

A NACE International White Paper

CORROSION CONTROL PLAN FOR BRIDGES



NACE[®]
INTERNATIONAL

THE CORROSION SOCIETY

1440 South Creek Drive
Houston, TX, USA 77084-4906
+1 281-228-6200
www.nace.org

November 2012

Contents

- Introduction i
- Acknowledgments..... ii
- Executive Summary 2
- Crumbling Infrastructure..... 4
- Introduction to Corrosion 6
- Bridges to Everywhere 7
- Corrosion Basics 11
- Corrosion in Concrete 14
- Exposure Conditions 18
- Corrosion Control 21
- The Highway Ahead 27
- References..... 29

Introduction

There is essentially no argument that the American infrastructure is in poor shape and there is little indication that significant improvement is on the horizon.

The amount of money needed to correct this problem is staggering, especially considering the current state of the economy.

One reason for this is the age profile of the nation’s bridges. Figure 1 shows this profile taken from the 2010 National Bridge Inventory¹. It shows bridges are approaching the maximum age distribution of around 50 years. Most bridges were built for a 50 year design life, which means state highway departments will have to maintain those bridges beyond their original design lives, which will be challenging because they were built to lower design standards than those used today.

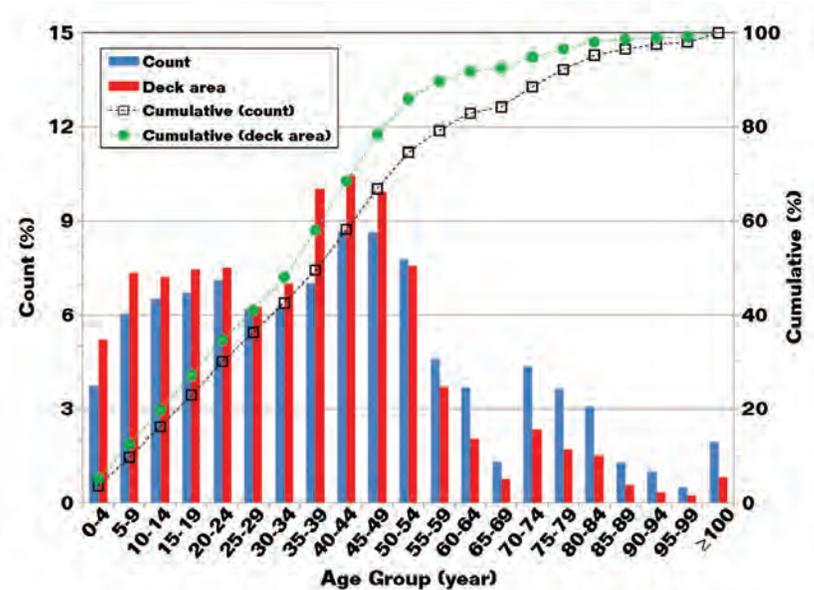


Figure 1: Distribution of bridges by age (2010 NBI data)

When the Eisenhower Interstate System was created, there was a general understanding that the federal government would pay for capital costs to build the systems, but that the states would have responsibility for operations and maintenance.

The United States highway system is mature and sustaining the system has required significant increases in maintenance dollars. Today, facing a fiscal crisis not seen since the Second World War, many states are making dramatic cuts in service and expenditures. At the federal level, there is an ongoing debate over the acceptable debt level. Combined, these factors create a challenging environment to seek funding.

Creative ways to address the issue of scarce financial resources must be found. The “civilian” interstate highway system is also a defense asset which is a compelling reason for the U.S. Department of Homeland Security’s Office of Infrastructure Protection to provide support.

This white paper looks at bridges and what makes them corrode. It also discusses how employing relatively low-cost corrosion control measures during initial construction can produce low-maintenance bridges with service lives of 75 to 100 years. Corrosion control protects initial bridge investment and dramatically reduces maintenance expenses in the future.

Acknowledgments

The author thanks the reviewers from several state departments of transportation and Dr. John Broomfield for their valuable assistance and input to this white paper. Thanks also go out to Linda Goldberg of NACE for her assistance and editing throughout this effort.

**The credit, savings,
and convenience
of this country all
require great roads,
leading from one place
to another, and should
be straightened and
established by law.
To me, these things
seem indispensably
necessary.²**

George Washington

Executive Summary

Well before becoming the first President of the United States, Major George Washington at the age of just 21 recognized the importance of roads and bridges to prosperity.

In July of 1919 another future general, Captain Dwight Eisenhower, left the Ellipse just south of the White House leading a convoy of Army trucks headed to San Francisco. They arrived two months later. As a General in World War II, Eisenhower obtained first-hand knowledge of the German Autobahn. President Eisenhower credited his memories as both a captain and a general with his leading the fight to get Congress to approve the Federal-Aid Highway Act of 1956, which produced the Interstate System we still use today. In 1990, the system's name was changed to the Eisenhower National System of Interstate and Defense Highways.

Current Condition

When bridges are inspected, owners evaluate whether the bridge is functional and does its intended job. If the bridge lacks proper safety shoulders, or cannot handle traffic volume, speed, or weight, it is classified as functionally obsolete.

Another attribute owners evaluate is whether a bridge is structurally satisfactory or deficient. Structural integrity is an area where proper implementation of corrosion control can make considerable impact in extending a bridge's lifetime.

Causes of Corrosion

Iron is not found as a metal in nature; it is found as an ore. A considerable amount of energy in the form of high heat must be applied to smelt iron from iron ore. The energy needed to put into refining speaks to the chemistry that wants to return steel to ore by making rust from the corrosion process.

If a reinforcing bar was kept on a desk in a climate-controlled office one would see little corrosion. Unfortunately, unlike in an office environment, low-alloy steel is not stable in many of the environments in which it is used, so it corrodes.



The corrosion of steel exposed to the atmosphere, soil, and water follows patterns most people would expect. For example, the steel corrodes faster in warm water than cold and faster in seawater than fresh water. Similar patterns happen with atmospheric exposure, where the corrosion rate of a steel beam will be lower when exposed to a desert in New Mexico than to the Everglades in Florida.

Steel in concrete is a different matter. The alkalinity of the concrete causes the embedded reinforcing bar to behave in a manner similar to stainless steel. This non-corroding condition is maintained until chloride ions from seawater or roadway deicers reach the surface of the reinforcing bar in sufficient concentration. When that happens, the steel corrodes and the expanding rust cracks the surrounding concrete and both functional and structural issues often result.

Corrosion Control

There are a number of measures that can be employed to control corrosion. For structural steel elements, protective coatings can be applied. Employing one of today's high-performance coating systems can provide a service life of 30 to 40 years. In the proper environment, weathering steels can be used. These are alloys that may not require a coating.

For reinforced concrete bridge elements, the key factor in selecting what corrosion control measure to use is the desired service life. If the owner is relatively certain that functional obsolescence will not be a problem, a 75 year service life, or more, should be considered. To reach that level of performance would require using stainless steel reinforcement, electrochemical techniques, or well-placed high-performance concrete. By this we mean a highly impermeable concrete with reinforcing bars embedded deeply enough to prevent significant chloride build-up at the surface of the bars.

**A penny saved is
twopence dear.³**

Benjamin Franklin

Costs

Although Benjamin Franklin is generally thought to have said “a penny saved is a penny earned,” he never made that exact statement. Rather, Poor Richard made the quote at the left. It is a subtle difference, but in the public arena, subtle differences can make a significant difference. Bridge maintenance is an area where changes can provide profound savings if institutional inertia can be overcome.

Corrosion Control Saves Money, Lots of Money

The extent of corrosion damage increases with time. Figure 2 shows the degradation of a typical bridge. Note that not only does the degree of damage increase with time, but that the rate at which damage occurs also increases with time. If we see 2% damage occur this year, next year we may see 3 or 4% more added to bring the total to 5 or 6% rather than 4%.

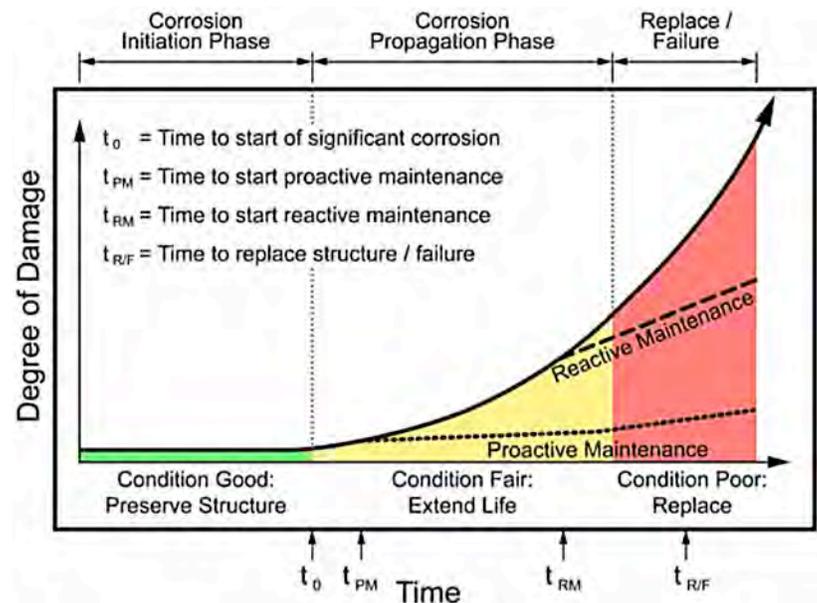


Figure 2: Typical bridge condition as a function of time

Corrosion Damage

The observed bridge corrosion damage can be broken down into three distinct phases: the corrosion initiation phase, the corrosion propagation phase, and the replacement phase.

Corrosion Initiation Phase

Early in a bridge's life corrosion-related damage is usually not a factor. Chloride ions from deicers or a marine environment have to penetrate the concrete to reach the reinforcement, and coatings are initially quite protective. This is the corrosion initiation phase.



The length of this initiation phase can be extended by selection of corrosion-resistant materials, upgrading the quality of the materials, and by construction detailing. For example, if a service life of over 75 years is desired, then serious consideration should be given to using a stainless steel for reinforcement.

Corrosion Propagation Phase

Once corrosion initiates, it takes time before the process creates damage that is visually obvious, or in the case of reinforced concrete, that can be detected using traditional sounding techniques. Measurement of corrosion potential can identify reinforcement corrosion before the rust that forms cracks the surrounding concrete to form a delamination, spall, or pothole. During this initial corrosion propagation phase is when maintenance repairs typically occur.

Replace / Failure Phase

At the far right of Figure 2, the condition of the bridge has degraded to poor, and the restoration costs may become prohibitive, and instead the structure must be replaced even if it is not functionally obsolete. This phase also is one where there is an increasing risk of failure.

Maintenance Costs

Monies required to repair the damage shown in Figure 2 follow a very similar pattern as shown below in Figure 3. This is because the costs to re-coat structural steel elements and repair unsound concrete in an existing bridge are directly related to the extent of the damage at the time of maintenance.

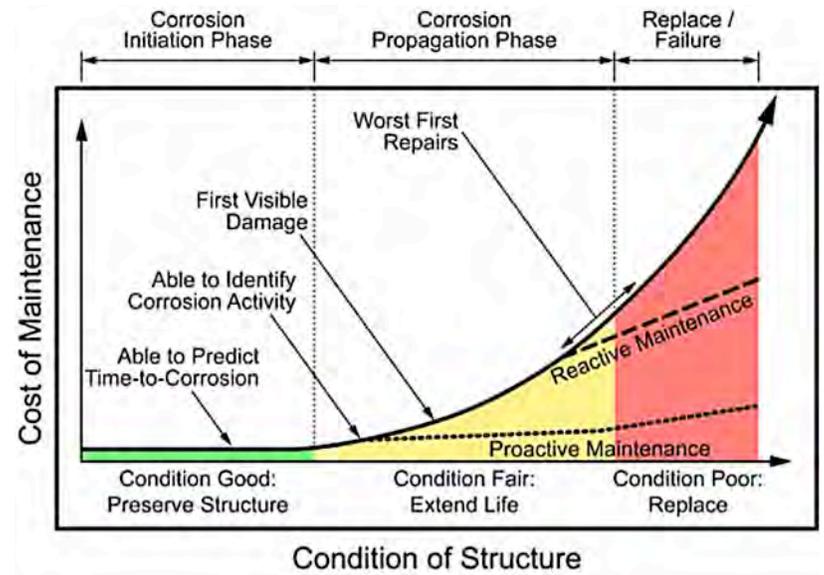


Figure 3: Typical bridge condition as a function of time



Corrosion Initiation Phase

Inspection during the initiation phase can provide information to make fairly accurate forecasts of the time-to-corrosion. For example, if after 10 or 15 years proper sampling of the concrete is made, variation in the chloride ion content with depth allows making a site-specific estimate of the chloride diffusion coefficient, D_c . If the “as built” concrete cover is also surveyed, then those values can be coupled with D_c to make accurate estimates of when the chloride content will reach corrosion threshold at the depth of the reinforcement.

Corrosion Propagation Phase

Surveys of the corrosion potential of the embedded reinforcement can clearly show the transition to corrosion propagation before the corrosion produces cracking in the concrete. If a cathodic protection (CP) system is installed before wholesale concrete repairs are needed, then that proactive CP installation avoids the requirement of concrete repairs that typically recur in less than 20 years. Avoiding one or more repair iterations not only provides the owner with dramatic cost savings, but also has significantly favorable implications for users of the structure, especially on congested routes.

Often repairs are approached from a “worst first” paradigm. The Federal Highway Administration’s **Bridge Preservation Guide**⁴ states:

A successful bridge program seeks a balanced approach to preservation and replacement. Focusing only on replacing deficient bridges while ignoring preservation needs will be inefficient and cost-prohibitive in the long term. Adopting a “worst first” approach to managing bridge assets may also yield ineffective results that allows bridges in good condition to deteriorate into the deficient category which generally is associated with higher costs and other challenges.

The objective of a good bridge preservation program is to employ cost effective strategies and actions to maximize the useful life of bridges. Applying the appropriate bridge preservation treatments and activities at the appropriate time can extend bridge useful life at lower lifetime cost.

Replace / Failure Phase

Restoration during this phase will always be expensive. That said, if significant corrosion-control measures are included, then future maintenance costs can be significantly reduced.

The tipping point has arrived: We either have to figure out a way to rebuild the Interstates or watch them fall apart.⁵

Car & Driver

Crumbling Infrastructure—an Introduction

The crumbling infrastructure is an exceptionally popular media topic. Hardly a day passes without new television, radio, print, or Internet coverage on some aspect of this topic. Outlets as diverse as The Economist to Car and Driver have published lengthy articles discussing the decay of the American highway system.

To get a sense of the scale of attention this topic receives, a Google search on **infrastructure** and **bridges** will result in more than 42,100,000 hits, while a search on **tax cuts** and **United States** results in 11,500,000 hits, one quarter the response.

Yet for all the interest in this imminent problem, no resolution is on the horizon. Perhaps foremost are differences of opinion over the role the federal government should play in the maintenance of highways and bridges. A ninth renewal of the 2005 surface transportation law passed in June 2012, but the resulting compromise does not provide a long-term resolution of U.S. surface transportation problems.

NACE International, the corrosion society, has nearly 30,000 members, many of whom specialize in corrosion control in highway bridges. These members possess expertise in corrosion inspection and prevention, including protective coatings and cathodic protection. NACE has prepared this white paper to provide a detailed context of corrosion-related degradation of highway bridges, and to facilitate development of practical solutions.

America's inability to improve and expand its infrastructure will directly result in the loss of economic productivity as crumbling highways and aging bridges impede the flow of products to markets at home and abroad.⁹

*Free Enterprise
U.S. Chamber of Commerce*

State of the Problem

When the Federal Highway Trust Fund was established in 1956 to create the interstate and other highway systems, there was general Congressional consensus that the federal government would pay the major share of capital costs while the states would assume responsibility for maintenance. Today the Federal Highway Administration (FHWA) provides some limited funds for maintenance.

Today many states find ways to package projects so that work that might have been regarded as patching and maintenance, such as removing a wearing course pavement and rebuilding from the sub base, is now classified as a capital expense.⁶

The American Society of Civil Engineers (ASCE) [*Report Card for America's Infrastructure*](#)⁷ gives the United States a composite grade of D. The Report Card provides a review of the condition of many aspects of the collective American infrastructure.

Global Infrastructure

In the World Economic Forum's (WEF) 2011-2012 evaluation of global competitiveness, America's infrastructure was ranked 16th.⁸ Five years ago, it ranked first. In that same WEF report, the United States' overall economic competitiveness dropped to 5th, even with the advantages attendant to its being overwhelmingly the world's largest domestic economy.

Free Enterprise, an online publication of the U.S. Chamber of Commerce, recently expressed concern over America's infrastructure, stating that "more money and more care are needed for our transportation networks, but that is not happening at the pace and scale needed." The article went on to note that the United States spends only about 0.6% of its GDP on infrastructure while other countries with smaller economies invest as much as 1.53%.⁹

Addressing the Problem

In the long term, improving the condition of highway bridges can be affected by corrosion prevention measures during initial construction and appropriate maintenance. If the bargain of 1956 remains in force, a federal incentive for proactive corrosion prevention is considered a best first step.

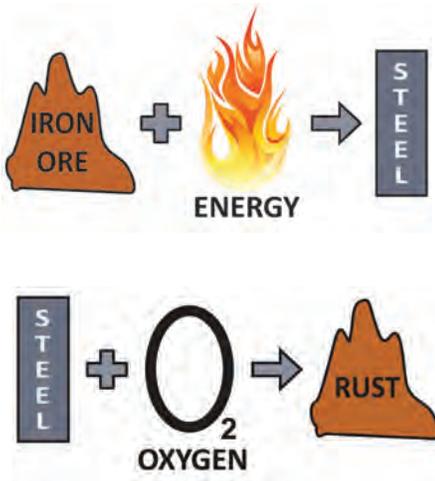


Figure 4: Smelting↔rusting



Figure 5: Refining steel takes lots of energy

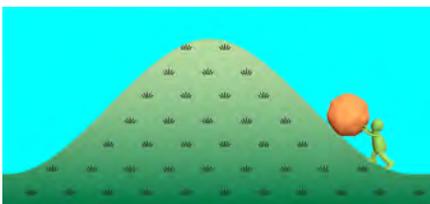


Figure 6: Energy hill

A Brief Introduction to Corrosion

Although corrosion is an electrochemical process, it is not necessary to be a scientist to be able to understand the process. A general grasp of the process that changes steel to rust is essential to understand methods of corrosion control.

When bare steel is exposed to the atmosphere, the metal corrodes with the loss typically spreading uniformly across the exposed surface. Most metals exist in their natural state combined with other elements such as oxygen, sulfur, or carbon dioxide. These compounds are known, respectively, as oxides, sulfides, and carbonates and are often comparable to corrosion products. Iron, the major constituent of steel, starts as iron ore that is very similar to rust.

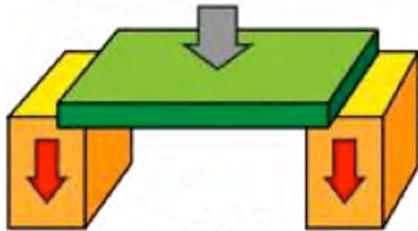
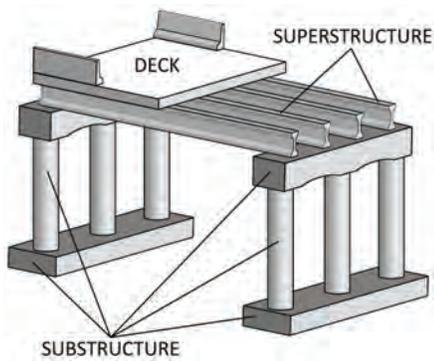
Refining metals typically requires applying a great deal of energy to the ore to convert it to a metal. When these metals are exposed to many environments, they will return to their natural state through the corrosion process. Figures 4a and 4b show this rust to metal to rust cycle.

Metals vary in their resistance to corrosion. Among pure metals, gold is often found in metal form in nature. It and similar metals like platinum and silver are called noble metals and are highly corrosion-resistant.

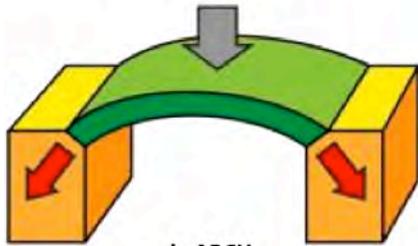
Some metals, like copper, are sometimes found free in nature and other times found as ore. Other metals, like iron, are never found as natural metals. Imagine for a moment that you are in a steel mill, like the one in Figure 5. Try to feel the waves of heat coming off the crucible filled with molten steel. Beads of perspiration would rapidly form on your forehead in this incredibly hot place.

A tremendous amount of energy from combustion is transferred to the iron ore to drive off the oxygen and produce metallic iron. Iron as a metal is not very stable, and without protection can rapidly start to rust, reverting back to a form similar to the ore from which it was refined.

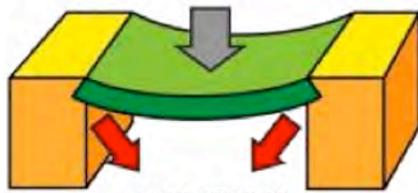
Another way to look at transferring energy is shown by the individual rolling the boulder up the hill (Figure 6). It takes considerable energy to complete this task. However, when the person gets the boulder to the top of the hill, he will need to take care to secure the boulder at the top or it will easily roll back down the hill. Corrosion control measures are analogous to those taken to prevent the boulder from rolling back down the hill.



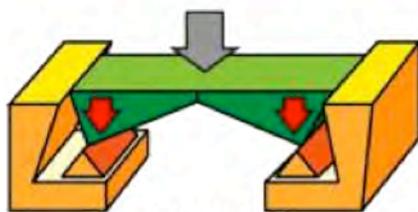
a. BEAM/TRUSS



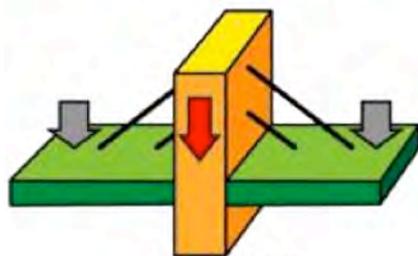
b. ARCH



c. SUSPENSION



d. CANTILEVER



e. CABLE STAY

Figure 7: Bridge elements and types

Bridges to Everywhere

There are some 603,310 bridges in the United States that link more than 4 million miles of roadways.¹⁰ America's highway system is mature. Nominally the original Eisenhower Interstate System was completed in 1992 with the opening of I-70 through Glenwood Canyon in Colorado. A few spurs and bypasses remain including work on I-22, I-69, and I-95.

The maturity of the highway system infers that future spending would be on maintenance rather than new installation capital expense.

As bridges age, degradation can lead to structural deficiency. However, many bridges have become functionally obsolete, including those with structural issues. These situations leave a fiscal reality where it is not clear whether maintenance, rehabilitation, and/or replacement of such bridges fall in the maintenance or capital column. Figure 7 and the following discussion of bridge structural components and types of bridges will assist the reader in understanding corrosion problems.

Structural Elements of Bridges

Deck: This is what directly carries traffic

Superstructure: These elements directly support the deck and include girders, deck, railing, and trusses.

Substructure: These elements support the superstructure and include piers which are the vertical support elements.

Types of Bridges

Beam/Truss: This form ranges from a simple log our ancestors put across a creek, to girder supported bridges, to the I-35W truss bridge that collapsed in Minneapolis.

Arch: Arch bridges also date back to antiquity, with the oldest existing bridge the Arkadiko Bridge in Greece that dates to about 1300 BC.

Suspension: Suspension bridges predate the Golden Gate Bridge. Vine suspension bridges that are popular in adventure movies are an old form of bridge construction.

Cantilever: Cantilever bridges are a newer form and were first employed in the nineteenth century

Cable Stay: Considered a new style of bridge; sketches of cable-stayed bridges date back to 1595. The Brooklyn Bridge is a composite cable-stayed suspension bridge.

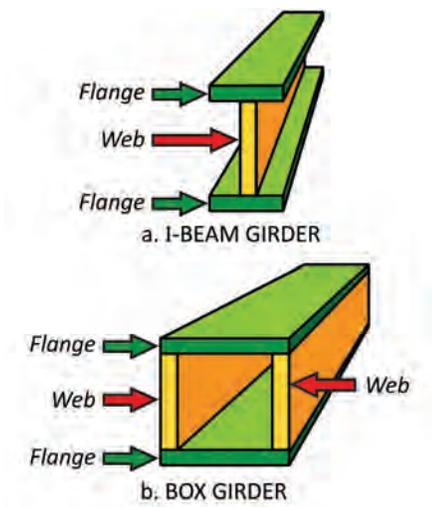


Figure 8: Types of girders



Figure 9: Luling Bridge, I-310

Steel Elements

Steel is incorporated in a number of structural elements of a bridge. Elements include towers and piers, girders, box girders, and trusses. Some girders are shown in Figure 8. Steel is usually used for the cables employed in cable stays and in suspension bridges. Steel is also used to reinforce concrete bridge elements. Several types of steel are employed in bridges.

Carbon Steel

Most steel bridge elements that are employed in bridges are protected from corrosion by protective coatings. Coatings can also provide a bridge a signature color as is the case with California's Golden Gate Bridge. Coatings can be formulated to provide resistance to a range of degradation processes such as abrasion, moisture, and ultraviolet light.

Weathering Steel

Figure 9 shows the Luling Bridge that crosses the Mississippi River just north of New Orleans. This 10,700 ft (3,260 m) long bridge was the third major cable-stayed bridge built in the United States. Its design includes unpainted weathering steel towers and steel box girder superstructure.

Stainless Steel

Although more expensive than carbon or weathering steel, stainless steels are being incorporated in a number of creative ways by bridge owners looking for design lives of up to 100 years or more. Stainless steel is used primarily as a corrosion-resistant reinforcement. It is occasionally also used in bearings and hinges.

Concrete Elements

Reinforced concrete can be used for all bridge structural elements. Concrete is a composite building material comprised of cement, aggregate, and water. The aggregate is a blend of sand, also known as fine aggregate, and gravel or crushed rock known as coarse aggregate.

The water is added to the cement and aggregate to allow the ensuing mixture to be poured, shaped, and molded. Concrete differs from mixtures of straw and mud used to make simple bricks. With straw-mud bricks the water dries, and clay present in the mud provides cohesive strength. In concrete the water and cement react chemically to form a new compound that bonds the concrete components together. The chemical reaction product between water and cement is similar to a mineral known as portlandite.

The Government Accountability Office has found that increased spending on highway programs over the years has tended to displace state and local funds that otherwise would have been spent on highways and bridges.¹¹

*Road Work Ahead
U.S. PIRG*

Concrete has excellent compressive strength. As shown in Figure 10, compressive strength is the capacity to resist pushing forces, and the compressive strength of concrete is reached when it is crushed. However, concrete has an undesirably low tensile strength and elasticity. Again as shown in Figure 10, tensile strength is the resistance to pulling forces.

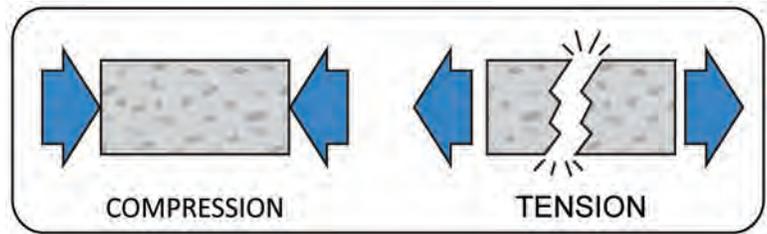


Figure 10: Compressive and tensile forces acting on concrete

Steel can be used to improve concrete's limited resistance to bending. There are two general categories of reinforced concrete, conventionally reinforced and prestressed.

Conventionally Reinforced Concrete

Conventionally reinforced concrete includes a material with high tensile strength within the composite. In most applications, round steel reinforcing bars are set within the concrete formwork and the concrete is then poured. The steel reinforcing bars have ridges to help improve their bond within the concrete. As shown in Figure 11, reinforced concrete is able to resist loads that would bend and/or crack unreinforced concrete.

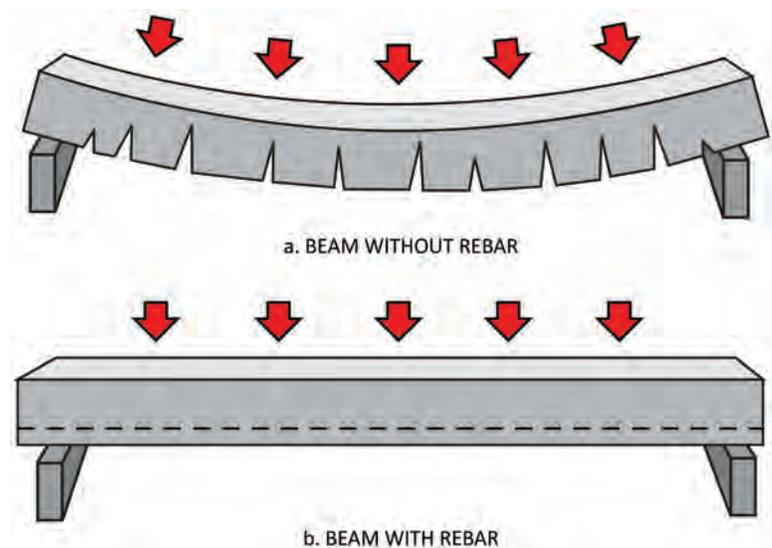


Figure 11: A concrete beam with and without steel reinforcement

The rehabilitation of America's transport network will be neither easy nor cheap. To make the necessary repairs and upgrades, America will need to spend a lot more.¹²

The Economist

Reinforcing bar can be galvanized, coated with epoxy, or be made from corrosion-resistant materials as stainless steel or plastics.

Steel Plate Construction (Stay-in-Place Forms)

Steel plates, typically corrugated, are used as the bottom form-work. The steel plates are left in place after construction and can take the place of some, or all, of the lower mat of reinforcing bar.

Fiber-Reinforced Concrete

Thin fibers that range from 1 to 3 in (25 to 50 mm) in length can be added to the concrete. This is often used to reduce concrete cracking and complement conventional reinforcing.

Prestressed Concrete

Prestressed concrete is another means to overcome concrete's weakness in tension. Prestressing is a technique that has profoundly changed our ability to make concrete structures. With prestressing far longer spans are possible than would be otherwise practical. As a means to reduce costs and improve productivity, prestressed concrete elements are manufactured in plants rather than constructed on the job site.

Figure 12a shows a stack of children's blocks. Although each block has both compressive and tensile strength, clearly this pile of blocks has no composite tensile strength. However, if we line up a few blocks and press in on the outer two blocks, we can lift this stack of blocks that now has some tensile strength.



a. Pile of blocks



b. A bridge

Figure 12: An elementary version of prestressing



Figure 13: Corroded pre-tensioning strand

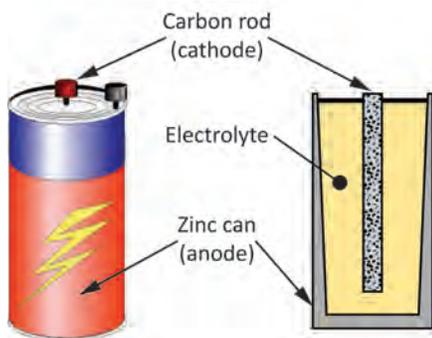


Figure 14: Dry cell battery

Although the “bridge” we constructed from children’s blocks is not going to carry significant loads, it gives a sense that independent elements can be brought together to form a stronger composite if we increase the force keeping the elements together.

Imagine we had larger blocks, say 2 ft (0.6 m) on each side, and they were fabricated with 1 in (25 mm) diameter holes on one pair of opposing faces. Now align six of these blocks in a manner similar to that shown in Figure 12b, but with the holes lined up so that we can see through all six blocks. Next take a $\frac{3}{4}$ in (19 mm) diameter rope and feed it through the holes in the six blocks and tie a large knot on one end. Moving to the other end, pull the other end very, very tight and secure it so that it cannot slip back into the line of blocks. We now have a bridge that a person could actually walk across.

With prestressed concrete, high-strength steel cables are used instead of fingers or ropes, and these are used to compress the concrete with many thousands of pounds (kg). We can now drive a large truck over our bridge. As they often carry larger loads than conventional reinforcement, failure of prestressing can result in greater loss of load-carrying capacity (see Figure 13).

Pre-Tensioning

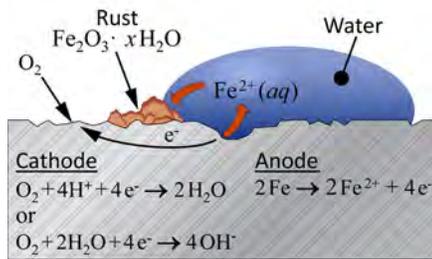
In pre-tensioned elements, the concrete is cast around steel tendons that are already under tension. After the concrete has cured, the ends of the tendons are cut, applying a direct transfer of that pre-tensioning to the concrete. This type of prestressing is usually performed in a factory.

Post-Tensioning

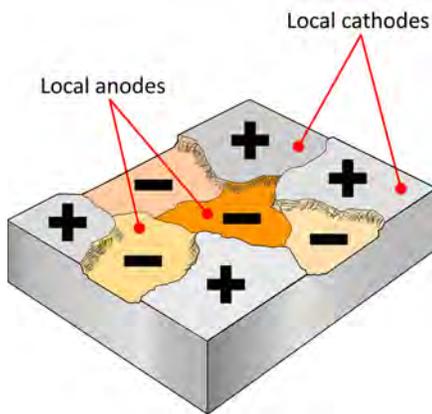
In post-tensioned concrete, the tension is applied after the concrete has been poured and cured. This type of prestressing is typically applied in the field.

Corrosion Basics

Corrosion is an electrochemical process that is similar to how a simple battery functions. Figure 14 shows a typical dry cell battery. If we use the battery to power a light bulb, when the light is turned on, the circuit connecting the positive and negative terminals of the battery allows electric current to flow from the battery through the light bulb. The electric power comes from the corrosion of the zinc can that forms the battery exterior. As each atom of zinc corrodes, the process produces two electrons. These electrons are what power the light.



a. Corrosion from the side



b. Corrosion from above

Figure 15: Corrosion's anodes and cathodes

Wires conduct the electricity from the two battery terminals to the light bulb or whatever else is connected to the circuit. Within those metal wires, the electric current is carried by the flow of electrons. Inside the battery, as shown in Figure 14, is a material called an electrolyte. In the electrolyte, the electric current is carried by ions. An ion is an atom or molecule that has gained or lost one or more electrons. Ions with a positive charge are called cations. Ions with a negative charge are called anions. Anions migrate toward the anode, the zinc in the battery. Cations migrate toward the cathode, the carbon rod in the battery. This migration of ions is what carries an electric current in an electrolyte. Electrolytes include seawater, soil, and even concrete.

General Corrosion

General corrosion is a process whereby metal loss is more or less evenly distributed across the exposed surface. Figure 15 shows how general corrosion progresses on a carbon steel surface. In side view you can see when iron gives up two electrons at the anode to change from Fe⁰ to Fe²⁺. The electrons are carried by the metal to the cathode where they react with oxygen to form water or hydroxide ions, depending on conditions. With general corrosion, damage is equated to the total amount of metal lost. This may be expressed in terms of thickness lost, for example an expression in mils (mm) per year, or the mass lost, such as grams per square meter per year.

In the view from above, the rust is not shown so that you can see how corrosion produces an irregular steel surface. The plus signs indicate local cathodes while the minus signs mark local anodes. Absent some geometric constraint, local anodes and cathodes change back and forth with time so that the general loss of metal remains fairly uniform. The table below shows typical ranges for corrosion of steel in differing environments.

Environment	Corrosion Rate	
	mils per year	mm per year
Atmospheric ¹³		
Industrial	1–2	0.025–0.050
Marine	5–40	0.125–1.0
Submerged—tropical ¹³		
Freshwater—year 16	1.8	0.045
Saltwater—year 16	2.9	0.074

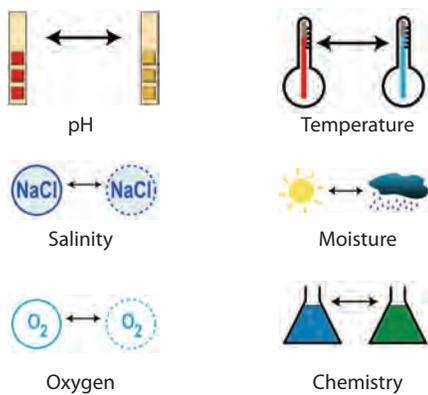
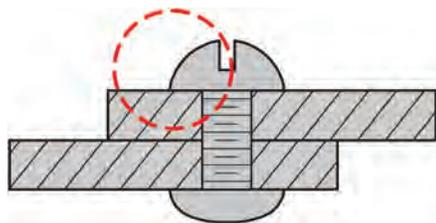
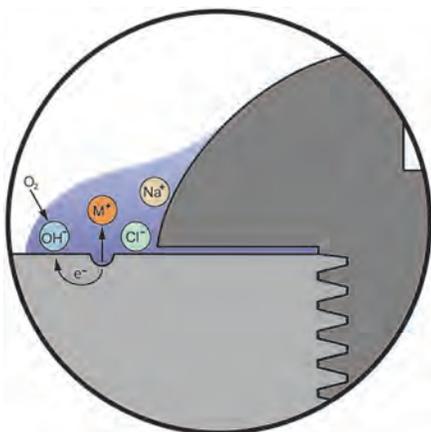


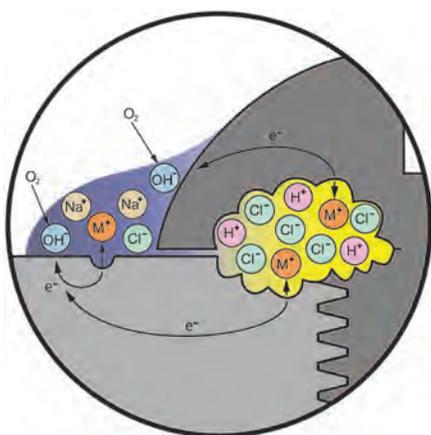
Figure 16: Differences help corrosion



a. Crevice created by plates and a fastener



b. Initial corrosion



c. Crevice corrosion after time

Figure 17: Crevice Corrosion

Localized Corrosion

In localized corrosion, loss is typically measured by the penetration rate. A pipe that is still structurally sound, but is leaking because of a pit, is considered failed. The problem with such a pit is not the volume of metal lost, as this would be small. The problem is that the loss was not spread over the entire structure, as with the general corrosion. Rather, the loss was suffered on a small, localized area and hence the term localized corrosion.

Environmental Differences

Environmental differences can accelerate corrosion. A classic case occurs when one area of a structure has a higher oxygen concentration than another. The area with the higher oxygen concentration is cathodic to the area with the lower oxygen concentration. The area with limited oxygen becomes the anode. As stated before, the anode is where metal dissolves, or corrodes.

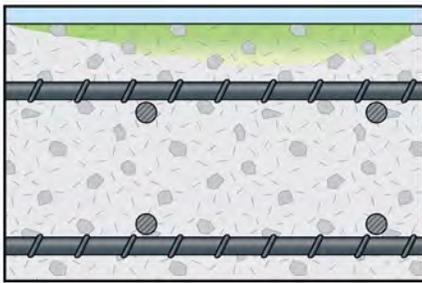
As shown in Figure 16, other conditions that can accelerate corrosion are marked differences in acidity (pH), temperature, salinity, moisture content, and chemistry.

Crevice Corrosion

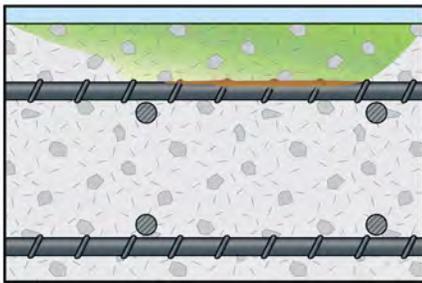
Crevice corrosion is a type of corrosion attack associated with small volumes of stagnant water, or moisture, often found near holes, gaskets, lap joints, bolts, rivets, and even under deposits and other crevice-like areas. The crevice must, at once, be wide enough to allow the transport of corrosion process reactants to and from the corrosion site, yet sufficiently narrow to maintain stagnation in the crevice area (see Figure 17a).

Crevices can result from mechanical gaps as shown in Figure 17. They can also occur under disbonded coatings, under insoluble deposits, and under microbiological colonies.

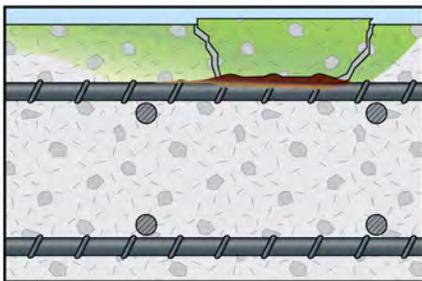
Initially the mechanism follows the same process as general corrosion, where the metal loses electrons as it corrodes at the anode. Those electrons lost by the metal are consumed at the cathode, typically by the reduction of oxygen (Figure 17b). With time, crevice corrosion can reduce the pH in the crevice, further accelerating the corrosion process (yellow in Figure 17c).



a. Chloride penetration



b. Chloride reaches reinforcing bar



c. Reinforcing bar corrosion spalls concrete

Figure 18: Chloride-induced corrosion

For corrosion to proceed, it is not necessary to have distinct anodes and cathodes. In general corrosion, distinguishing anodes from cathodes is difficult at best, and is not necessary to describe the process. In localized corrosion, however, the anodes and cathodes frequently are separated, and a better understanding of the processes involved is achieved by discussing the two processes driving the corrosion cell.

Corrosion in Concrete

Steel embedded in concrete normally does not corrode. This is not because the concrete keeps the steel dry as internally concrete is typically wet with a relative humidity at or near 100%.

Carbon steel embedded in concrete does not corrode because the concrete provides reinforcing steel a benign, corrosion-free environment. The portland cement provides the steel a high pH, or alkaline, environment. In the alkaline cement, carbon steels are passive to corrosion and their behavior is similar to that of stainless steels.

Basics of Reinforcing Bar Corrosion

For corrosion to occur, oxygen must travel through a complex and tortuous cement matrix to reach the surface of the steel. Certain aggressive ions, like chlorides, can disrupt the passive film that protects the reinforcing bar. Other contaminants include those capable of lowering the pH, like carbon dioxide. Lowering the pH sufficiently destabilizes the passive film allowing reinforcing steel to corrode.

When aggressive ions reach the surface of the reinforcement, or if pH is reduced, the steel loses its passive protection and corrodes. The resulting corrosion product occupies greater volume than the parent metal with variations resulting from the oxidation state and the amount of water included in the final product. The corrosion process follows a two-step process:



In oxygenated concrete, the insoluble corrosion products collect at the reinforcement-concrete interface. In time, this process will crack, delaminate, or spall the concrete to relieve the stress. Generally, section loss of the steel is quite modest until the loss of concrete bond and/or cover from cracking and spalling. Figures 18a through 18c show the process of chloride ion penetration into the concrete, to corrosion initiation, and then the loss of concrete bond and cracking resulting in spalled overlying concrete.

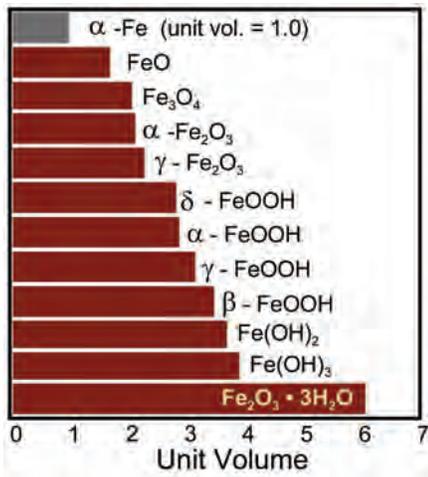
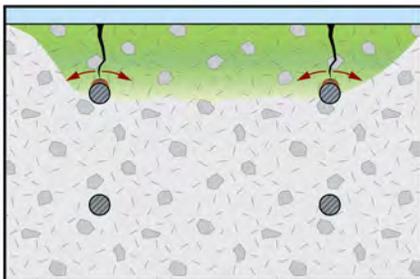
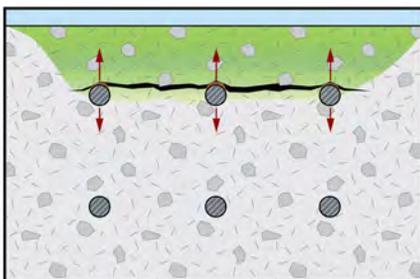


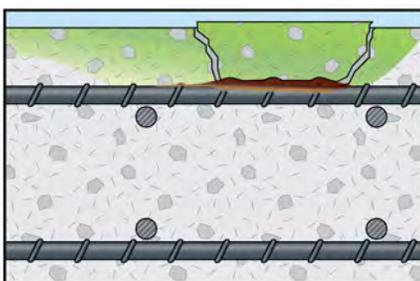
Figure 19: Rust volume relative to steel



a. Cracks form directly above the reinforcing bar



b. Delamination forms a level of reinforcing bar



c. Concrete spalls (pothole)

Figure 20: Variations in corrosion damage

The reason that corrosion leads to cracking and spalling of the concrete is because the corrosion product, the rust, occupies a greater volume than did the steel whose corrosion produced it. Figure 19 shows the relative volume of common reinforcing bar corrosion products. Note that $\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$, common red rust, occupies a volume a little over six times that of the steel that corroded. This increase in volume is restrained by the presence of the reinforcing bar and generates tensile hoop stresses in the surrounding concrete. Recall that concrete does not have good tensile strength so the concrete cracks. Depending on the depth and spacing of the reinforcing bar, these cracks may form perpendicular to the concrete surface and immediately above the corroding bar or the crack may form parallel to the surface of the concrete and at the level of the bar.

If the concrete cover over the reinforcing bar is relatively shallow, and/or the reinforcing bars are widely spaced, cracks form that are aligned with the reinforcing bar and are perpendicular with the concrete surface as shown in Figure 20a.

If the concrete cover over the reinforcing bar is relatively deep, and/or the reinforcing bars are closely spaced, cracks form parallel with the concrete surface. Initially these cracks are not visible from the surface but they can be detected by sounding using a hammer or steel chain and are known as delaminations (see Figure 20b). When struck, delaminated areas sound hollow if the delamination is not filled with water. As the corrosion product continues to develop, the delamination can break away as shown in Figure 20c. This is known as a spall, or pothole if present on the deck of a bridge.

Chloride Ions in Concrete

The chloride ions that cause corrosion can come from highway deicers. Deicers applied to bridge decks can present problems to reinforcing bar in those decks. Large trucks driving through can spray salt-laden slush and water on the columns and beams that support the bridge. Poorly designed drains can aspirate salty runoff water onto underlying super- and substructure elements.

Chloride ions can also come from marine environments. Bridges immediately adjacent to seawater can be at risk, but wave action and winds can carry salt particles 20 miles (32 km) or more inland. Because wave action varies considerably, bridge owners need to know their local environment. For example, along the Oregon Coast, the surf changes near the city of Florence. Park your car in Florence or north, say in Waldport, and your windshield quickly dirties from airborne sea salts. Park that same car south in Reedsport or Coos Bay and that rarely will happen. This is the same stretch of coast, but 30 miles or so difference north or south can produce a tremendous difference in the chloride ion deposition rate. Environments can change rapidly.

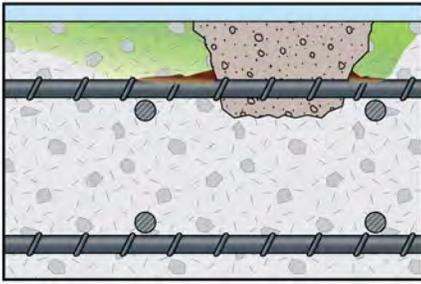


Figure 21: Halo corrosion around patch

The delaminated or spalled concrete can be chipped out, removed, and the resulting cavity patched. However, if the surrounding “sound” concrete has chloride contamination, then the chloride-free patch can actually accelerate corrosion in the reinforcing bar in the chloride-contaminated halo surrounding the patch as shown in Figure 21. If nothing is done about the chloride contamination of the surrounding concrete, a chip-and-patch strategy will lead to future patches of ever-increasing size. Sealing of chloride-contaminated concrete does nothing to remove chloride ions already in the concrete. The sealing of contaminated concrete will help reduce future contamination, but the chloride ions that were already in the concrete before sealing remain and will aggravate corrosion-related deterioration.

Carbonation of Concrete

As previously noted, the primary corrosion protection concrete provides to steel comes from the alkalinity of the cement binder. Not counting water, carbon dioxide is the fourth largest component of the earth’s atmosphere, comprising about 0.04% of the volume of dry air.

When carbon dioxide dissolves in water, it forms carbonic acid, and the acidity that results is part of what we taste when we drink carbonated beverages.

Carbon dioxide present in the air dissolves in rain and fog drops as they form and fall. Even without other atmospheric pollutants, rain water is naturally acidic. When rain penetrates concrete, the dissolved carbon dioxide reacts with lime from the cement to form calcium carbonate. This process reduces the alkalinity of the concrete and makes it less protective of embedded steel. With continued carbonation, eventually the embedded steel will lose its passivity and start to corrode. Special indicator solutions can identify carbonation as shown in Figure 22.



Figure 22: Carbonation testing

The rate at which carbonation proceeds depends on the initial alkalinity of the cement and also on the porosity of the concrete matrix. In North America, carbonation has been more of a problem on reinforced concrete structures built before 1950 and with reinforcing bar in brick and mortar structures. In newer structures, the typical concrete is sufficiently dense such that the pore structure becomes blocked by calcium carbonate formed through carbonation and the process becomes self-limiting. However, blended cements with lower alkali reserves may not perform similarly to portland cement alone.

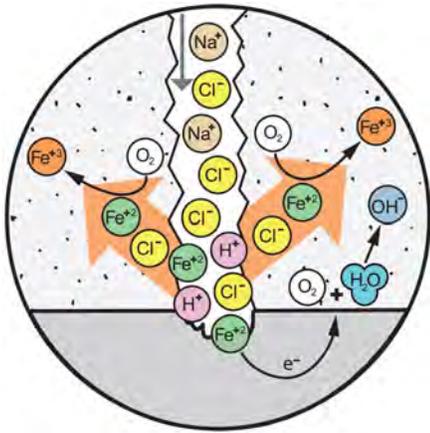


Figure 24: Localized reinforcing bar corrosion



Figure 25: Localized corrosion at crack

Localized Corrosion of Reinforcing Bar

Cracks in concrete may come from a number of sources other than corrosion. These cracks can be from shrinkage, mechanical action, or even construction joints formed when a second pour of concrete is placed after the first pour had set and become hard.

The presence of such cracks can disrupt the normal protection and allow corrosion to occur where the crack intersects the reinforcement. Here the corrosion activity is localized and frequently involves what are known as macrocells. Crevices, transitions, or similar artifacts can also accelerate corrosion. Localized corrosion in such conditions can lead to rapid section loss without generation of either spalls or delaminations that can be detected using traditional sounding techniques.

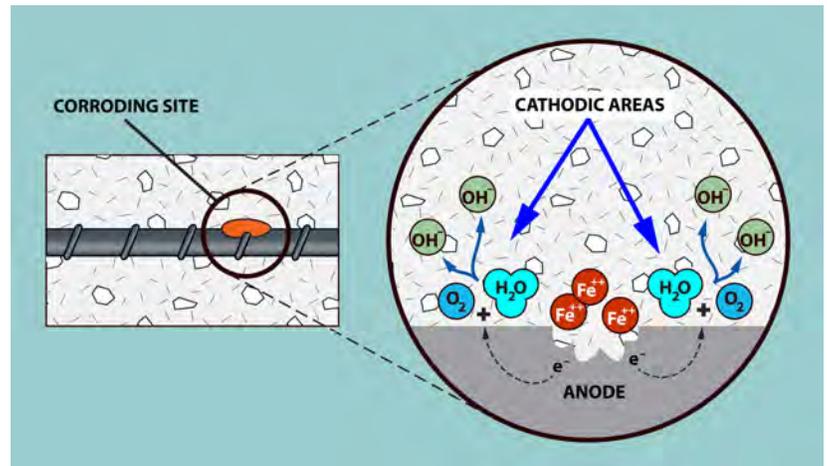


Figure 23: Typical reinforcing bar corrosion

Figure 23 above shows the process whereby steel embedded in concrete corrodes. The rust builds up at the interface between the steel and the concrete and generates tensile hoop stress that cracks the concrete (see Figures 20a–20c).

In some conditions, as shown in Figure 24 (above left), the corrosion rate is so rapid at a crack that it is possible to transport the iron away from the corrosion site as a soluble iron II chloride. At pores and entrained air voids at some distance from the reinforcing bar, the iron II is further oxidized to the relatively high-volume $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$ red rust. This process allows rapid attack of the bar as shown in Figure 25.

Exposure Conditions

The corrosion of bridges is greatly influenced by exposure conditions. As can be seen in the map below (Figure 26), the states with the highest percentage of structurally deficient bridges as of December 2011 are concentrated in what is known as the “rust belt.” These are locations where the use of deicers is prevalent. These are also locations with significant temperature ranges that can have an adverse impact on corrosion.

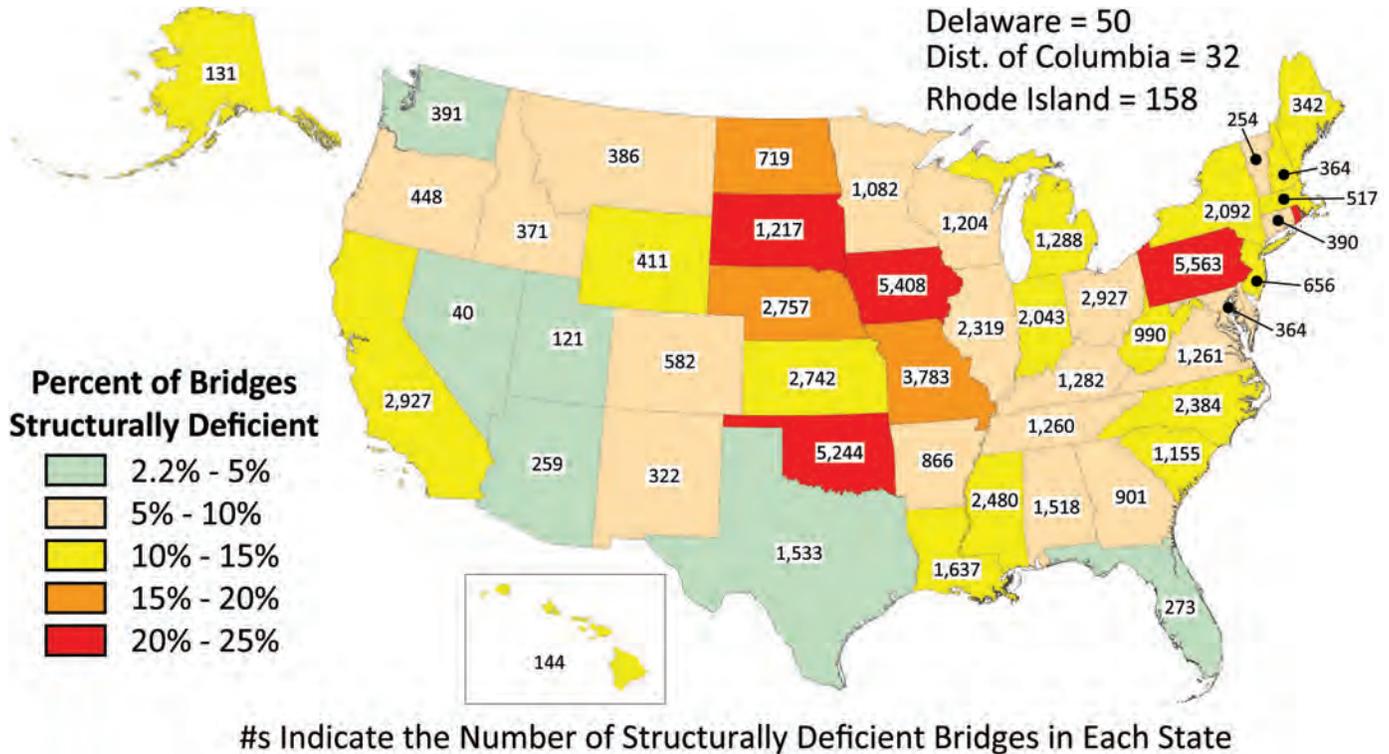


Figure 26: Structurally Deficient Bridges by State, December 2011

General Ambient Conditions

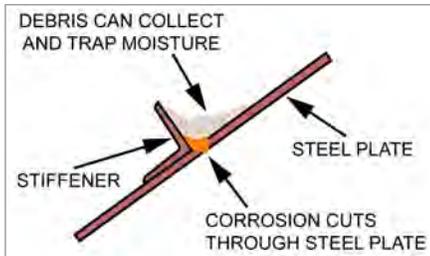
General ambient conditions form what is known as a macro environment. These are long-term conditions that affect bridges.

Temperature

Temperature impacts corrosion. When the temperature plunges below zero, the corrosion rate for steel slows considerably. When the temperature is hot, the corrosion rate increases, if all other conditions are consistent. A rough rule of thumb can be derived from the Arrhenius Equation, and that is for ambient temperatures above freezing, the corrosion rate will double if the temperature increases by 10 °C, or 18 °F. Because Seattle, Washington has an average temperature of about 52 °F and Orlando, Florida’s temperature is about 72 °F (11 and 22 °C), this means that with other things being consistent, galvanized bridge elements in Seattle will last about twice as long as they would in Orlando.



a. Corrosion penetration of steel plate



b. Section through plate in above photo

Figure 27: Perforation of steel sheet

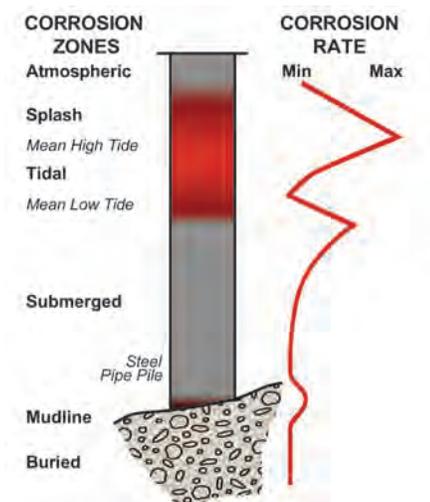


Figure 28: Tide zones

Freeze-Thaw

When water freezes, its volume expands a little less than 10 percent. Each time water freezes and then thaws is referred to as a freeze-thaw cycle. Numerous freeze-thaw cycles create far greater weathering damage to bridges than is created when the temperature drops below freezing and remains there without the ice being able to thaw. Areas with relatively high numbers of freeze-thaw cycles see accelerated weathering of bridge concrete and other elements into which water can permeate.

Humidity and Wetness

High relative humidity can accelerate corrosion. In corrosion, relative humidity is included as a parameter of what is known as time of wetness (TOW), a measure of the time period when atmospheric conditions are favorable to the formation of a layer of moisture on the surface of a structure, similar to the formation of dew. The formal definition of TOW is a period of time when the relative humidity is greater than 80% and the temperature is above the freezing point of water.¹⁴ It can be measured in hours per year or as a percentage.

The TOW for bridges built in the United States varies considerably. For example, Eugene, Oregon, has a TOW of about 70%; Cape Cod, Massachusetts 55%; Michigan City, Indiana 27%; and Phoenix, Arizona only 4%.

Atmospheric Contaminants & Debris

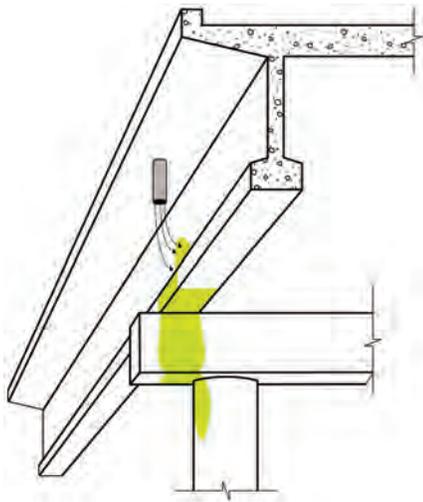
Factors other than water in the air around a bridge can be corrosive. These include pollutants typically found in urban areas or near rural point sources such as sulfur and nitrous oxides and carbon dioxide. It also includes airborne chloride ions that may be produced by wave and storm action in or near marine environments or from traffic splashing deicer-laden water.

If detailing isn't done carefully, debris that can trap both water and atmospheric contaminants can collect. Figure 27 shows how debris collected between a stiffener and steel plate leads to full-penetration corrosion of the plate under a bridge that is more than 100 ft (30 m) above the heavily navigated Mississippi River.

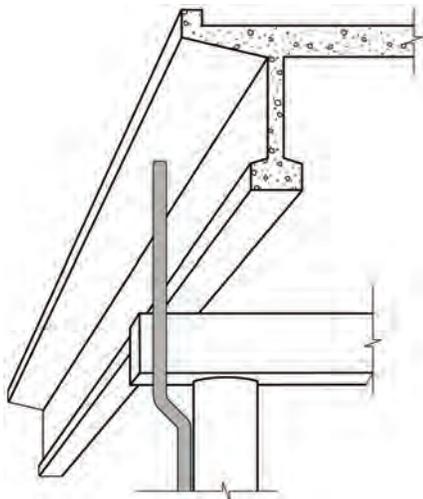
Marine Environments

We have discussed above how the presence of chloride ions creates corrosion problems for both steel structural elements of bridges and steel reinforcement embedded in concrete. Marine environments are notoriously aggressive toward corrosion. Given this situation, is it not surprising that in the early 1900s the first papers published regarding the corrosion of reinforcing bar discussed conditions in coastal environments.

As shown in Figure 28, chloride contamination can affect bridge elements submerged in seawater; in the tidal zone; in the splash zone above high tide; and in the atmospheric zone. Figure 28 also shows how typical corrosion rates vary in each of these areas. In areas with consistent large breaking waves, significant chloride contamination can extend inland many miles.



a. Drain wets super and substructure



b. Properly designed drain

Figure 29: Proper drainage is important

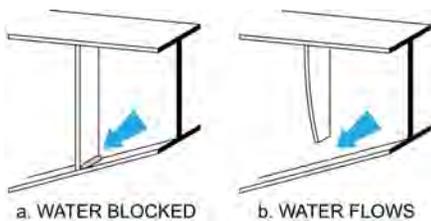


Figure 30: Structural steel detailing

Locations that Employ Deicers

The use of deicers on highways came later in the history of highways. It received a major jump with the “Bare Roads” policy enacted by state, provincial, and federal agencies in the late 1950s and early 1960s. These early deicers, initially all chloride-based, have saved many lives over the decades, but have essentially brought the ocean to the bridges in our continental interior.

Soil Exposure

Soils can contain chloride ions that aggravate corrosion of bridge foundation elements. The presence of other ions, like sulfates, can also cause problems if present in sufficient quantities. Barriers are low-cost protection for buried bridge foundation elements. These include polypropylene and polyethylene composite sheets that are fixed to grade and/or the outer formwork that act as capillary breaks between the concrete and the surrounding soil.

Microenvironment

The microenvironment includes differences in exposure within the bridge itself. This can include variations that are inherent in construction of large structures, such as the depth of concrete covering an embedded reinforcing bar. It also includes design detailing, which is an area in which the bridge designer can make a significant impact on the service life of a structure.

Drainage

With deicing applications, although the reinforced concrete deck receives the initial application, passing vehicles splash or generate mists and clouds of saltwater that can reach many other bridge components. Poor drainage can also be a problem.

Figure 29a shows how a short drain aspirates salt-contaminated runoff water onto beams and piers that support a bridge. Figure 29b shows how extending the drain can avoid this problem. Over the service life of a bridge, items as trivial as the configuration shown in Figures 29a and b can have a profound impact on the corrosion degradation of that structure. In the scope of a bridge project, paying attention to runoff water can have a dramatic impact on future corrosion and environmental impact for an extremely small addition to initial project costs.

Drainage extends beyond drains that carry runoff water from the bridge deck. Figure 30 shows how simple detailing in a stiffener can greatly improve long-term corrosion performance. In Figure 30a notice how the stiffener and lower flange meet and would both block the flow of water and provide a place for debris that tends to hold moisture and aggressive corrosion contaminants to collect. A simple change as shown in Figure 30b allows water to flow freely and does not make a trap that can collect debris. Unfortunately in trying to reduce first costs to an absolute minimum, such detailing is cut and long-term service life is sacrificed.

Corrosion Control

Corrosion control comes in many forms. Simple attention to design details can make significant improvements in service life for trivial increases in initial costs. There are many corrosion control measures available that can dramatically improve a bridge's resistance to corrosion and greatly extend the time the owner enjoys essentially maintenance-free use.

Protective Coatings

Protective coatings can be used to protect metals exposed to a corrosive environment. In simplest terms, they are pigments or fillers embedded in a variety of binders. Protective coatings can employ one or more protective mechanisms. These include:

- Providing a barrier between the protected metal and the surrounding corrosive environment
- Providing sacrificial corrosion protection
- Providing corrosion inhibitors

Barrier Coatings

Barrier coatings act like the walls of a fort and prevent the corrosive environment from reaching the surface of the steel below (see Figure 31). The current general practice for bridges today is to apply a zinc-rich primer over abrasive blast-cleaned steel. The primer is then followed with one or two additional coats that can provide a service life of 30 years.¹⁵

In response to environmental concerns, primers have changed from those that relied on lead and chromate to zinc-based materials, and organic solvents have been replaced.

Testing

In the early 1990s, Department of Transportation officials from several New England states decided to work collectively to evaluate coatings being applied to their structures. They formed the North East Protective Coating Committee (NEPCOAT) to establish a protocol whereby products could be tested and used to develop a common qualified products list.¹⁶

Using the NEPCOAT protocol as a starting point, the American Association of State Highway Transportation Officials (AASHTO) added coating evaluation as part of its National Transportation Product Evaluation Program (NTPEP). NTPEP's first effort was Specification R31, "Evaluation of Coatings Systems with Zinc-Rich Primers."¹⁷ R31 provided state departments of transportation an independent evaluation of commercial coating products, and those test results are now available on-line. Since their initial work with zinc-rich primers, the NTPEP program is available to evaluate other coating products.

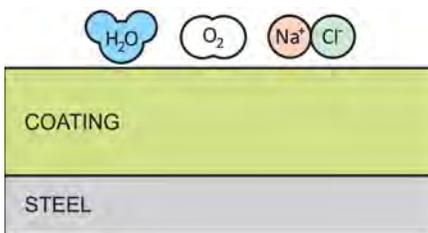


Figure 31: Barrier coating



Figure 32: NTPEP test panel15

Primers

Primers are coatings that are formulated to provide good adhesion to the substrate on which they are applied. Different primers are formulated for different substrates like steel, galvanized steel, and nonmetallics. Generally primers are not suitable for direct exposure to the atmosphere, water, or soil and need to be covered with a top coat or coats that are formulated for those conditions.

Primers can include fillers that provide corrosion protection. For example, inorganic zinc-rich primers contain metallic zinc that can provide galvanic protection to the underlying steel if the coating system is mechanically damaged.

Intermediate and Top Coats

Intermediate and top coats complete the multicoat system. Some types of coatings provide excellent mechanical strength.

Others provide good resistance to chalking and fading from being exposed to ultraviolet (UV) light from the sun. Often two different types of coatings are used, such as using an epoxy coating as the intermediate coat, and then covering that with a polyurethane coating that is resistant to UV degradation. The right coating system is the coating system that is suitable for the job. That system should be defined by what substrate is being coated, exposure conditions, and the desired service life.

Cutting Edge Technology

From the 1970s through the 1990s, coating systems incrementally changed to meet changing owner demands and environmental regulations. Today coatings are again changing, now bringing new technology advances that improve performance and reduce costs.

Nanotechnology is being used to formulate coatings that can be self-healing if the coating is nicked or otherwise mechanically damaged. Technology is also being used to improve the ability of coatings as a delivery system for corrosion inhibitors.

To reduce the costs of the typical three-coat systems, a number of one-coat systems for bridges have been formulated. Research work supported by the FHWA reports that although some one-coat systems show promise, they do not yet perform as well as three-coat systems in accelerated laboratory or outdoor testing.¹⁸

Galvanizing

Galvanizing is the application of zinc metal to the surface of steel to control corrosion of the steel. As was explained in Figure 14 and its accompanying text, a dry cell battery gets its electricity from the corrosion of zinc. When zinc and iron are electrically connected they will form a battery, also known as a galvanic couple, and if both are exposed to an electrolyte, such as water, the zinc will corrode and in the process cathodically protect the steel. For bridge applications, most galvanizing is accomplished using the hot-dip process (HDG) wherein the steel element is dipped into molten zinc. This is possible because zinc melts at a much lower temperature than steel. As with other types of coatings, surface preparation is a very important key to success. After HDG, ash and other surface contaminants should be removed (see Figure 33).

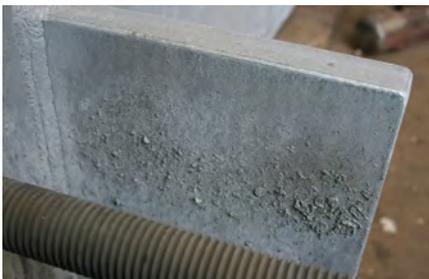


Figure 33: Ash on HDG element



a. Wallpaper Corrosion



b. Rust packing

Figure 34: Weathering steel corrosion



Figure 35: Duplex SS hinge
photo courtesy of Oregon DOT

Metallizing

Metallizing is similar to spray painting, except that molten metal or ceramics are sprayed instead of paint. The metal being applied can be melted using either a flame or an electric arc. Metallized coatings can be porous, so they are often sealed with an organic coating. The U.S. Navy employs metallizing as a means to control corrosion of exposed steel on its vessels. The Navy has found that metallizing is often more cost-effective than traditional coating and, by proper selection of the alloy being sprayed, can even be used on hot exhaust stacks.

Corrosion-Resistant Materials

If an extended maintenance-free service life is desired, then corrosion-resistant materials must be incorporated into the bridge design. This requires consideration of corrosion control options for structural steel elements, protective coatings, and reinforced concrete members.

Structural Steel Elements

Structural steel elements can be fabricated from corrosion-resistant materials. Most often this would be weathering steels, but in some locations stainless steels and aluminum can be used.

Weathering Steels

Weathering steels are special alloys that develop a corrosion-resistant patina, or rust. To successfully develop a stable patina requires attention to several key conditions including average TOW and chloride ion deposition.

Weathering steel bridges have been used successfully in a number of locations. Typically, these are locations that do not have high TOW or high chloride and/or SO_2 deposition rates. Figure 34 shows what can happen with too high a TOW.

Stainless Steels

Stainless steel can also be incorporated in bridges. Usually stainless steels would be too expensive to use as beams. However, they can find use in other critical components that will be exposed to corrosive environments. Figure 35 shows a hinge made from a duplex stainless alloy. Duplex alloys are often used where stainless elements will move against each other, as is the case here with the hinge rotating on the pin that can be seen in the lower left-hand corner of the photograph. Care must be taken to select the optimum stainless steel alloy.



Figure 36: Cross-section of ECR bar

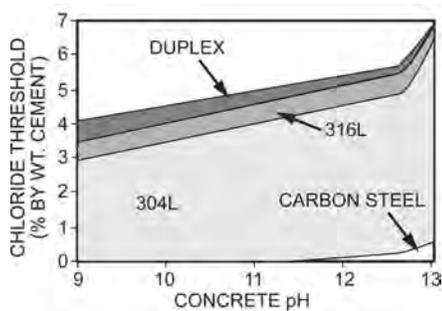


Figure 37: Stainless corrosion threshold

Aluminum

Aluminum is actually a reactive metal. The reason we normally consider it corrosion-resistant is because it forms an oxide layer that generally is quite stable and protects the underlying reactive metal. Aluminum is also an amphoteric metal, which means that it can be attacked if exposed to either acidic or alkaline conditions. As was discussed above, concrete is an alkaline material. Concrete's alkalinity passivates embedded steel reinforcing bar, but it will corrode exposed aluminum. This means care must be taken combining aluminum elements with reinforced concrete.

Corrosion-Resistant Reinforcing Bar

As with structural steel elements, there are several approaches that provide corrosion-resistant reinforcement. One approach is to apply a barrier coating for the reinforcing bar. Stainless steels and near-stainless alloys are a second approach. A third technique is to avoid using metal reinforcement.

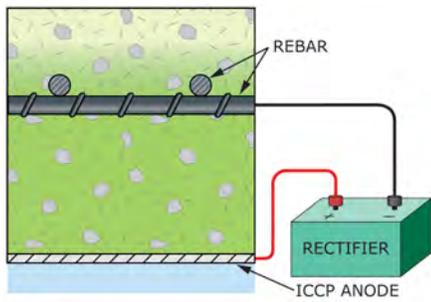
Epoxy-Coated Reinforcement

Epoxy-coated reinforcement (ECR) employs fusion-bonded epoxy coatings as a barrier coating. The effectiveness of ECR is an area of debate. When used, ECR should be used in all mats of reinforcement. For example, to save construction costs some owners have installed ECR on the top mat of a bridge deck and black steel reinforcing bar on the bottom mat. If the underside of the deck is not covered, say with stay-in-place form work, this type of installation could dramatically increase the chance of localized corrosion at pinholes in the top mat epoxy, and significant cutting of the reinforcing bar at that location without generating cracks or spalls. When ECR is effective it may provide a typical service life of 30 to 40 years (see Figure 36).

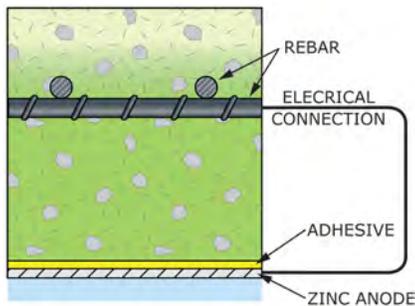
Stainless Steels and Other Alloys

A number of stainless steel alloys have been used as concrete reinforcing bars. In some applications the entire reinforcing bar is stainless. In other fabrications, a stainless jacket is placed over a carbon steel core. Pure stainless steels can provide over 100 years of corrosion-free service in concrete contaminated with chloride ions far beyond the nominal corrosion threshold value for carbon steel reinforcing bar (see Figure 37).

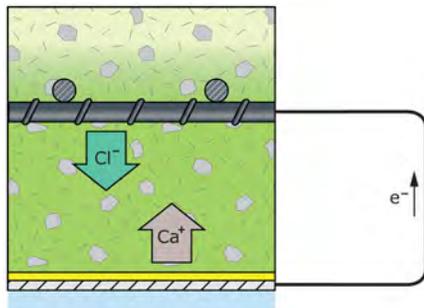
For 75 to 100 year or longer service life bridges the extra cost to use stainless reinforcement is the most cost-effective solution. If a 40 to 75 year service life is preferred, then near-stainless alloys are a more appropriate solution.



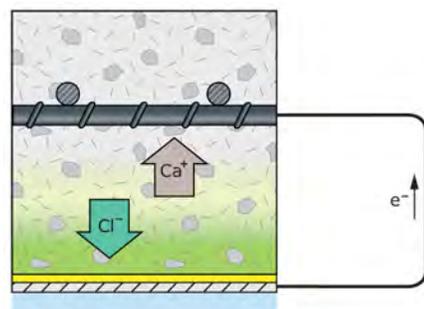
a. Impressed current CP



b. Galvanic CP



c. Initial CP conditions



d. Chloride migration due to CP

Figure 38: Cathodic Protection

Nonmetallic Reinforcement

Fiber-reinforced plastic (FRP) reinforcement can provide corrosion-free service. FRP bars have had problems with an aging process known as creep, but that can be avoided with attention to loading. The fiber production technology is improving so this is an area that deserves consideration in future construction projects.

Electrochemical Techniques

These techniques are usually applied as rehabilitation of corrosion-damaged bridges.

Cathodic Protection

As mentioned above, corrosion is a process similar to that by which a dry cell battery produces electricity. Following that explanation, cathodic protection (CP) is a battery charger and forces the electric current to flow in the opposite direction.

Impressed Current

An impressed current CP (ICCP) system is shown in Figure 38a. The anode is shown on the surface of the concrete, but it could be embedded as well. ICCP anodes must be fabricated from essentially inert materials. The direct current (DC) power comes from a device known as a rectifier that changes alternating current (AC), which powers buildings, into DC. Note that the chloride contamination is shown by the degree of green tinting of the concrete in the several figures.

Galvanic

With galvanic anode CP (GACP), a metal that is more electrochemically active than steel, typically zinc, is directly connected to the reinforcement (Figure 38b). The electrochemical difference between the two metals creates a galvanic couple that powers the system, in a process similar to the dry cell battery.

Chloride Ion Migration

In both CP systems the concrete is the electrolyte and passing of electric current occurs through the movement of ions. In Figure 38c, arrows show the general direction that two types of ions move. The negatively charged chloride anion moves toward the anode, while the positively charged calcium, or alkali, cation moves toward the reinforcing bar. With time, as shown in 38d, two things happen. First, moving the cations to the reinforcing bar surface increases the pH at the surface of the reinforcing bar. Second, the movement of the chloride ions toward the anode reduces the chloride content near the reinforcing bar to below the normal corrosion threshold. This speaks to the fact often observed in the operation of reinforcing bar CP systems that less current is needed with time, and in fact intermittent operation is possible.

Only through aggressive investment in infrastructure will Americans in every state be confident that they are safe crossing today's bridges, and that the road ahead leads to a shared prosperity.¹⁹

*America's Infrastructure
EPI*

Cathodic Prevention

Cathodic prevention differs from CP as anodes are installed during initial construction rather than as part of a restoration project. Cathodic prevention currents are significantly lower than CP currents and can be provided using impressed current anodes.

Corrosion Monitoring Equipment

Typical CP systems include monitoring equipment to track the performance of the systems. This almost always includes embedded reference electrodes.

There are other embeddable devices that can be installed during initial bridge construction that can monitor the migration of chloride through the concrete. Such monitoring would allow an owner to install a CP system or apply other corrosion control measures such as coatings, sealers, or membranes before the corrosion threshold is reached. If the CP system is installed at that time, there will be little to no repair costs caused by reinforcing bar corrosion-related damage. This provides significant savings compared to most CP projects that are installed after large areas of concrete have become unsound as a result of corrosion and require repair.

Chloride Removal

Chloride removal is like a high-intensity application of CP. Temporary anodes are used, and currents much higher than those required for CP are applied. The intent is not long-term application, but rather a relatively quick (6 to 8 weeks) removal of the chloride ions from the concrete. The anodes are bedded in a special exchange media that makes electrical contact with the concrete and collects the chloride ions after their migration.

Design Details

As previously mentioned, proper attention to design details can dramatically extend a bridge's service life. The necessary initial costs required are nominal compared to the maintenance dollar savings over time.

Drainage

It is to be expected that any bridge will be exposed to rain, but the bridge can also be exposed to water from below, from storms, or from passing traffic below if the bridge is an overpass. It is important that both the deck and the structural elements be designed to freely drain water, avoid ponding, and avoid creating areas that are prone to collecting debris. Drainage is important for both coated and concrete elements. While drainage systems should be as maintenance free as possible, they must be inspected and cleared of blockages on a regular basis.

The challenge is pursuing an investment strategy that can most effectively repair, upgrade and expand America's existing infrastructure and, by extension, support the U.S. economy.²⁰

*Public-Private Partnerships
U.S. Chamber of Commerce*

Concrete

Concrete is the first line of defense to extend the service life for reinforcement that will be exposed to chlorides or carbonation. Both the quality of the concrete in which the reinforcing bar is embedded and the depth of cover are important. Quality concrete slows the general penetration rate of both chloride ions and carbonation.

It is important, however, not to push the concrete mix too far. In recent years there has been a significant push to include what is known as high-performance concrete in many public works projects. These efforts can produce a concrete that can be made in small batches in the laboratory, but produce concretes that are prone to cracking if not placed correctly by the contractor.

The problem with cracking in concrete was discussed above, and the concern is that of localized corrosion if the cracks that form intersect the embedded reinforcing bar. Compared to the bulk concrete, cracks are freeways to move chloride ions to the surface of the reinforcing bar, with the corrosion localized at the crack.

Mechanical

Over the life of a structure, the mechanical action of concrete flexing will help chloride ions diffuse from the surface of the concrete to the reinforcing bar.²¹ Lighter construction generally means quicker construction at a lower cost. However, in areas where there is exposure to chlorides, a bit of stiffness may impede the progress of chloride ions from diffusing in from the surface.

The Highway Ahead

America's infrastructure needs work, especially highway bridges. The nation's bridge stock is aging and will need increased resources just to maintain its present condition.

Although state governments have the greatest operating and maintenance burden for bridges, they are facing a profoundly challenging fiscal climate, the worst since the end of the Great Depression. With major debates over debt increases at the federal level, it is highly unlikely that Congress will provide infrastructure expenditures to bring government public works financing over the next five years to the estimated \$2.2 trillion level needed. If this is the case, then it may be time to bring entrepreneurial thinking to the problem.

States already receive bond ratings. By that same principle, the U.S. Department of Transportation could develop a system to rate states based on their progress, or lack thereof, on preventative maintenance, and resources dedicated to repair.¹¹

*Road Work Ahead
U.S. PIRG*

Design-Build Approach

Traditional public works transportation projects follow a design-bid-build path for project delivery. An alternative approach is the design-build contract where the private sector is responsible for both engineering and construction.

Owners appreciate design-build projects for a number of reasons including:

- Projects are typically completed much faster
- Projects typically cost less
- The owner avoids the risk of being between the contractor and the engineer regarding disputes

Although there are valid criticisms regarding the design-build approach, researchers at Pennsylvania State University note that design-build projects get completed 12% faster at a cost 6% lower than do similar design-bid-build works.²²

Reduce Maintenance

It is also possible to dramatically reduce very hard-to-fund future maintenance requirements through requiring inclusion of corrosion control measures in new bridge projects.

Material Selection Consistent with Service Life

If the owner feels certain that functional obsolescence will not be a problem and a design life of over 75 years is desired, then stainless steel reinforcement should be required for decking in the request for proposal (RFP), and high-performance concrete and increased concrete cover for the sub- and superstructure.

If the owner wants a coating system that will provide a service life of 30 to 35 years before significant maintenance painting is required, then with today's technology, a three-coat system with a metallized primer would be the proper first choice, with a three-coat system with zinc-rich primer as a second choice. Such coating systems too can be included in the design-build RFP. The same holds true for inclusion of quality detailing, concreting, and cathodic prevention.

Design-build RFPs and contracts that require performance-based corrosion control measures can lead to building bridges with extended maintenance-free service lives.

References

1. S.K. Lee, "Current State of Bridge Deterioration in the U.S. – Part 1," *Materials Performance* 51, 1 (2012).
2. G. Washington, *Letter to Patrick Henry, Governor of Virginia* (VA, November 30, 1785).
3. *Poor Richard's Almanac* (Benjamin Franklin, 1736).
4. *Maintaining State of Good Repair Using Cost Effective Investment Strategies; Status of the Nation's Highways, Bridges, and Transit* (Washington, DC: FHWA, 2010).
5. Z. Rosenberg, "The State of the Union's Roads: An Investigative Report," *Car and Driver* (July 2011).
6. M.H. Adams, R. Hiatt, M.C. Hill, R. Russo, M. Wachs, A. Weingstein, "Financing Transportation in California: Strategies for Change" (Berkeley, CA: University of California, 2001).
7. "Report Card for America's Infrastructure" (Washington, DC: ASCE, 2009).
8. K. Schwab, "The Global Competitiveness Report: 2011-2012" (Geneva, Switzerland: World Economic Forum, 2011).
9. J.F. Kavinoky, "The Real Cost of Infrastructure," *Free Enterprise* (January 30, 2012).
10. "2010 Status of the Nation's Highways, Bridges, and Transit: Conditions & Performance, FHWA Report to Congress" (Washington, DC: U.S. Department of Transportation, 2010).
11. T. Madsen, B. Davis, P. Baxandall, "Road Work Ahead" (Washington, DC: U.S. PIRG Education Fund, 2010).
12. "Life in the Slow Lane: America's Transport Infrastructure," *The Economist* (April 28, 2011).
13. ASM Metals Handbook, Vol. 1, 9th ed. Materials Park, OH: ASM, 1978), p. 720.
14. ISO 9223 (latest revision), "Corrosivity of Atmospheres" (Geneva, Switzerland: International Organization for Standardization [ISO]).
15. E.S. Kline, "Steel Bridges: Corrosion Protection for 100 Years," *Journal of Protective Coatings and Linings* (May 2008): pp. 22-31.
16. W.D. Corbett, "The Future of Bridge Coating: A National Qualification System for Structural Steel Coatings," *Journal of Protective Coatings and Linings* (January 2004), p. 14.
17. AASHTO R 31-06, "Standard Practice for Evaluation of Coating Systems with Zinc-Rich Primers" (Washington, DC: American Association of State and Highway Transportation Officials, 2006) note: replaced by AASHTO R 31-09.
18. U.K. Yau, P. Kodumuri, S.K. Lee, "FHWA-HRT-11-046, Performance Evaluation of One-Coat Systems for New Steel Bridges" (Washington, DC: U.S. Federal Highway Administration, 2011).
19. D. Hall, "The Economic Policy Institute Blog," retrieved May 22, 2012, from Economic Policy Institute: <http://www.epi.org/blog/americas-infrastructure-bridges-jobs/>
20. E. Boyer, R. Cooper, J.F. Kavinoky, "Public-Private Partnerships and Infrastructure Resilience" (Washington, DC: National Chamber Foundation, 2011).
21. J.S. Tinnea, N.J. Feuer, "Evaluation of Structural Fatigue and Reinforcement Corrosion Interrelationships," CORROSION/85, paper no. 259 (Houston, TX: NACE, 1985).
22. V. Sanvido, M. Konchar, "Researches on Selecting Project Delivery Systems, Construction Industry Institute Research Report 133-1" (Austin, TX: CII, 1998).