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Section 2
Bridge Materials

Steel Description	Steel Designation		Years in Use
	American Society for Testing and Materials (ASTM)	American Association of State Highway and Transportation Officials (AASHTO)	
Structural Carbon Steel	A7	M94	1900-1967
Structural Nickel Steel	A8	M96	1912-1962
Structural Steel	A36 (A709 Grade 36)	M183 (M270 Grade 36)	1960-Present (1974-Present)
Structural Silicon Steel	A94	M95	1925-1965
Structural Steel	A140		1932-1933
Structural Rivet Steel	A141	M97	1932-1966
High-Strength Structural Rivet Steel	A195	M98	1936-1966
High-Strength Low-Alloy Structural Steel	A242	M161	1941-Present
Low and Intermediate Tensile Strength Carbon Steel Plates	A283		1946-Present
Low and Intermediate Tensile Strength Carbon-Silicon Steel Plates	A284		1946-Present
Steel Sheet Piling	A328	M202	1950-Present
Structural Steel for Welding	A373	M165	1954-1965
High-Strength Structural Steel	A440	M187	1959-1979
High-Strength Low-Alloy Structural Manganese Vanadium Steel	A441	M188	1954-1989
High-Yield-Strength, Quenched and Tempered Alloy Steel Plate (Suitable for Welding)	A514 (A709 Grade 100/100W)	M244 (M270 Grade 100/100W)	1964-Present (1974-Present)
Hi Strength Low-Alloy Columbium-Vanadium Steel of Structural Quality	A572 (A709 Grade 50)	M223 (M270 Grade 50)	1966-Present (1974-Present)
Hi-Strength Low-Alloy Structural Steel with 50 ksi Minimum Yield Point to 4 inches Thick	A588 (A709 Grade 50W)	M222 (M270 Grade 50W)	1968-Present (1974-Present)
High-Strength Low-Alloy Steel H-Piles and Sheet Piling	A690		1974-Present
Quenched and Tempered Low-Alloy Structural Steel Plate with 70 ksi Minimum Yield Strength to 4 inches Thick	A852 (A709 Grade 70W)	M313 (M270 Grade 70W)	1985-Present (1985-Present)

Summary of Steel Designations (Primary Source: Beer and Johnston, *Mechanics of Materials*, New York: McGraw-Hill, 1981)

Topic 2.3 Steel

2.3.1 Introduction

Steel is a widely used construction material for bridges due to its strength, relative ductility, and reliability. It is found in a variety of members on a large number of bridges. Therefore, the bridge inspector should be familiar with the various properties and types of steel.

2.3.2 Common Methods of Steel Member Fabrication

Rolled Beams

Rolled beams are manufactured in structural rolling mills. The flanges and web are one piece of steel. Rolled beams in the past were generally available no deeper than 914 mm (36") in depth but are now available from some mills as deep as 1120 mm (44").

Rolled beams are generally compact' sections which satisfy flange to web thickness ratios to prevent buckling.

Rolled beams generally will have bearing stiffeners but no intermediate stiffeners since they are compact.

Plate Girders

Plate girders are often specified when the design calls for members deeper than 914 mm (36") or 1120 mm (44").

Plate girders are built-up shapes composed of any combination of plates, bars, and rolled shapes. The term "built-up" describes the way the final shape is made.

Older fabricated multi-girders were constructed of riveted built-up members. Today's fabricated multi-girders are constructed from welded members.

2.3.3 Common Steel Shapes Used in Bridge Construction

Steel as a bridge construction material is available as wire, cable, plates, bars, rolled shapes, and built-up shapes. Typical areas of application for the various types of steel shapes are listed below:

- Wires are typically used as prestressing strands or tendons in beams and girders (See Figure 2.2.4).
- Cable-stay and steel suspension bridges are primarily supported by steel cables (see Figure 2.3.1).
- Steel plates have a wide variety of uses. They are primarily used to construct built-up shapes (see Figure 2.3.2).
- Steel bars are generally placed in concrete to provide tensile reinforcement in the form of deformed round bars. Steel bars can also be used as primary or secondary tension members (see Figure 2.3.3).

- Rolled shapes are used as structural beams and columns and are made by placing a block of steel through a series of rollers that transform the steel into the desired shape. These steel shapes are either hot rolled or cold rolled. The typical rolled shape is an “I” shape. The “I” shape comes in many sizes and weights (see Figure 2.3.4). They can also be fabricated with a straight or tapered flange thickness. Other rolled shapes are channel or “C” shapes, angles, and “T” shapes.

- Built-up shapes are also used as structural beams and columns but are composed of any combination of plates, bars, and rolled shapes. The term “built-up” describes the way the final shape is made. Built-up shapes are used when an individual rolled shape cannot carry the required load or when a unique shape is desired. Built-up shapes are riveted, bolted, or welded together. Common built-up shapes include I-girders, box girders, and truss members (see Figure 2.3.5).

Figure 2.3.1 Steel Cables

Figure 2.3.2 Steel Plates

Figure 2.3.3 Steel Bars

Figure 2.3.4 Rolled Shapes

Figure 2.3.5 Built-up Shapes

2.3.4
Properties of Steel

Physical Properties

Many of the nation's largest bridges are constructed primarily of steel. When compared with iron, steel has greater strength characteristics, it is more elastic, and can withstand the effects of impact and vibration better.

Iron consists of small amounts of carbon. However, when the carbon content is greater than 0.l%, the material is classified as steel. Steel has a unit weight of about 7850 kg/m^3 (490 pcf).

ASTM and AASHTO define the required properties for various steel types. ASTM classifies each type with an "A" designation, while AASHTO uses an “M” designation.

Low carbon steel, steel with carbon content less than approximately 0.3%, defines some of the most common steel types:

- A7 steel - the most widely used bridge steel up to about 1967; obsolete due to poor weldability characteristics
- A373 steel - similar to A7 steel but has improved weldability characteristics due to controlled carbon content
- A36 steel - the latest of the low carbon steels, first used in 1960; it features good weldability and improved strength

Structural nickel steel (A8) was used widely prior to the 1960's in bridge construction, but welding problems occurred due to relatively high carbon content.

Structural silicon steel (A94) was used extensively in riveted or bolted bridge structures prior to the development of low alloy steels in the 1950's. This steel also has poor weldability characteristics due to high carbon content.

Quenched and tempered alloy steel plate (A514) was developed primarily for use in welded bridge members.

High strength, low alloy steel is used where weight reduction is required, where increased durability is important, and where atmospheric corrosion resistance is desired; examples include:

- A441 steel - manganese vanadium steel
- A572 steel - columbium-vanadium steel (replaced by A441 in 1989)
- A588 & A852 steel - a "weathering steel," was developed to be left unpainted, which develops a protective oxide coating upon exposure to the atmosphere under proper design and service conditions (refer to Topic 2.3.5 for a further description of weathering steel)

These steels are also copper bearing, which provides increased resistance to atmospheric corrosion and a slight increase in strength.

Some of the steel types listed above were used widely in the past but are no longer being manufactured. A new ASTM designation (A709) was developed in 1974. This designation covers carbon and high-strength low-alloy steel structural shapes, plates, and bars, and quenched and tempered alloy steel for structural plates intended for use in bridges. Six grades are available in four yield strength levels (36, 50, 70, and 100). The steel grade is equivalent to the yield strength in units of kips per square inch (ksi). Grades 36, 50, 50W, 70W, and 100/100W are also included in ASTM Specifications A36, A572, A588, A852, and A514, respectively. Grades 50W, 70W, and 100W have enhanced atmospheric corrosion resistance and are labeled with a “W” for weathering steel.

In 1996, a new steel type, High Performance Steel (HPS), was introduced to bridge construction. This type of steel was designed to improve weldability, toughness, and atmospheric corrosion resistance. Prior to the new steel designs, a set of “goal properties” was implemented and then testing took place to meet the goals. The first grade of HPS was HPS-70W, which was produced by Thermo-Mechanical-Controlled Processing (TMCP). The HPS-70W has improved Charpy V-Notch impact properties compared to 70W. Currently the HPS grades available are HPS-50W, HPS-70W, and HPS-100W.

In addition to the ASTM steel designations, the American Association of State Highway and Transportation Officials (AASHTO) also publishes its own steel designation (M270). For each ASTM steel designation, there is generally a corresponding AASHTO steel designation. For a summary of the various ASTM and AASHTO steel designations, refer to the table at the beginning of Topic 2.3.

Mechanical Properties

Some of the mechanical properties of steel include:

- Strength - steel is isotropic and possesses great compressive and tensile strength, which varies widely with type of steel
- Elasticity - the modulus of elasticity is nearly independent of steel type and is commonly assigned as 200,000 MPa (29,000,000 psi)
- Ductility - both the low carbon and low alloy steels normally used in bridge construction are quite ductile; however, brittleness may occur because of heat treatment, welding, or metal fatigue
- Fire resistance - steel is subject to a loss of strength when exposed to high temperatures such as those resulting from fire (see Topic 2.3.5 – for specific temperature information)
- Corrosion resistance - unprotected carbon steel corrodes (i.e., rusts) readily; however, steel can be protected
- Weldability - steel is weldable, but it is necessary to select a suitable welding procedure based on the chemistry of the steel
- Fatigue - fatigue problems in steel members and connections can occur in bridges due to numerous live load stress cycles combined with poor weld or connection details

2.3.5

Types and Causes of Steel Deterioration

Corrosion

To properly inspect a steel bridge, the inspector must be able to recognize the various types of steel defects and deterioration. The inspector must also understand the causes of the defects and how to examine them. The most recognizable type of steel deterioration is corrosion (see Figure 2.3.6). Bridge inspectors should be familiar with corrosion since it can lead to a substantial reduction in member capacity. Corrosion is the primary cause of section loss in steel members and is most commonly caused by the wet-dry cycles of exposed steel. When deicing chemicals are present, the effect of corrosion is accelerated.

Figure 2.3.6 Steel Corrosion and Complete Section Loss on a Stringer Web

Some of the common types of corrosion include:

- Environmental corrosion - primarily affects metal in contact with soil or water and is caused by formation of a corrosion cell due to deicing salt concentrations, moisture content, oxygen content, and accumulated foreign matter such as roadway debris and bird droppings
- Stray current corrosion - caused by electric railways, railway signal systems, cathodic protection systems for pipelines or foundation pilings, DC industrial generators, DC welding equipment, central power stations, and large substations
- Bacteriological corrosion - organisms found in swamps, bogs, heavy clay, stagnant waters, and contaminated waters can contribute to corrosion of metals
- Stress corrosion - occurs when tensile forces expose an increased portion of the metal at the grain boundaries, leading to corrosion and ultimately fracture
- Fretting corrosion - takes place on closely fitted parts which are under vibration, such as machinery and metal fittings, and can be identified by pitting and a red deposit of iron oxide at the interface

Fatigue Cracking

Another type of deterioration is fatigue cracking (see Figure 2.3.7). Fatigue failure occurs at a stress level below the yield stress and is due to repeated loading.

Fatigue cracking has occurred in several types of bridge structures around the nation. This type of cracking can lead to sudden and catastrophic failure on certain bridge types. Therefore, the bridge inspector should know where to look and how to recognize early stages of fatigue crack development.

Figure 2.3.7 Fatigue Crack at Coped Top Flange of Riveted Connection

Some factors leading to the development of fatigue cracks are:

- Frequency of truck traffic
- Age or load history of the bridge
- Magnitude of stress range
- Type of detail
- Quality of the fabricated detail
- Material fracture toughness (base metal and weld metal)
- Weld quality
- Ambient temperature

There are two basic types of bending in bridge members: in-plane and out-of-plane. When in-plane bending occurs, the cross section of the member resists the load according to the design and undergoes nominal elastic deformation. Out-of-plane bending implies that the cross section of the member is loaded in a plane other than that for which it was designed and undergoes significant elastic deformation or distortion. More correctly, out-of-plane bending should be referred to as out-of-plane distortion. Out-of-plane distortion is common in beam webs where transverse members, such as floorbeams, connect and can lead to fatigue cracking (see Figure 2.3.8).

There is a distinction between fatigue that is caused from in-plane (as designed) bending and out-of-plane distortion.

Additional information about fatigue and fracture in steel bridges is presented in Topic 8.1.

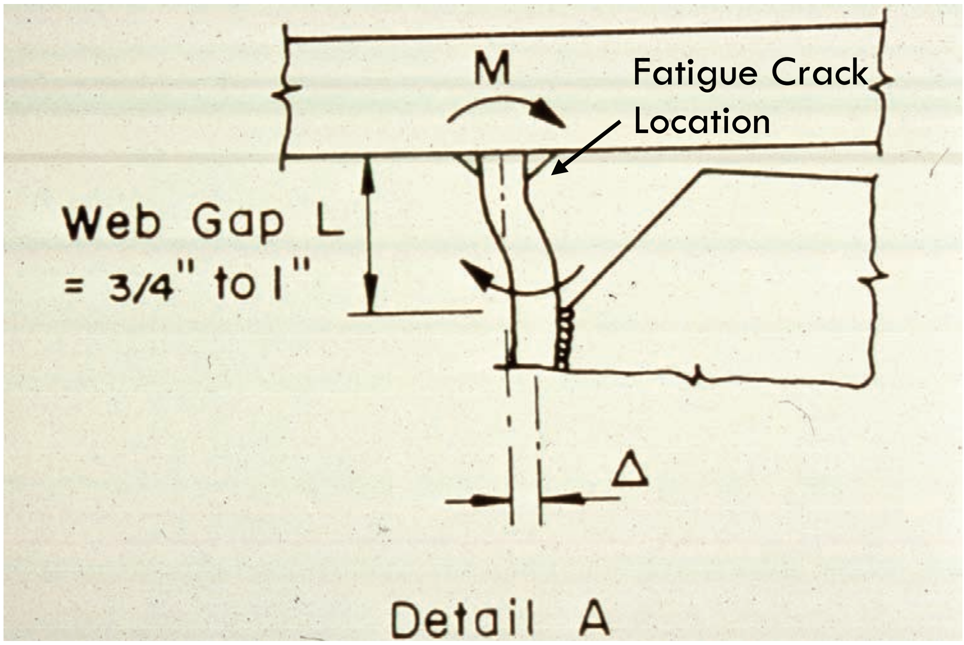

Figure 2.3.8 Out-of-plane Distortion

Overloads

Overloads are loads that exceed member or structure design loads. Steel is elastic (i.e., it returns to the original shape when a load is removed) up to a certain point, known as the yield point (see Topic P.2). When yield occurs, steel will bend or elongate and remain bent or elongated after the load has been removed. This type of permanent deformation of material beyond the elastic range is called plastic deformation. Plastic deformations due to overload conditions may be encountered in both tension and compression members.

The symptoms of plastic deformation in tension members are:

- Elongation
- Decrease in cross section, commonly called "necking down"

The symptoms of plastic deformation in compression members are:

- Buckling in the form of a single bow
- Buckling in the form of a double bow or "S" type, usually occurring where the section under compression is pinned or braced at the center point

An overload can lead to plastic deformation, as well as complete failure of the member and structure. This occurs when a tension member breaks or when a compression member exhibits buckling distortion at the point of failure.

Collision Damage

Components and structural members of a bridge that is adjacent to a roadway or waterway are susceptible to impact damage. Indications of impact damage include dislocated and distorted members (see Figure 2.3.9).

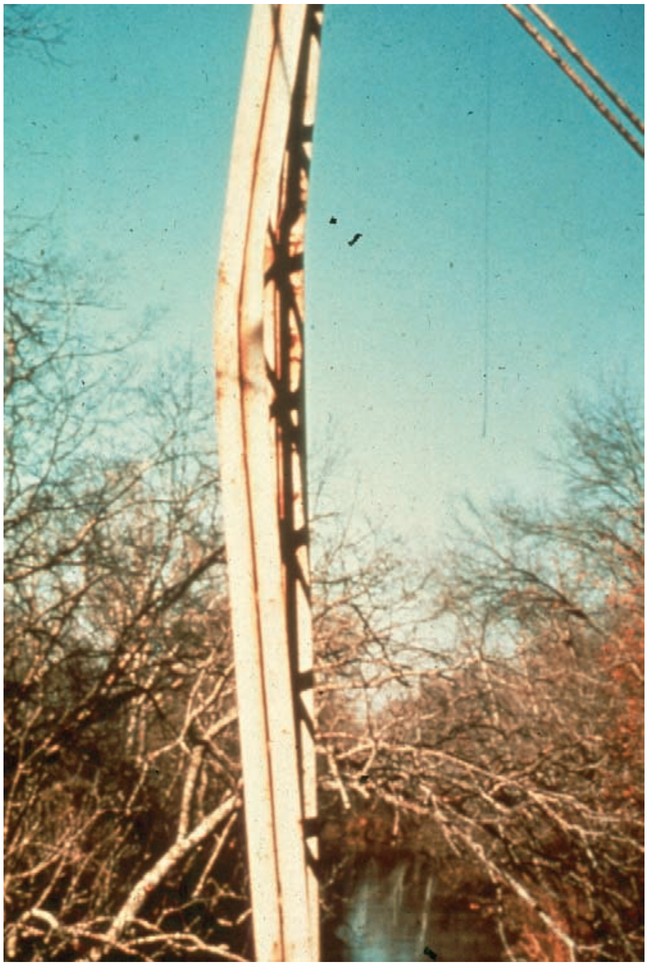

Figure 2.3.9 Collision Damage on a Steel Bridge

Heat Damage

Steel members will undergo serious deformation upon exposure to extreme heat (see Figure 2.3.10). In addition to sagging, or elongation of the metal, intense heat often causes members to buckle and twist; rivets and bolts may fail at connection points. Buckling could be expected where the member is under compression, particularly in thin sections such as the web of a girder.

Figure 2.3.10 Heat Damage

Temperatures affecting steel strength are as follows:

- 204–260°C (400°-500°F) - starts to affect strength
- 482–538°C (900°-1000°F) - major loss of strength

Paint Failures

The following paint failures are common on steel:

- Chalking, erosion, checking, cracking, and wrinkling (see Figure 2.3.11), as described in ASTM D-3359.
- Blisters are caused by painting over oil, grease, water, salt, or by solvent retention. Corrosion can occur under blisters.
- Undercutting occurs when surface rust advances under paint. It commonly occurs along scratches that expose the steel or along sharp edges (see Figure 2.3.12). The corrosion undermines intact paint, causing it to blister and peel.
- Pinpoint rusting can occur at pinholes in the paint, which are tiny, deep holes in the paint, exposing the steel (see Figure 2.3.13). It can also be caused by thin paint coverage. In this case, the "peaks" of the roughened steel surface protrude through the paint and corrode.
- Microorganism failure is caused by bacteria or fungi attacking biodegradable coatings. Oil/alkyds are the most often affected.
- Alligatoring can be considered a widely spaced checking failure, caused by internal stresses set up within the surface of a coating during drying (see Figure 2.3.14). The stresses cause the surface of the coating to shrink more rapidly to a much greater extent than the body of the coating. This causes large surface checks that do not reach the steel substrate.

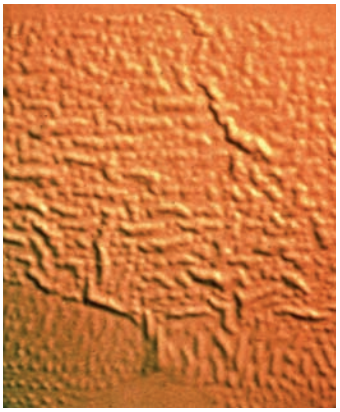

Figure 2.3.11 Paint Wrinkling

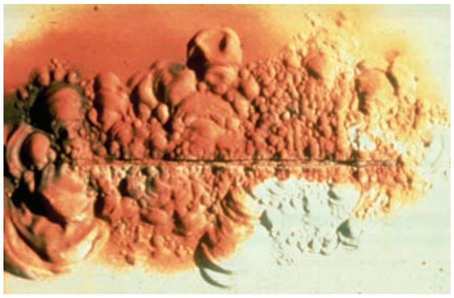

Figure 2.3.12 Rust Undercutting at Scratched Area

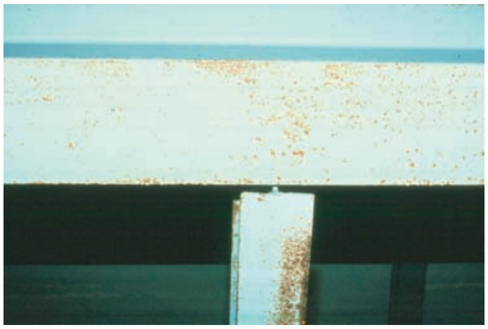

Figure 2.3.13 Pinpoint Rusting

Figure 2.3.14 Paint Peeling from Steel Bridge Members

- Mudcracking can be considered a widely spaced cracking failure, where the breaks in the coating extend to the steel substrate, allowing rapid corrosion (see Figure 2.3.15). Mudcracking is often a phenomenon of inorganic zinc-rich primers, which are applied as a very thick layer or are applied on a hot surface. Rapid curing causes the shrinkage, which yields the alligatoring, and ultimately, mudcracks.
- Bleeding occurs when soluble colored pigment from an undercoat penetrates the topcoat, causing discoloration.

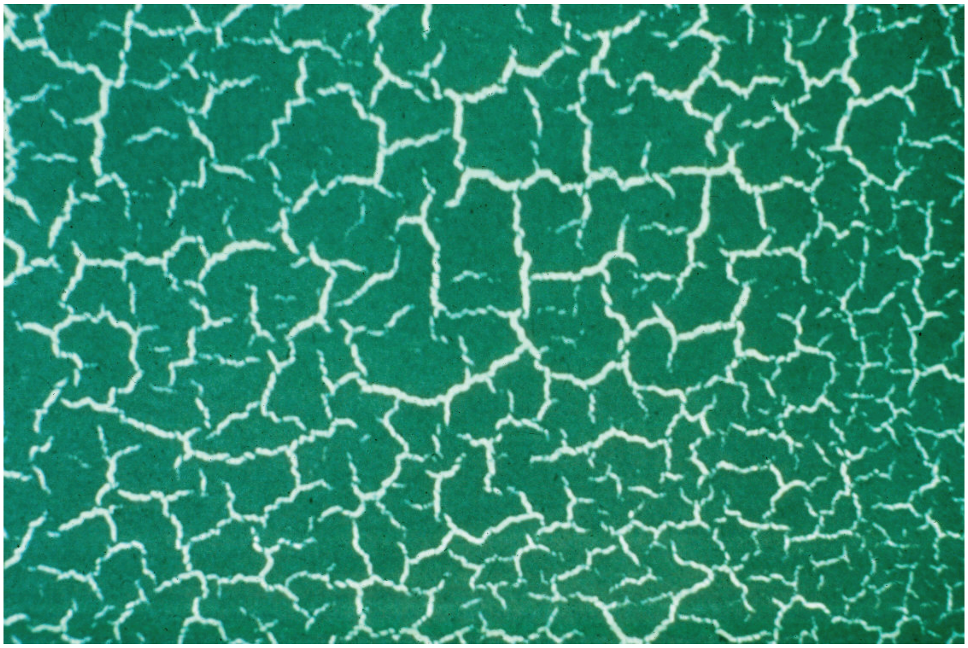

Figure 2.3.15 Mudcracking Paint

2.3.6

Factors that Influence Fatigue Life

Main factors influencing the development of fatigue cracks are:

1. **Magnitude of Stress Range**
   Trucks (not cars or buses) produce stress ranges that may lead to fatigue cracks.

2. **Number of Cycles (Frequency)**
   This is dependent on:
   - Frequency of truck traffic
   - Age or load history of the bridge

3. **Fatigue Prone Details**
   This depends on:
   - The type of detail
   - Quality of the fabricated detail
   - Weld quality

Other factors influencing the development of fatigue cracks are:

Material Fracture Toughness

Toughness of the:

- Base metal
- Weld metal

Toughness is based on the chemical composition of the steel.

Ambient Temperature

- Colder – more likely to crack

Fatigue and fracture are discussed in further detail in Topic 8.1 and the "Fracture Critical Inspection Techniques for Steel Bridges" NHI Course number FHWA-NHI-130078.

2.3.7

Protective Systems

Protective systems, when applied properly, provide protection needed against rust or corrosion**.** A thorough understanding of the steel corrosion process will help in the inspection of protective systems on bridge members.

Corrosion of Steel

Corrosion can be defined as a wearing away of metal by a chemical or electrochemical oxidizing process. Corrosion in metals is a form of oxidation caused by a flow of electricity from one part of the surface of one piece of metal to another part of the same piece. The result is the conversion of metallic iron to iron oxide. Once the corrosion process takes place, the steel member has a loss of section which results in a loss of structural capacity. Both conduction and soluble oxygen are necessary for the corrosion process to occur.

A conductive solution (water) or electrolyte must be present in order for current to flow. Corrosion occurs very slowly in distilled water, but much faster in salty water, because the presence of salt (notably sodium chloride) improves the ability of water to conduct electricity and contributes to the corrosion process. In the absence of chlorides, steel (iron) corrodes slowly in the presence of water. Water is both the medium in which corrosion normally occurs and provides the corrosion reaction. In addition, oxygen accelerates the corrosion process. Corrosion stops or proceeds at a reduced rate when access to water and oxygen is eliminated or limited. Water and oxygen are therefore essential for the corrosion process. For example, corrosion of steel does not occur in moisture-free air and is negligible when the relative humidity of the air is below 30% at normal or lower temperatures. The presence of chlorides in the water will accelerate corrosion by increasing the conductivity of the water.

To have corrosion take place in steel, then, one must have:

- Oxygen
- An electrolyte to conduct current

- An area or region on a metallic surface with a negative charge (cathode)
- An area or region on the metallic surface with a positive charge (anode)

Exposure of steel to the atmosphere provides a plentiful supply of oxygen. The presence of oxygen can limit corrosion by the formation of corrosion product films that coat the surface and prevent water and oxygen from reaching the uncorroded steel. The presence of contaminants such as chlorides accelerates the corrosion rate on steel surfaces by disrupting the protective oxide film.

Galvanic Action

The term "galvanic action" is generally restricted to the changes in normal corrosion behavior that result from the current generated when one metal is in contact with a different one. The two metals are in a corrosive solution when one metal may become an anode when it contacts a dissimilar metal. In such a "galvanic couple," the corrosion of one of the metals (e.g., zinc) will be accelerated, and the corrosion of the other (e.g., steel) will be reduced or possibly stopped. Galvanized coatings on highway guardrails and zinc-rich paint on structural steel are examples of galvanic protection using such a sacrificial (zinc) anode.

Types and Characteristics of Steel Coatings

Surface Preparation for Painting

The steel surface must be properly prepared prior to paint application. All foreign material must be removed. The following steps must be taken when preparing the surface for painting:

- Dirt and dust particles or spent abrasive from blast cleaning interfere with paint adhesion to the steel substrate and prevent application of a smooth, uniform film of paint. Debris embedded in the paint can also wick moisture and corrosive elements through the film to the substrate.
- Rust cannot be penetrated by most paints. Rust can become poorly adherent. In such cases, disbonding of the rust carries away the paint layers, permitting accelerated corrosion.
- Flash rust is a light layer of rust, which forms on the cleaned steel soon after exposure to the air, particularly in moist or humid environments. This layer may not be thoroughly wetted and may impede adhesion.
- Salts trapped in the paint film can cause blistering and disbonding.
- Oil and grease prevent good paint adhesion and must be completely removed. Welding smoke and inspection markings leave an oily residue that must also be completely removed.
- Dead paint that is loose, cracking, or flaking will eventually lift from the surface, carrying any new paint with it.
- Mill scale is a layer of iron oxide on the surface of steel. It forms when the steel is heated at high temperatures in a furnace. Mill scale has a bluish, somewhat shiny appearance, which may be difficult to see on partially blast cleaned steel. It must be completely removed when using most coating materials, as it may disbond upon expansion and contraction, carrying the paint with it.
- Weld spatter may also dislodge, leaving a bare exposed steel surface.

The surface should also be roughened to promote paint adhesion, as paint will not adhere well to a smooth surface.

Methods of Surface Preparation

The Society of Protective Coatings publishes a set of standards and specifications describing the following methods of surface preparation:

- Solvent cleaning
- Hand tool cleaning
- Power tool cleaning
- Abrasive blast cleaning
- Water blast cleaning

Solvent cleaning removes oil and grease. It is usually used in conjunction with or prior to the mechanical preparation methods. Common solvents include petroleum and coal tar solvents, turpentine, mineral spirits, alkaline cleaners, and emulsion cleaners, which contain oil soaps mixed with kerosene or mineral spirits.

Hand tool cleaning is used for removing loosely adhering paint, rust, or mill scale. It will not remove tightly adhering mill scale, or dirt and oils in crevices. Due to its slow speed, hand tool cleaning is used mostly for small area spot cleaning. Common hand tools include scrapers, wire brushes, chipping hammers, knives, chisels, and abrasive pads.

Power tool cleaning is effective on both plane and contoured steel surfaces. Power tool cleaning devices remove loose paint, rust, and scale. Power tools do not leave the residue common with blast cleaning. Also, power tools are used on small areas and where the abrasive could damage sensitive surroundings.

Abrasive blast cleaning is the preferred surface preparation method for coatings, which require a high degree of cleanliness and a uniformly roughened surface profile. Blast cleaning is a production method, which can remove mill scale. A water collar is sometimes used with abrasive blast cleaning to prevent abrasive rust and paint particles from becoming airborne.

Water blast cleaning (hydroblasting) may be high or low pressure, hot or cold, with or without detergent, depending upon the type of cleaning desired. Water does not etch a steel surface and may not remove tight paint, rust, or mill scale. Abrasives may be injected into the water stream to remove tightly adhering material for faster clearing or to produce a roughened surface profile. Sand is the most common abrasive. The process can remove old paint, rust, and mill scale. It yields a degree of cleanliness equivalent to open nozzle abrasive blast cleaning. High water pressure may cause flash rusting. Water blast cleaned areas must be either cleaned by dry abrasive blast cleaning or a corrosion inhibiting chemical must be added to prevent flash rusting.

Paint

Once the steel surface is properly prepared, the appropriate type and application of paint must be chosen based on the paint characteristics.

Paint is by far the most common coating used to protect steel bridges. Paint is composed of four basic compounds: pigments, vehicle (also called binder), solvents (also called thinners), and additives (such as thickeners and mildewoides). The pigments contribute such properties as inhibition of corrosion of the metal surface (e.g., zinc, zinc oxide, red lead, and zinc chromate), reinforcement of the dry paint film, stabilization against deterioration by sunlight, color, and hardness. Pigments are generally powders before being mixed into paint. The vehicle also remains in the dry-cured paint layer. It binds the pigment particles together and provides adhesion to the steel substrate and to other paint layers. Thus, the strength of the binder contributes to the useful life of the coating. Paint can be classified as inorganic or organic, depending on the vehicle. Inorganic paint uses a water soluble silicate binder which reacts with water during paint curing. Most types of paint contain one of a variety of available organic binders. The organic binders cure (harden) by one or more of the following mechanisms:

- Evaporation of solvents
- Reaction with oxygen in the air
- Polymerization through the action of heat or a catalyst
- Combination of reactive components in the binder

Solvents, which are liquids (such as water and mineral spirits), are included in paint to transport the pigment-binder combination to the substrate, to lower paint viscosity for easier application, to help the coating penetrate the surface, and to wet the substrate. Since the solvent is volatile, it eventually evaporates from the dry paint film. Additives are special purpose ingredients that give the product extra performance features. For example, mildewoides reduce mildew problems, and thickeners lengthen the drying time for application in hot weather.

Paint used on steel bridges acts as a physical barrier to moisture, oxygen, and chlorides, all of which promote corrosion. While water and oxygen are important to corrosion, chlorides from deicing road salts or seawater spray accelerate the corrosion process significantly.

Paint Layers

Paint on steel is usually applied in up to three layers, or coats:

- Primer coat
- Intermediate coat
- Topcoat

The primer coat is in direct contact with the steel substrate. It is formulated to have good wetting and bonding properties and may or may not contain passivating (corrosion-inhibiting) pigments.

The intermediate coat must strongly adhere to the primer. It provides increased thickness of the total coating system, abrasion and impact resistance, and a barrier to chemical attack.

The topcoat (also called the finish coat) is typically a tough, resilient layer, providing a seal to environmental attack, water, impact, and abrasion. It is also formulated for an aesthetic appearance.

Types of Paint

A wide variety of paints are applied to steel bridges. All of them except some zinc-rich primers use an organic binder.

Oil/alkyd Paint

Oil/alkyd paints use an oil such as linseed oil and an alkyd resin as the binding agent. Alkyd resin is synthetically produced by reacting a drying oil acid with an alcohol. Alkyd paints are low cost, with good durability, flexibility, and gloss retention. They are also tough, with moderate heat and solvent resistance. They should not be used in water immersion service or in alkaline environments.

A disadvantage is their offensive odor. They are also slow drying, difficult to clean up, and have poor exterior exposure. Alkyd paints often contain lead pigments, which are known to cause numerous health problems. The removal and disposal of lead-based paints is a regulated activity in all states.

Vinyl Paint

Vinyl paints are based on various vinyl polymer binding agents dissolved in a strong solvent. These paints cure by solvent evaporation. Vinyls have excellent chemical, water, salt, acid, and alkali resistance, good gloss retention, and are applicable at low temperatures. Conversely, their disadvantages include poor heat and solvent resistance, and poor adhesion. Vinyls are usually not used with other types of paint in a paint system. Vinyl coatings can be formulated to serve as primer, intermediate, and topcoat in paint systems.

Epoxies

Epoxies utilize an epoxy polymer binder, which forms a tough, resilient film upon drying and curing. Drying is by solvent evaporation, while curing entails a chemical reaction between the coating components. Epoxy coatings have excellent atmospheric exposure characteristics, as well as resistance to chemicals and water. They are often used as the intermediate coat in a three-layer paint system. There are also two- and three-layer systems, which use only epoxies. One disadvantage of epoxies is that they chalk when exposed to sunlight. This chalking must be removed prior to topcoating with another layer of epoxy or another material. If not removed, the chalking will compromise subsequent adhesion.

Epoxy Mastics

Epoxy mastics are heavy, high solid content epoxy paints, often formulated with flaking aluminum pigment. The mastics are useful in applications where a heavy paint layer is required in one application. They can be formulated with wetting and penetrating agents, which permit application on minimally prepared steel surfaces.

Urethanes

Urethanes are commonly used as the topcoat layer. They provide excellent sunlight resistance, hardness, flexibility (i.e., resistance to cracking), gloss retention, and resistance to water, harmful chemicals, and abrasion. All-urethane systems are also available which utilize urethane paints as primer, intermediate, and topcoat.

Zinc-rich Primers

Zinc-rich primers contain finely divided zinc powder (75% to 95%) and either an organic or inorganic binder. They protect the steel substrate by galvanic action, wherein the metallic zinc corrodes in preference to the steel. The materials have excellent adhesion and resist rust undercutting when applied over a properly prepared surface. The zinc-rich primers must be well mixed prior to application, or some coated areas will be deficient in zinc, lowering the substrate protection.

Latex Paint

Latex paint consists of a resin emulsion. The term covers a wide range of materials, each formulated for a different application. Latex on steel has excellent flexibility (allowing it to expand and contract with the steel as the temperature changes) and color retention, with good adhesion, hardness, and resistance to chemicals. Latex paint has low odor, faster drying time, and easier clean up.

The disadvantages of latex paint include sacrificed durability, and it must be applied at temperatures over 10°C (50°F).

It is important to document the existing paint system on a bridge. The paint type may be shown on the bridge drawings or specifications. Some agencies list the paint type and application date on the bridge. Once the existing paint is determined, a compatible paint for any required rehabilitation can be chosen.

Protection of Suspension Cables

Suspension cables of steel suspension bridges are particularly difficult to protect from corrosion. One method is to wrap the cables with a neoprene elastomeric cable wrap system or with a glass-fabric-reinforced plastic shell. In some cases, the elastomeric cable wrap has retained water and accelerated corrosion. Another method is to pour or inject paints into the spaces between the cable strands. Commonly, inhibitive pigments, such as zinc oxide, in an oil medium are used. Red lead pigment was commonly used in the past. Lead constitutes a significant health hazard, and care must be exercised care when inspecting cables. Do not inhale or ingest old paint. The paint on the exterior surface of a suspension cable dries, but the paint on the interior, surrounding individual strands, stays in the liquid, uncured state for years. The exterior of the cable is often topcoated with a different paint, such as an aluminum pigmented oil-based paint. Another option to protect suspension cables is to wrap tightly with small diameter wires. This allows the cable to “breath” while still providing a protective cover.

A newer technique used to resist the corrosion process of suspension cables is forced air dehumidification. On larger structures (such as the Kobe Bridge in Japan and the Ben Franklin Bridge in Pennsylvania), dry air is passed through the cables, which does not allow the steel to be exposed to moisture. For this protection system to work, the relative humidity of the forced air should be less than approximately 60%.

Weathering Steel

In the proper environments, weathering steel does not require painting but produces its own protective coating. When exposed to the atmosphere, weathering steel develops a protective oxide film, which seals and protects the steel from further corrosion. This oxide film is actually an intended layer of surface rust, which protects the member from further corrosion and loss of material thickness.

Weathering steel was first used for bridges in 1964 in Michigan. Since then, thousands of bridges have been constructed of weathering steel in the United States. The early successes of weathering steel in bridges led to the use of this steel in locations where the steel could not attain a protective oxide layer and where corrosion progressed beyond the intended layer of surface rust. Therefore, it is important for the inspector to distinguish between the protective layer of rust and advanced corrosion that can lead to section loss. It is also important to note that fatigue cracks can initiate in rust pitted areas of weathering steel.

The frequency of surface wetting and drying cycles determines the oxide film's texture and protective nature. The wetting cycle includes the accumulation of moisture from rainfall, dew, humidity, and fog, in addition to the spray of water from traffic. The drying cycle involves drying by sun and wind. Alternate cycles of wetting and drying are essential to the formation of the protective oxide coating. The protective film will not form if weathering steels remain wet for long periods of time.

Uses of Weathering Steel

Weathering steels may be unsuitable in the following environments:

- Areas with frequent high rainfall, high humidity, or persistent fog
- Marine coastal areas where the salt-laden air may deposit salt on the steel, which leads to moisture retention and corrosion
- Industrial areas where chemical fumes may drift directly onto the steel and cause corrosion
- Areas subject to “acid rain” which has a sulfuric acid component

The location and geometrics of a bridge also influence performance of weathering steel. Locations where weathering steel may be unsuitable include:

- Tunnel-like situations which permit concentrated salt-laden road sprays, caused by high-speed traffic passing under the bridge, to accumulate on the superstructure
- Low level water crossings where insufficient clearance over bodies of water exists so that spray and condensation of water vapor result in prolonged periods of wetness

2.3.8

Inspection Procedures for Steel

There are three basic procedures used to inspect a steel member. Depending on the type of inspection, the inspector may be required to use only one individual procedure or all procedures. They include:

- Visual
- Physical
- Advanced inspection techniques

Visual Examination

Steel Members

Steel members should be inspected for corrosion, section loss, buckling, and cracking.

In the inspection records, identify the location of FCMs and describe the FCM inspection frequency and procedures. Inspect FCMs according to the AASHTO "Manual for Condition Evaluation and Load and Resistance Factor Rating". See Topic 8.1 for detailed description of inspection procedures of fracture critical members.

Some common inspection locations and signs of fatigue distress include:

- Bent or damaged members - determine the type of damage (e.g., collision, overload, or fire), inspect for proper alignment, and check for cracks, tears, and gouges near the damaged location
- Corrosion, which could reduce structural capacity through a decrease in member section and make the member less resistant to both repetitive and static stress conditions; since rust continually flakes off of a member, the severity of corrosion cannot always be determined by the amount of rust; therefore, corroded members must be examined by physical as well as visual means (see Figure 2.3.16)
- Fatigue cracks - fatigue cracks are common at certain locations on a bridge, and certain inspection procedures should be followed when fatigue cracks are observed (see Figure 2.3.17 and Topic 8.1 for additional information about fatigue cracks)
- Other stress-related cracks - determine the length, size, and location of the crack
- Points on the structure where a discontinuity or restraint is introduced
- Loose members which could force the member or other members to carry unequal or excessive stress
- Damaged members, regardless of damage magnitude, which are misaligned, bent, or torn
- Welded details
- Repairs that show indiscriminate welding or cutting procedures
- Areas of excessive vibrations or twisting

Inspection procedures for in-plane fatigue cracks:

- Report the fatigue crack immediately
- Determine the visual ends of the crack
- Examine other identical details on the bridge for cracks
- Examine other details for breaks in the paint and the formation of oxide (rust)
- If a suspect area is located, a more detailed non-destructive examination, may be required (see Topic 13.3).

Figure 2.3.16 Corrosion of Steel

Figure 2.3.17 Fatigue Crack

Protective Coatings

Rust typically starts in a few characteristic places, then spreads to larger areas.

Examine sharp edges and square corners of structural members (see Figure 2.3.18). Paint is generally thinner at sharp edges and corners than at rounded edges and corners or flat surfaces. Rusting starts at sharp edges, then undercuts intact paint as it spreads away from the edge. Inside square corners often receive an extra thick layer of paint due to double or triple passes made over them. Extra thick layers are prone to cracking, exposing the steel. It is difficult to completely remove dirt and spent blast cleaning abrasive from inside corners. Painting over this foreign material results in early peeling and corrosion.

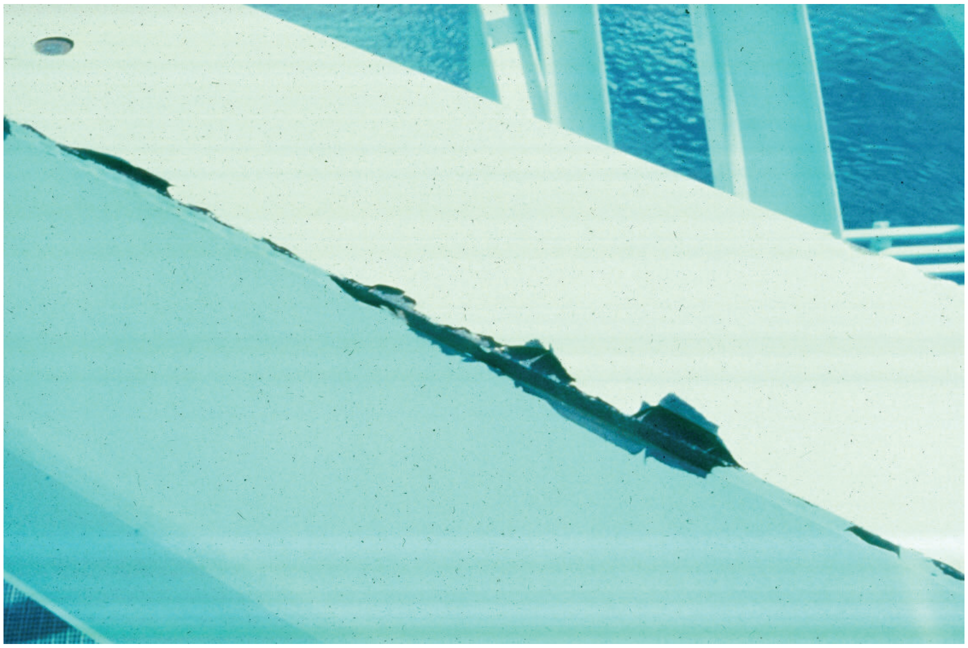

Figure 2.3.18 Paint Failure on Edge of Steel Truss Member

Examine all areas that retain moisture and salt. Check under scuppers and beneath downspouts. Check horizontal surfaces under the edge of bridge decks and under expansion dams, where roadway deicing salt runoff collects (see Figure 2.3.19). Examine the bottom inside flange of girders.

Inspect inaccessible or hard-to-reach areas that may have been missed during painting. A flashlight and inspection mirror may be needed here. Examine the inside surfaces of lattice girders and beams. Examine the top surface of girder upper flanges under the bridge deck, if possible.

Inspect around bolts, rivets, and pins (see Figure 2.3.20). Rust detected around the heads may indicate corrosion along the entire length of the bolt, rivet, or pin, causing reduced structural integrity.

Examine roadway splash or spray zones, where debris and corrosive deicing salt-laden water are directly deposited on painted members by passing traffic (see Figure 2.3.21). On through-truss bridges, this includes some bracing members above the roadway.

Examine areas exposed to wind and rain, seawater spray, and other adverse weather conditions.

Figure 2.3.19 Water and Salt Runoff Under Expansion Dam Deck Opening

Figure 2.3.20 Corroding Rivet Head

Figure 2.3.21 Roadway Spray Zone Damage

Weathering Steel

It is particularly important for weathering steel to be inspected in the following locations:

- Where water ponds or the steel remains damp for long periods of time due to rain, condensation, leaky joints, or traffic spray
- Where debris is likely to accumulate
- Where the steel is exposed to salts and atmospheric pollutants
- Near defective joints or drainage devices

Color

The color of the surface of weathering steel is an indicator of the protective oxide film (see Figure 2.3.22). The color changes as the oxide film matures to a fully protective coating.

A yellow-orange, for new steel with initial exposure, is acceptable (see Figures 2.3.23 and 2.3.24). For bridges that have been in service for several years, purple brown color is acceptable (see Figure 2.3.25), while black color indicates failed condition (see Figure 2.3.26).

Figure 2.3.22 Color of Oxide Film is Critical in the Inspection of Weathering Steel; Dark Black Color in an Indication of Non-protective Oxide

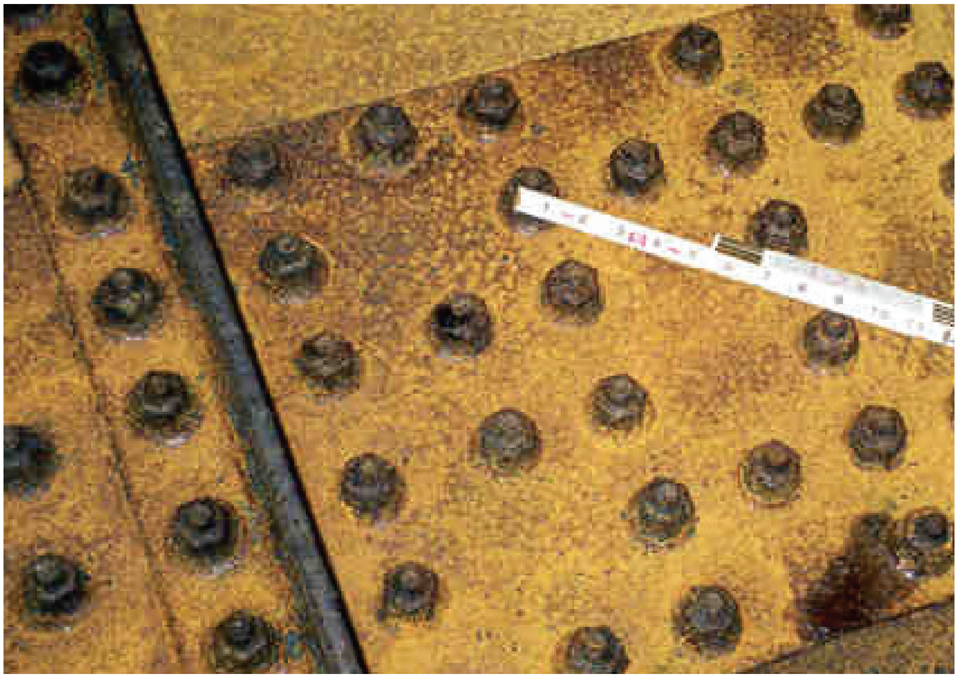

Figure 2.3.23 Yellow Orange – Early Stage of Exposure or Active Corrosion

Figure 2.3.24   Light Brown – Early Stage of Exposure

Figure 2.3.25   Chocolate Brown to Purple Brown - Boldly Exposed and Good Degree of Protection

Figure 2.3.26 Black – Non-protective Oxide

An area of steel, which is a different color than the surrounding steel indicates a potential problem. The discolored area should be investigated to determine the cause of the discoloration. Color photographs are an ideal way to record the color of the weathering steel over time. A color coupon should be included in each photograph to enable comparison.

Texture

The texture of the oxide film also indicates the degree of protection of the film. An inspection of the surface by tapping with a hammer and vigorously brushing the surface with a wire brush determines the adhesion of the oxide film to the steel substrate. Surfaces, which have granules, flakes, or laminar sheets are examples of non-adhesion. Table 2.3.1 presents a correlation between the texture of the weathering steel and the degree of protection.

Appearance	Degree of Protection
Tightly adhered, capable of withstanding hammering or vigorous wire brushing	Protective oxide
Dusty	Early stages of exposure; should change after few years
Granular	Possible indication of problem, depending on length of exposure and location of member
Small flakes, 6 mm (1/4 inch) in diameter	Initial indication of non-protective oxide
Large flakes, 13 mm (1/2 inch) in diameter or greater	Non-protective oxide
Laminar sheets or nodules	Non-protective oxide, severe conditions

Table 2.3.1 Correlation Between Weathering Steel Texture and Condition

Physical Examination

Steel Members

Once the defects are identified visually, physical procedures must be used to verify the extent of the defect. For steel members, the main physical inspection procedures involve the use of an inspection hammer or wire brush. Excessive hammering, brushing or grinding may close surface cracks and make the cracks difficult to find. Corrosion results in loss of member material. This partial loss of cross section due to corrosion is known as section loss. Section loss may be measured using a straight edge and a tape measure. However, a more exact method of measurement, such as calipers or an ultrasonic thickness gauge (D-meter), should be used to measure the remaining section of steel. The inspector must remove all corrosion products (rust scale) prior to making measurements.

The inspector should measure the bridge members to verify that the sizes recorded in the plans or inspection report are accurate. If incorrect member sizes are used, the load rating analysis for safe load capacity of the bridge will be inaccurate.

Protective Coatings

The degree of coating corrosion must be assessed during the inspection. Coating corrosion is measured differently than structural corrosion. There are a variety of proprietary procedures which use a set of photographic standards to evaluate and categorize the degree and extent of coating corrosion on composite spans, cross frames, exterior fascias, and bearings. A simple method entails evaluation of painted surfaces in accordance with SSPC-Vis 2. Vis 2 is a pictorial standard for evaluating the degree of rusting on painted steel surfaces.

Mill Scale

Incomplete removal of mill scale can provide a starting point for corrosion. When mill scale cracks, it allows moisture and oxygen to reach the steel substrate. Mill scale accelerates corrosion of the substrate because of its electrochemical properties. To check for mill scale corrosion during a paint inspection, use a knife to remove a small patch of paint in random spots. Inspect the exposed surface for mill scale, either intact or rusted. Probe with a knife or other sharp object at weld spatter to check for rusting. Re-coat areas where paint is removed.

Invisible microscopic chloride deposits from deicing salt or seawater spray may permeate a corroding steel surface. Painting over a partially cleaned chloride-contaminated surface simply seals in the contaminant. Salt deposits draw moisture through the paint by osmosis, and corrosion will continue.

Paint Adhesion

Paint can undergo adhesion failure between paint layers or between the primer and steel. Some bridge painting contracts specify minimum acceptable paint adhesion strength for new paint. Over time, however, adhesion strength may degrade as the paint weathers and is affected by sunlight, or as rusting occurs under the paint.

The simplest test of adhesion is to probe under paint with the point of a knife. A more quantitative evaluation is performed by a tape test, as described in Topic 2.1.

Paint Dry Film Thickness

There are a variety of instruments to measure the dry film thickness of paint applied to steel. Accuracy ranges from 10% +/- to 15% +/-, and they fall into three classes:

- Magnetic pull-off
- Fixed probe
- Destructive test

The magnetic pull-off dry film thickness gages use the attractive force between a magnet and the steel substrate to determine the paint thickness. The thicker the paint, the lower the magnetic force. These instruments must be calibrated prior to and during use with plastic shims of known thickness, or with ferrous plates coated with a non-ferrous layer. Such shims are produced by the National Bureau of Standards (NBS).

The fixed probe gages also use a magnet. Measurement of paint thickness is done by an electrical measurement of the interaction of the probe's magnetic field with the steel rather than by the force to move the magnet. They are normally calibrated with plastic shims. Neither the magnetic pull-off nor fixed probe gages can be used closer than one inch to edges, as this will distort the reading. SSPC-PA2 "Measurement of Dry Paint Thickness With Magnetic Gages" provides a detailed description of how to calibrate and take measurements using magnetic gages.

A destructive method for measuring dry film thickness uses the Tooke Gage described in Topic 2.1. An advantage of this method is that it can be used at any location, including close to edges. While the magnetic gages measure the combined thickness of all paint layers, the Tooke Gage measures each layer individually. Limitations of the destructive test are that only coatings up to 50 mils thick can be measured and multiple layers of the same color cannot be distinguished.

Repainting

If the coating is to be repainted, the type of in-place paint must be known, since different type paints may not adhere to each other. Methods described in Topic 2.1 can be used to determine the type of in-service paint.

Weathering Steel

Weathering steel with any of the following degree of protection should be inspected:

- Laminar texture of steel surface, such as slab rust or thin and fragile sheets of rust
- Granular and flaky rust texture of steel surface
- A very coarse texture
- Large granular (3 mm (1/8 inch) in diameter) texture
- Flakes (13 mm (1/2 inch) in diameter)
- Surface rubs off by hand or wire brush revealing a black substrate
- Surface is typically covered with deep pits

If such conditions are discovered, the following steps should be taken to determine the adequacy of the oxide film:

- Scrape the surface of the steel to the bare metal
- Check to determine the extent of pitting
- Measure the remaining section thickness with calipers or an ultrasonic thickness gauge

It is important to set a benchmark at the point where the metal thickness measurement is taken so that any metal loss may be monitored with future measurements. Benchmarks are important since steel rolled sections and steel plates often vary within acceptable tolerances in thickness from the nominal thickness values.

Data obtained from the inspection should include visual observations of the steel (e.g., color, texture, and flaking), physical measurements with a thickness gauge, and observation of environmental conditions.

Advanced Inspection Techniques

In addition, several advanced techniques are available for steel inspection. Nondestructive methods, described in Topic 13.3.2, include:

- Acoustic emissions testing
- Computer programs
- Computer tomography
- Corrosion sensors
- Smart paint 1 is paint with microencapsulated dyes that outline a fatigue crack as it forms and propagates
- Smart paint 2 is paint that sends out electrical signals which are picked up by electrodes if material begins to vibrate
- Dye penetrant
- Magnetic particle
- Radiographic testing
- Robotic inspection
- Ultrasonic testing
- Eddy current

Other methods, described in Topic 13.3.3, include:

- Brinell hardness test
- Charpy impact test
- Chemical analysis
- Tensile strength test

2.3.9

Other Bridge Materials

Cast Iron

Iron is an elemental metal smelted from iron ore. Cast iron is the most widely used cast metal. However, it is easily fractured by shocks and has low tensile strength due to a large percentage of free carbon and slag. Consequently, it is basically a poor bridge construction material and is not used in new bridge construction today. It may, however, be found in compression members of old bridges.

Cast iron is gray in color due to the presence of tiny flake-like particles of graphite (carbon) on the surface. It has a unit weight of approximately 7210 kg/m^3 (450 pcf).

Properties of Cast Iron

Some of the mechanical properties of cast iron include:

- Strength - tensile strength varies from 172 MPa (25,000 psi) to 345 MPa (50,000 psi), while compressive strength varies from 448 MPa (65,000 psi) to 1,035 MPa (150,000 psi)
- Elasticity - cast iron has an elastic modulus of 89,635 MPa (13,000,000 psi) to 206,850 MPa (30,000,000 psi): elasticity increases with a decrease in carbon content
- Workability - cast iron possesses good machinability, and casting is relatively easy and inexpensive
- Weldability - cast iron can not be effectively welded due to its high free carbon content
- Corrosion resistance - cast iron is generally more corrosion resistant than the other ferrous metals
- Brittleness - cast iron is very brittle and prone to fatigue-related failure when subjected to bending or tension stresses

Types of Cast Iron Deterioration

The primary forms of deterioration in cast iron are similar to those in steel.

Wrought Iron

When iron is mechanically worked or rolled into a specific shape, it is classified as wrought iron. This process results in slag inclusions that are embedded between the microscopic grains of iron. It also results in a fibrous material with properties in the worked direction similar to steel. Wrought iron is no longer made in the United States. However, wrought iron tension members still exist on some older bridges, and it was well-suited for use in the early suspension bridges.

Properties of Wrought Iron

Some of the mechanical properties of wrought iron include:

- Strength - wrought iron is anisotropic (i.e., its strength varies with the orientation of its grain) due to the presence of slag inclusions; compressive strength is about 241 MPa (35,000 psi), while tensile strength varies between 248 MPa (36,000 psi) and 345 MPa (50,000 psi)
- Elasticity - modulus of elasticity ranges from 165,000 MPa (24,000,000 psi) to 200,000 MPa (29,000,000 psi), nearly as high as steel
- Impact resistance - wrought iron is tough and is noted for impact and shock resistance
- Workability - wrought iron possesses good machinability
- Weldability - wrought iron can be welded, but care should be exercised when welding the metal of an existing bridge
- Corrosion resistance - the fibrous nature of wrought iron produces a tight rust which is less likely to progress to flaking and scaling than is rust on carbon steel
- Ductility - wrought iron is generally ductile; reworking the wrought iron

causes a finer and more thread-like distribution of the slag, thereby increasing ductility

Types of Wrought Iron Deterioration

The primary forms of deterioration in wrought iron are similar to those in steel.

Aluminum

Aluminum is widely used for signs, light standards, railings, and sign structures. Aluminum is seldom used as a primary material in the construction of vehicular bridges.

Properties of Aluminum

The properties of aluminum are generally similar to those of steel. However, a few notable differences exist:

- Weight - aluminum alloy has a unit weight of about 2800 kg/m^3 (175 pcf)
- Strength - aluminum is not as strong as steel, but alloying can increase its strength to that of steel
- Corrosion resistance - aluminum is highly resistant to atmospheric corrosion
- Workability - aluminum is easily fabricated, but welding of aluminum requires special procedures
- Durability - aluminum is durable
- Expense - aluminum is more expensive than steel

Types of Aluminum Deterioration

The primary forms of deterioration in aluminum are:

- Fatigue cracking - the combination of high stresses and vibration caused by wind produces fatigue
- Pitting - aluminum can pit slightly, but this condition rarely becomes serious

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Topic 2.4 Stone Masonry

2.4.1

Introduction

Stone masonry is seldom used in new bridge construction today except as facing or ornamentation. However, many old stone bridges are still in use and require inspections (see Figure 2.4.1). Granite, limestone, and sandstone are the most common types of stone that were used and are still seen today in bridges. In addition, many smaller bridges and culverts were built of locally available stone. Stone masonry typically has a unit weight of approximately 170 pcf.

Figure 2.4.1 Stone Masonry Arch

2.4.2

Properties of Stone Masonry

The physical properties of stone masonry in bridge applications are of primary concern. Strength, hardness, workability, durability, and porosity properties of both the stone and the mortar play important roles in the usage of stone masonry.

Physical Properties

The major physical properties of stone masonry are:

- Hardness – the hardness of stone varies based on the stone type. Some types of sandstone are soft enough to scratch easily, while other stones may be harder than some grades of steel
- Workability - measures the amount of effort needed to cut or shape the stone. Harder stones are not as workable as softer stones stones
- Porosity – porosity in a stone indicates the amount of open or void space within that stone. All stones have some degree of porosity. A stone that is less porous can resist freeze/thaw action better than a stone with a higher degree of porosity. Water absorption is directly related to the degree of porosity

Mechanical Properties

The major mechanical properties of stone masonry are:

- Strength – a stone generally has sufficient strength to be used as a load-bearing bridge member, even though the strength of an individual stone type may vary tremendously. As an example, granite's compressive strength can vary from 7,700 to 60,000 psi (53 to 414 MPa). For the typical bridge application, a stone with a compressive strength of 5,000 psi (34.5 MPa) is acceptable. The mortar is almost always weaker than the stone
- Durability – durability of a stone depends on how well it can resist exposure to the elements, rain, wind, dust, frost action, heat, fire, and air-borne chemicals. Some stone types are so durable that they are able to effectively resist the elements for two hundred years, while other stone types deteriorate after about ten years

Mortar

Mortar is primarily composed of sand, cement, lime and water. The cement is generally Portland cement and provides strength and durability. Lime provides workability, water retentivity and elasticity. Sand is filler and contributes to economy and strength. The water, as in the case of concrete, can be almost any potable water. See Topic 2.2 for more information on mortar.

2.4.3

Stone Masonry Construction Methods

There are three general methods of stone masonry construction:

- Rubble masonry
- Squared-stone masonry
- Ashlar Masonry

Rubble Masonry

Rubble masonry consists of rough stones which are un-squared and used as they come from the quarry. It could be constructed to approximate regular rows or courses (coursed rubble) or could be un-coursed (random rubble). Random rubble was the least expensive type of stone masonry construction and was considered strong and durable for small spans if well constructed.

Squared-Stone Masonry

Squared-stone masonry consists of stones, which are squared and dressed roughly. It could be laid randomly or in courses.

Ashlar Masonry

Ashlar consists of stones, which are precisely squared and finely dressed. Like squared-stone masonry, it could be laid randomly or in courses.

2.4.4

Types and Causes of Stone Masonry and Mortar Deterioration

The primary types of deterioration in stone masonry are:

- Weathering – hard surfaces degenerate into small granules, giving stones a smooth, rounded look; mortar disintegrates
- Spalling – small pieces of rock break out
- Splitting – seams or cracks open up in rocks, eventually breaking them into smaller pieces (see Figure 2.4.2)
- Fire – masonry is not flammable but can be damaged by high temperatures

Figure 2.4.2 Splitting in Stone Masonry

Some of the major causes of these forms of deterioration are:

- Chemicals – gases and solids, such as deicing agents, dissolved in water often attack stone and mortar; oxidation and hydration of some compounds found in rock can also cause damage
- Volume changes – seasonal expansion and contraction can cause fractures to develop, weakening the stone
- Frost and freezing – water freezing in the seams and pores can spall or split stone or mortar
- Abrasion – due primarily to wind or waterborne particles
- Plant growth – roots and stems growing in crevices and joints can exert a wedging force, and lichen and ivy can chemically attack stone surfaces
- Marine growth – chemical secretions from rock-boring mollusks deteriorate stone

Two major factors that affect the durability of stone masonry include:

- The proper curing of mortar
- Correct placement of stones during construction

2.4.5

Protective Systems

The different types of protective systems used for concrete can also be used for stone masonry. The two most common systems that are used are paints and water repellant membranes or sealers. See Topic 2.2 for a complete description of the different types of protective systems.

2.4.6

Inspection Procedures for Stone Masonry and Mortar

The examination of stone masonry and mortar is similar to that of concrete. The joints should be carefully inspected for cracks, loose or missing mortar, vegetation, water seepage and other forms of mortar deterioration. The stones should be carefully inspected for cracks, crushing, missing, bulging, and misalignment. Inspection techniques are generally the same as for concrete. (See Topic 2.2 for the examination of concrete). Masonry arches or masonry-faced concrete arches should be checked for mortar cracks, vegetation, water seepage through cracks, loose or missing stones or blocks, weathering, and spalled or split blocks and stones.