoated and one coated with a full length scribe to bare metal to simulate ice damage. The electric potential between the anodes and pipes were adjusted to levels typical of full scale systems. Three unprotected pipe samples were installed as references; one coated with scribe, one uncoated, and one uncoated and attached to existing sheet pile.

Preliminary observations show that CPS systems appear to be effective against DSH corrosion, although some tubercle growth has been observed on protected samples - although less severe than those unprotected. Figure 9 shows the condition of a coated pipe with no visible corrosion (left image) and the tubercle growths forming on the unprotected sample (right image) after only 8 months of immersion.

Figure 9. Pipe Samples With and Without Cathodic Protection

A full analysis of the samples will be conducted in December 2010 including documentation of corrosion losses, anode consumption, electrical potential and current variations, and possibly biological testing similar to other parts of the studies.

Corrosion Levels at Other Great Lakes Ports

Once the accelerated corrosion in the DSH had been discovered and reported, other Great Lakes ports and harbors also started to observe steel corrosion concerns in some structures, although usually not as severe as in the DSH. In the summer of 2009, a full inspection of another corroded Lake Superior harbor structure was conducted. Water, biological and steel samples were collected for analysis to compare corrosion and environmental conditions to the DSH. Visual observations and non destructive testing show the corrosion levels and overall deterioration to be very similar to the DSH; with the only notable difference being the lack of zebra mussels at the site. Figure 10 shows an example from this location (left figure) while the center and right figures are examples from other Lake Superior harbors.

Figure 10. Other Harbors With Lake Superior Corrosion Examples

Additional formal inspections and analysis are being scheduled for the coming years in other Great Lakes harbors to further determine the extent of corrosion problems, and if the cause for the DSH accelerated corrosion is isolated or widespread.

On-Going & Future Studies

In addition to monitoring the already initiated long term coating and alternative protection trials and investigating for accelerated corrosion at other ports; further biological testing will continue in order to determine the exact cause and origin of the MIC, as well as potentially develop a means to inhibit their influence on harbor structures. Additional full scale coating and alternative technology protective systems will also be installed and monitored for effectiveness.

Conclusion

Results from our studies to date have established average steel corrosion rates in the DSH, initiated a long term corrosion rate monitoring program to alert of any changes, and shown that the accelerated corrosion problem is not isolated to this harbor. Analysis has shown that the source of the acceleration is likely related to MIC, and final results in regards to the exact nature MIC is contributing is expected to be reported soon, and work to find a means to mitigate the problem will begin. Long term testing already initiated, in conjunction with trials that will soon start, will determine the best coatings and protection technologies that will prevent corrosion in the DSH as well as other fresh water harbors experiencing similar deterioration.