



Table of Contents

2.1 General ..... 2

    2.1.1 Introduction..... 2

    2.1.2 Overview of Bridge Mechanics ..... 4

        2.1.2.1 Design Loads ..... 4

        2.1.2.2 Simply Supported Spans..... 5

        2.1.2.3 Continuous Spans..... 7

        2.1.2.4 Cantilever Spans..... 9

        2.1.2.5 Span Definition Overview ..... 11

    2.1.3 Fixed Bridge Components ..... 12

        2.1.3.1 Deck ..... 12

        2.1.3.2 Superstructure ..... 12

        2.1.3.3 Substructure ..... 13

    2.1.4 Materials..... 13

        2.1.4.1 Concrete ..... 13

        2.1.4.2 Steel ..... 24

        2.1.4.3 Timber ..... 34

        2.1.4.4 Other Materials ..... 38

    2.1.5 Classification of Fixed Bridges..... 44

        2.1.5.1 Slab ..... 44

        2.1.5.2 Beam/Girder ..... 45

        2.1.5.3 Truss..... 47

        2.1.5.4 Arch ..... 49

        2.1.5.5 Rigid Frame ..... 50

        2.1.5.6 Cable-Stayed ..... 51

        2.1.5.7 Suspension ..... 52



### 2.1 GENERAL

This chapter describes the mechanics, components, construction materials, and classifications of bridges. This part of the Manual addresses subjects common to fixed and movable (Complex) bridges.

The chapters are broken down into basic bridge components (i.e., Deck, Superstructure, Substructure, etc.). Within each chapter the bridge components are broken down into construction material (i.e., Concrete, Steel, Timber, Masonry, etc.). Under each material section are listed the appropriate elements. The elements are described and element level inspection procedures are discussed for the inspector's use. Each element has an associated list of material defects which determine the Condition States of a portion or the entire element depending on the unit of measurement for that element. Refer to Appendix A at the end of Part 2 for full descriptions of the element defects and the appropriate Condition States for each defect.

Refer to Part 3 of this Manual for a complete treatment of components unique to movable (Complex) bridges.

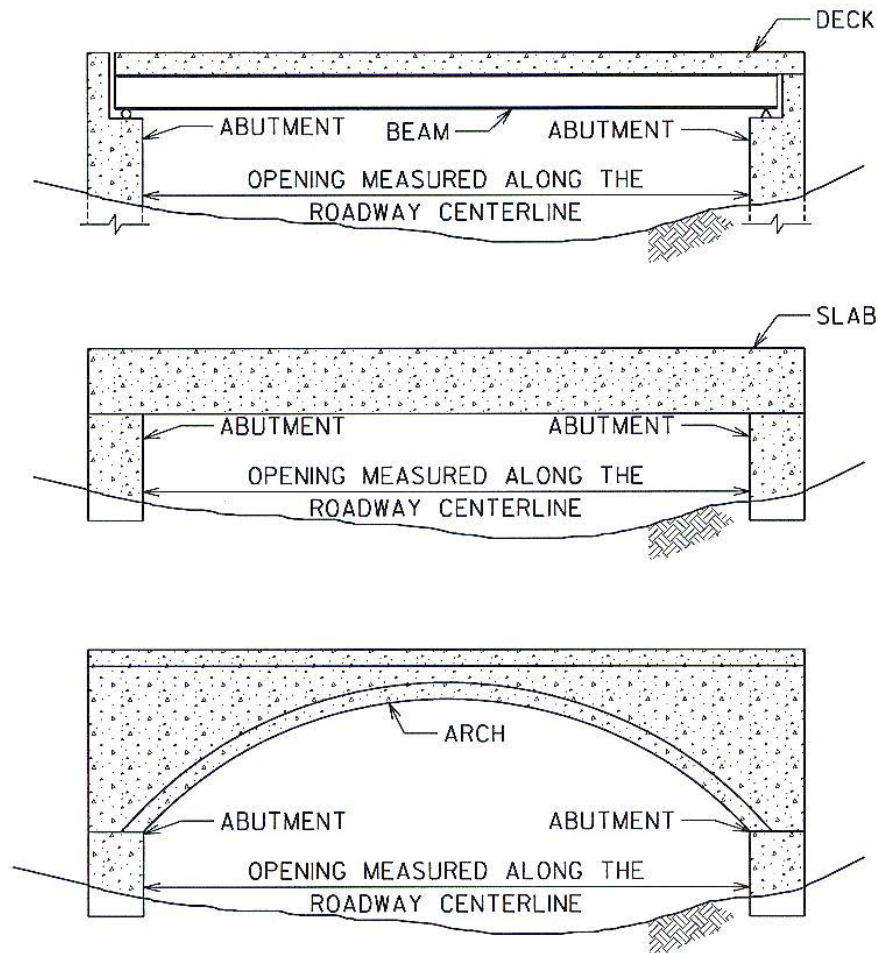
#### 2.1.1 Introduction

Fixed bridges are by far the most common structures which carry the traveling public (both vehicular and pedestrian) over roadways, railways, waterways, and valleys. Movable bridges are common over navigable waterways where the height of a fixed bridge would otherwise restrict marine traffic. It is the responsibility of the agencies that own these structures to uphold the public's confidence in the infrastructure by knowing the condition of their structures and by maintaining them in a safe and cost-effective manner.

According to Federal Highway Administration Policy, any highway structure over 20 feet in length is defined as a "bridge". However, Trans 212.02(2) of the Wisconsin Administrative Code more clearly defines a bridge as:

[A] structure, including supports, erected over a depression or an obstruction, such as water, a highway, or a railway, having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the centerline of the roadway of more than 20 feet between the under coping of abutments or spring lines of arches, or extreme ends of the openings for multiple boxes. It may include multiple pipes where the clear distance between openings is less than half of the smaller contiguous opening.

An abutment under coping is its front face. Along public roads, structures 20 feet or less in length are considered to be Ancillary structures and are covered in Part 4 of this manual. Other highway structures are also defined in other parts of this Manual.



**Figure 2.1.1-1:** Opening Measurement Used to Define a Bridge.

In Wisconsin (2017), there are about 5300 structures classified as bridges maintained by the State and about 8,900 maintained by local government agencies. The ages, materials, span lengths, design details, etc. result in a wide variety of bridge styles in public use. Regardless of their status, the bridges continue to endure daily traffic fatigue and the deteriorating effects of deicing salts and weather. Since design codes dictate that bridges conservatively incorporate safety factors in their design, bridges are able to tolerate some amount of overload and deterioration. At some point the wear becomes excessive, and the bridge's ability to safely carry traffic loads may need to be evaluated.

It is critical to know when a structure or component thereof has deteriorated to such an extent that it is unable to support the loads it was designed to carry. One of the responsibilities of a bridge inspector is to recognize this condition. To make this judgment, as well as to write a meaningful inspection report, an inspector must be knowledgeable about structural mechanics, be able to identify the components of a bridge and know their functions, and understand the behavior of different materials. Understanding the critical areas of components along with the common deficiencies found in each material is paramount in inspecting structures.



## 2.1.2 Overview of Bridge Mechanics

A bridge inspector must know how a bridge functions to recognize and judge how a defect affects the load-carrying ability of a member and eventually the entire bridge. This section briefly describes bridge loads and bridge geometric classifications with the associated behavior of each. A more complete discussion may be found in Chapter 5 of the *Bridge Inspector's Reference Manual*.

### 2.1.2.1 Design Loads

Bridges are designed to withstand a variety of loads. These loads can be divided into three general categories: dead, primary transient (live) and secondary transient (live).

Dead loads are the permanent self-weight loads of the bridge. Dead loads include the weight of the girders, deck, railings, diaphragms, overlays, etc. Utilities mounted on a bridge are also considered dead loads.

Primary transient (live loads) are the temporary gravity loads that act on the structure. These include all moving vehicles (trucks, cars, trains), with their associated impact loads, and pedestrians. Current American Association of State Transportation and Highway Officials (AASHTO) specifications for bridges establish the design live loads for highway bridges. Depending on a bridge's use, different design trucks are specified. Major highways may be designed for an alternate vehicle configuration as well. It should be noted that the design vehicles do not represent actual trucks found on highways, but were developed to represent an approximate live load for consistent design. The maximum pedestrian load on sidewalks or pedestrian bridges is 85 pounds per square foot.

Dead and primary live loads are gravity loads and exert downward forces on the bridge. Secondary loads are all remaining loads which act on the bridge, many of which act in a lateral direction. These loads include:

1. **Earth pressure** – Lateral soil pressure on abutments and retaining walls.
2. **Buoyancy** – Upward forces on substructures when submerged in water.
3. **Wind load on the structure** – Pressures due to wind blowing on the sides of girders, parapets, arches, etc.
4. **Wind load on the primary live loads** – Lateral pressures transferred to the bridge due to wind blowing on the sides of vehicles traveling across the bridge.
5. **Longitudinal forces** – Forces parallel to the bridge span due to vehicles braking and accelerating.
6. **Centrifugal forces** – Forces transverse to curved bridges due to vehicles traveling around a curve.
7. **Rib shortening** – Forces in arches and frames caused by dead load deformations.
8. **Shrinkage** – Forces within concrete members caused by member dimensional changes due to curing.

9. **Temperature** – Forces within members caused by member dimensional changes due to temperature fluctuations.
10. **Earthquake** – Lateral and vertical forces caused by seismic events.
11. **Stream flow pressures** – Lateral forces caused by river or stream flow acting on bridge members.
12. **Ice pressure** – Lateral forces caused by river or stream ice flow hitting bridge components.
13. **Curb loads** – Lateral forces due to vehicle wheels.
14. **Rail loads** – Lateral forces due to errant vehicles.

### 2.1.2.2 Simply Supported Spans

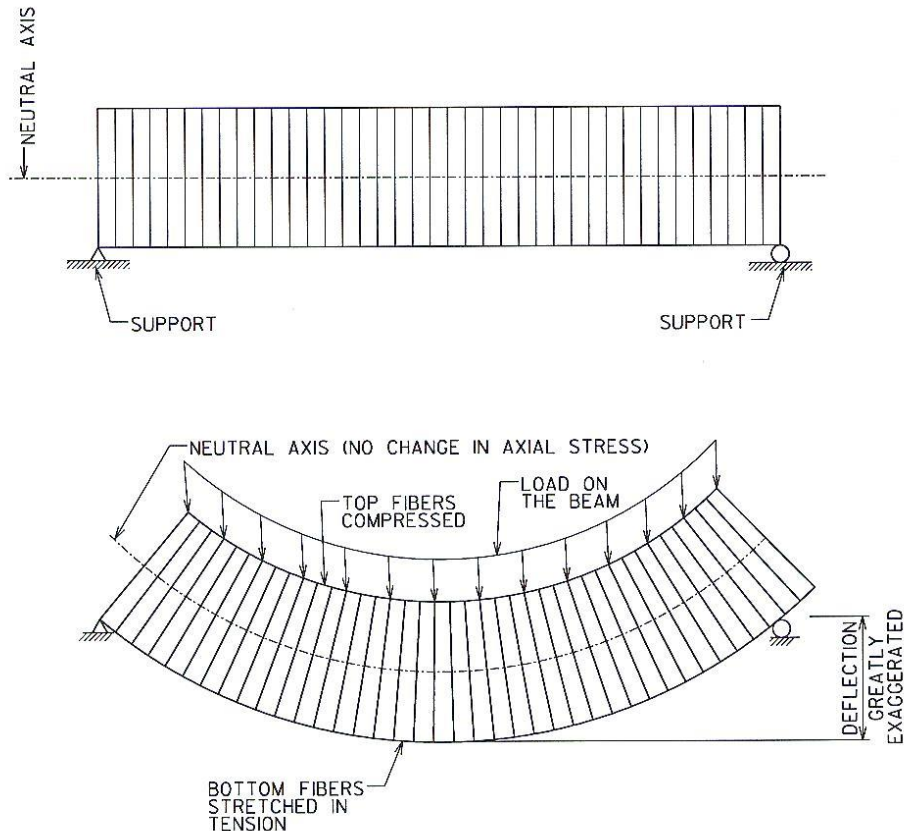
A simply supported span is the most basic type of bridge and the easiest for an engineer to analyze and design. It forms a stand-alone, single span, with its beams or trusses commonly supported with one fixed end and one movable end. The movable end bearing devices allow the bridge to rotate and expand under load and temperature changes. On some bridges, the beam ends are encased within a concrete diaphragm over the abutments, hiding the bearing devices. Simply supported bridges can be very forgiving structures should one of the supports settle, since the bearings act like hinges to allow for unrestrained, free movement. Simply supported bridges can also be very unforgiving structures should the beams ever fail between the supports. A failed beam section may act as a third hinge, allowing the beam to collapse.



**Figure 2.1.2.2-1:** Simply Supported Span – Prestressed Concrete Girders.

Most commonly, simply supported bridges are single span structures with the beam ends bearing on abutments. Alternatively, a bridge may be built up of a series of simply supported spans, with the beam ends supported on either abutments or piers. Each pier will therefore support two lines of bearings. To allow for unrestrained rotation of the bridge ends, joints are normally provided in the deck above all abutments and piers with simply supported spans.

When a simply supported span is loaded, it deflects downward between its supports and rotates at its bearings. For the most basic case of a uniformly loaded beam, shear forces (vertical forces within the beam) are highest at the supports, and zero at midspan. Point loads produce uniform shears of varying magnitudes along the beam. For any type of loading, the amount of bending is zero at the supports. Bending is a maximum at midspan (for uniform loading) or directly under the load (for point loading).



**Figure 2.1.2.2-2:** Simply Supported Beam Unloaded (Top), and Loaded (Bottom).

An important mechanical concept to understand as it relates to bridges is beam bending. Bending is measured in units of length multiplied by force (defined as a moment). Most commonly in the U.S., moment is currently measured in foot-kips or foot-pounds. For example, suppose a person wanted to hold out horizontally a 5-pound hammer with a 1-foot-long handle in one hand. The person’s wrist would need to resist a 5-pound X 1-foot = 5 foot-pound bending moment. If the hammer weighed 10 pounds, a 10-pound X 1-foot = 10 foot-pound bending moment would need to be resisted. Similarly, a 5-pound-hammer with a 2-foot-long handle would produce a 5-pound X 2-foot = 10 foot-pound bending moment.

As it relates to a beam, bending is classified as either a positive or negative. A deflected beam having a concave curve (producing a “smiling face”) will be resisting positive bending moments. A deflected beam having a convex curve (producing a “frowning face”) will be resisting negative bending moments. When a beam is resisting positive bending moments,



the fibers at the top surface of the beam are shortened and experience compressive stresses, while the fibers at the bottom surface are stretched and experience tensile stresses. Conversely, when a beam is resisting negative bending moments, the fibers at the bottom surface of the beam are experiencing compressive stresses, while the fibers at the top surface are experiencing tensile stresses. In both situations, there is a point somewhere between the beam's top and bottom that does not change length. Since there is no length change, there are no stresses generated. This point on the beam's cross-section is known as the neutral axis. Simply supported spans will always deflect in a concave shaped curve and will therefore only experience positive bending moments. As a result, the top fibers, or flanges, of the beams will always be in compression, and the bottom fibers, or bottom flanges, will always be in tension.

### 2.1.2.3 Continuous Spans

Continuous spans are more complex in their behavior, design, and analysis than simply supported spans. Continuous spans are essentially beams or trusses with supports at their ends, but also with one or more intermediate supports. In other words, the beams are continuous over the supports. As with simply supported spans, the supports are most commonly pins, rockers, rollers, or bearing pads which allow the bridge to rock, rotate, and expand under load. Continuous bridges can be very forgiving structures should the beams ever fail between the supports. To illustrate this, if the middle span of a three-span bridge fails and creates a hinge, the end spans can act as anchor spans. In doing so, the end spans can prevent a collapse by acting as levers with pivots at the piers to hold up the failed middle span. Continuous bridges can also be unforgiving structures should one of the supports settle. Since continuous spans have no internal hinges, support settlements act like additional loads to the bridge. Depending on which support settles, the settlement load may overstress and possibly fail the beams.

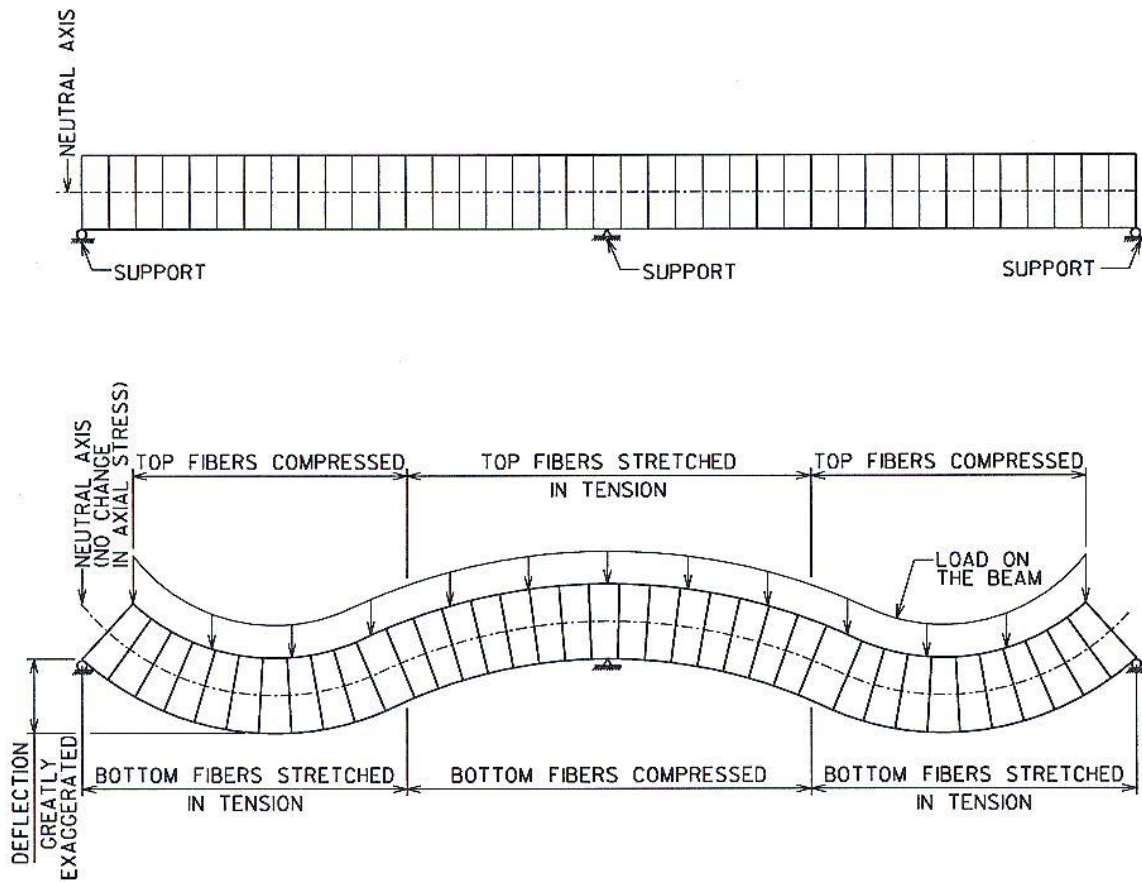
One advantage of using continuous spans versus multiple simple spans is that the beam depths will be smaller, deflections will be less, and spans can be made longer. Also, each pier under a continuous span will have only one line of bearings, resulting in cost savings in multi-span structures. Because the beams are continuous over the intermediate supports, deck joints are not required – yet another economic advantage. This also provides a serviceability advantage in the form of a smoother riding surface for the traveling public. Disadvantages of continuous bridges include the transverse deck cracks that develop over the piers and the increased costs of design, fabrication, and erection.



**Figure 2.1.2.3-1:** Continuous Spans – Steel Girders.

When a continuous span bridge is uniformly loaded, it deflects downward between the supports and rotates at its supports. Shear forces are at a maximum at the supports and zero at or near midspan. Positive bending moments are at a maximum between supports, while negative bending moments are at a maximum directly over the interior supports. The deflected shape of the bridge will therefore have a concave curve between supports and convex curvature over the supports. Point loads produce more complex patterns of shears and bending moments. Briefly, however, point loads will deflect the beam downward in the loaded span; produce uniform shears of varying magnitudes, and produce maximum bending moments at the point of the load. For any loading type, the bending moment is zero at locations where the curvature changes from concave to convex and also at the end supports.





**Figure 2.1.2.3-2:** Two-span Continuous Beam Unloaded (Top), and Loaded (Bottom).

#### 2.1.2.4 Cantilever Spans

A cantilever span has one end that is free to deflect and rotate, and one end that is fixed against deflection. The fixed end is ideally fixed against rotation, but in reality a small amount of tilt will occur. The deflected shape of a cantilever span will always be convex. Therefore, bending moments are always negative and vary from zero at the free end to a maximum at the fixed end. At the free end, shear forces may be zero, but are usually relatively high since tips of the cantilevers are commonly used to support the end of another span. Shear forces are a maximum at the fixed end. The free ends of cantilever spans are always locations for expansion joints.



**Figure 2.1.2.4-1:** Steel Cantilever Span.

Cantilever spans will rarely form an entire bridge but are typically portions of a structure. Usually, fixed cantilevers are simply extensions of continuous spans, with the continuous spans providing anchorage for the cantilever. Long span truss bridges frequently employ cantilevers to form part of the main crossing. Cantilever spans are built on either side of the obstruction, extending out towards midspan. The tips of the two cantilevers sometimes meet in the middle, but more commonly an independent simply supported structure is suspended between the tips of each cantilever. On some large girder bridges, short cantilever spans may be used to join a series of independent continuous bridges to form a single, long structure. The cantilever span free end is sometimes called a ship lap joint, since the supported span of one structure laps over the cantilever supporting span.

Advantages of using cantilever spans include a positive bending moment reduction in the adjacent spans and eliminating the use of expensive shoring for main span construction of truss cantilevers.

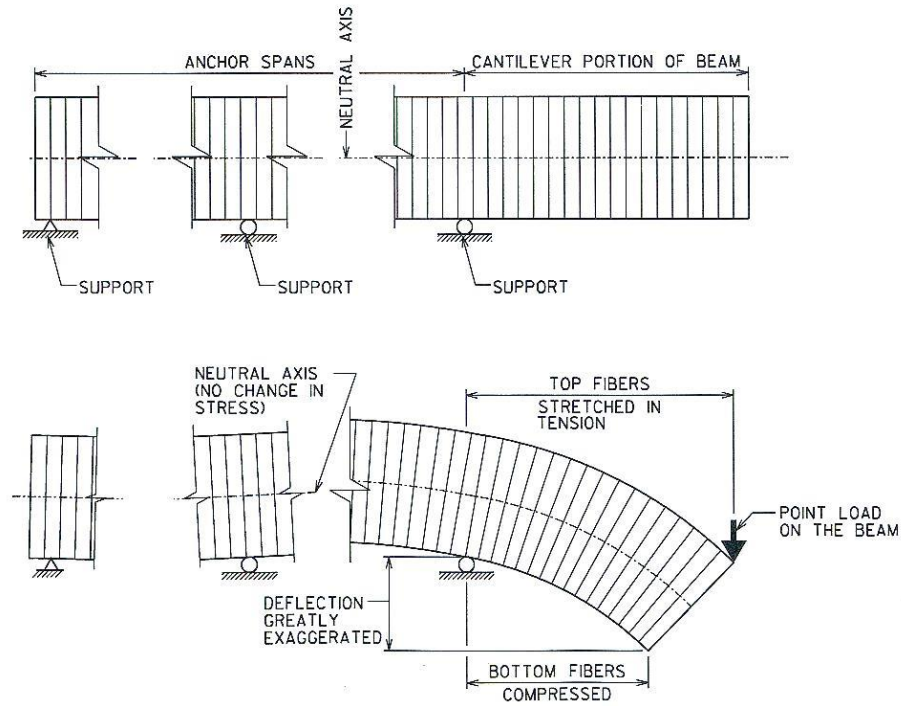


Figure 2.1.2.4-2: Cantilever Beam Unloaded (Top), and Loaded (Bottom).

2.1.2.5 Span Definition Overview

The following figure will help to summarize the definitions of simple, continuous, and cantilever spans.

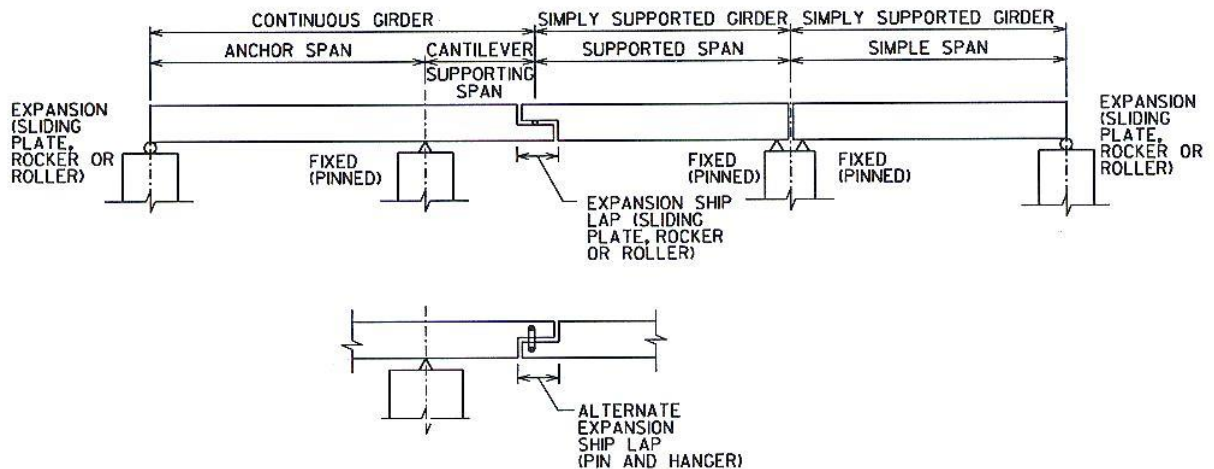
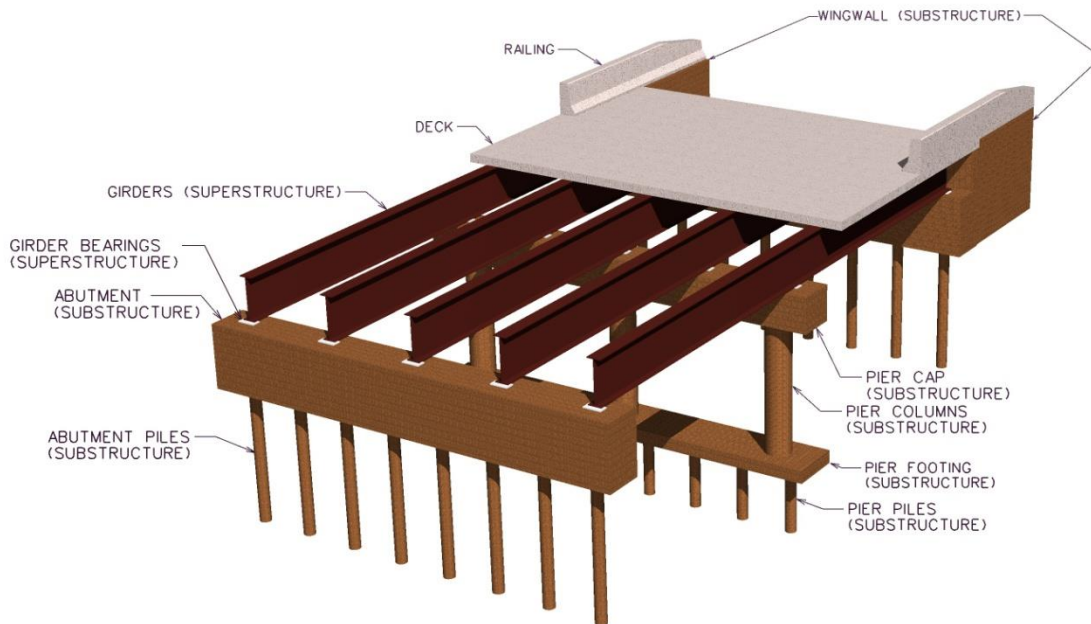


Figure 2.1.2.5-1: Span Definition Overview.

### 2.1.3 Fixed Bridge Components

There are three basic components common to most fixed bridges. These components are the deck, superstructure, and substructure.



**Figure 2.1.3-1:** Bridge Components.

#### 2.1.3.1 Deck

A deck is the bridge component that directly receives the vehicular wheel loads in the case of a roadway, or foot traffic loads in the case of a pedestrian bridge. A deck’s purpose on all bridges is to provide a smooth driving or walking surface. On most bridges, it functions to transfer the live loads, superimposed dead loads (overlays, sidewalks, parapets, etc.), and its own weight laterally to the beams/girders/stringers/floorbeams. Sometimes, the deck acts compositely to become part of the beam’s top compression flange. On concrete slab bridges, the deck itself is the main load-carrying member, delivering all live and dead loads directly to the substructure units.

#### 2.1.3.2 Superstructure

The superstructure supports the deck and all of the live and dead loads applied to it, delivering these loads to the substructure units. There are three main types of bridge superstructures: beam bridges (slabs, beams, girders, and trusses), arch bridges, and cable-supported bridges (cable-stayed, suspension). The differences between the types are in how each superstructure delivers loads to the bridge supports. Beam type superstructures act primarily in bending, arches in compression, and cable-supported in tension.



### 2.1.3.3 Substructure

Substructure units of a bridge support the superstructure and deliver all of the bridge live and dead loads to the foundation soil or rock. Substructure units include the abutments, wingwalls, piers/bents, and, in the case of suspension bridges, the cable anchorages. Abutments provide superstructure support at the ends of the bridge, while piers and bents provide intermediate support. In addition to providing support for vertical loads, other loads must be resisted by the substructure, such as horizontal loads due to lateral pressures (soil, wind, current, and impact) and temperature expansion effects. Substructure components must therefore function as both compression and bending elements.

### **2.1.4 Materials**

Several materials can be used to construct the various components of a bridge. Each has its own advantages and disadvantages with respect to material properties, weight, durability, cost, and appearance. It is of primary importance for a bridge inspector to understand the material properties, to understand the durability of each material, to recognize the seriousness of the material's deterioration and its causes, and to know the best remedial actions for each material.

#### 2.1.4.1 Concrete

Concrete is a building material used since the ancient Roman Empire. It is a mixture of Portland cement, water, and aggregate (sand and stone). When cement is mixed with water, a chemical reaction takes place that produces a strong, durable, construction bonding material. Aggregates, which typically comprise approximately 75 percent of a concrete mix by volume, are used as an inexpensive filler material. In addition, aggregate improves a concrete's abrasion and weather resistance. Entrained air increases workability while the concrete is being placed and improves its durability against freeze/thaw once the concrete has cured.

#### **Physical Properties**

Plain concrete weighs about 145 pounds per cubic foot, and concrete reinforced with steel bars weighs approximately 150 pounds per cubic foot. Entrained air within the cement paste allows the absorption and passage of water, making concrete a porous material. It expands and contracts with increasing and decreasing temperatures, respectively.

#### **Mechanical Properties**

Concrete is a material used for its compressive strength, which generally ranges from 2,500 pounds per square inch to 8,000 pounds per square inch. Its tensile and shear strengths are poor, being only about 10 percent and 12 percent, respectively, of its compressive strength. Since it is a brittle material, a beam made out of plain concrete will snap like a piece of chalk under relatively small loads.

To make concrete ductile and usable, reinforcing steel bars (often referred to as rebar) are cast within the concrete mass to create a heterogeneous material (one with a varying composition within its volume) known as reinforced concrete. The reinforcing steel is able to resist the tensile forces that the concrete is unable to withstand. The concrete and reinforcing



steel also work together in carrying a member's shear forces. Reinforcing steel bars that transfer shear forces are placed as vertical stirrups in beams and as horizontal ties in columns. Reinforcing steel resists the tensile forces generated as a member undergoes bending. As an example, a simply supported reinforced concrete beam experiences only positive bending moments, generating compressive stresses near the top of the beam and tensile stresses near the bottom. As the beam is ultimately loaded, the concrete's tensile capacity near the bottom surface will be exceeded, and the concrete will crack. A simply supported reinforced concrete beam will therefore have its reinforcing steel placed near the beam's bottom surface to resist the tensile load. Concrete near the top surface resists the compressive loads.

Reinforcing steel is "deformed", or has transverse ribs, to provide a mechanical interlock with the concrete. In prestressed or post-tensioned concrete, high strength steel strands or bars replace deformed reinforcing steel. For prestressed concrete beams, the strands are pulled into tension, concrete cast around them, and the strands are released (cut) after the concrete is cured. The released strand's tensile force introduces compressive stresses into the concrete. For post-tensioned concrete beams (usually made in the field), concrete is cast around ducts placed near the beam's tension surfaces. After curing, post-tensioning strands or rods are placed into the ducts, anchored at one end, and stretched into tension by jacking at the other end of the beam. Locking or anchoring the jacked ends keeps the strands/bars in tension, introducing compression into the concrete. Prestressing/post-tensioning minimizes or eliminates net tensile stresses in the concrete. With the concrete and steel working together, a strong, ductile, and durable construction material is created.

### Concrete Deterioration

Concrete can experience many types of defects, and the causes of each can vary. It is important for the inspector to understand these causes so that a proper evaluation and recommendation can be made.

#### Cracks

Cracks are linear fractures in the concrete that may extend partially or completely through a member. Due to the nature of reinforced concrete, it is not possible to prevent crack development. Prestressed concrete, on the other hand, should not develop any cracks (other than shrinkage cracks) under normal use. Cracks are described by their length, width, type, and orientation.

#### *Crack Widths*

The *Manual for Bridge Element Inspection* classifies cracks as insignificant, moderate, or wide. As shown in Field Manual under the material tabs for reinforced concrete and prestressed concrete. Insignificant cracks are visible, but cannot be measured with a ruler. By definition, insignificant cracks are less than 0.012 inches wide. Structurally, insignificant cracks are not a concern. Moderate cracks have widths from 0.012 inches wide up to 0.05 inches and may be measured with a finely-divided ruler or crack comparator card. Moderate cracks cause no distress to the structure, but will allow water and salts to enter the concrete mass with a path to the steel reinforcement. Moderate cracks should be regularly monitored to track any crack growth. Wide cracks are widths greater than 0.05 inches. Depending on their location, wide cracks can be structurally significant and the condition could warrant a

structural review, see the field manual condition state 4 guidance in the reinforced concrete and prestressed concrete sections.



**Figure 2.1.4.1-1:** Map Cracking in Reinforced Concrete.



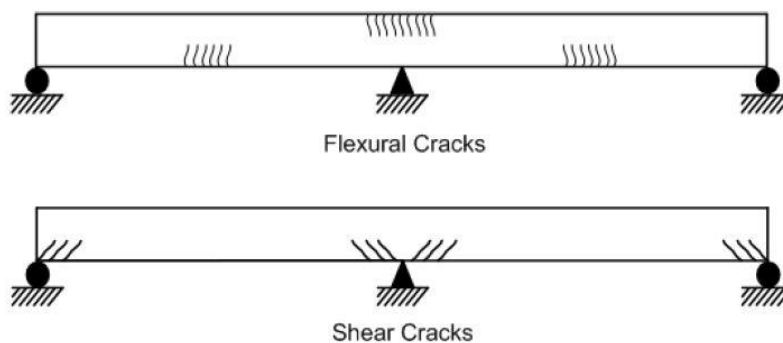
**Figure 2.1.4.1-2:** Moderate Longitudinal Crack in a Concrete Deck.



**Figure 2.1.4.1-3:** Wide Vertical Crack in an Abutment.

### Crack Types

Cracks are grouped into two categories: structural and nonstructural. Structural cracks are caused by dead and live loads and include flexural and shear cracks. Flexural cracks always develop on the tension surface of reinforced concrete members. Flexural cracks are most commonly seen on undersides of beams between the piers, but are also found on continuous beam tops and decks above the piers due to negative bending moments. Columns under fixed supports may develop flexural cracks when expansion/shrinkage of the superstructure bends the pier. Flexural cracks are oriented perpendicular to the length of the member. The longest cracks are located in areas of the highest bending moment, sometimes extending up to about 75 percent of the member's depth. Flexural crack lengths shorten as bending moments are reduced. Shear cracks, if present, will always develop near piers and abutments and are always oriented diagonally. These cracks begin near the bearing and extend up towards midspan at an approximate forty-five degree angle.



**Figure 2.1.4.1-4:** Flexural and Shear Cracking in a Beam.





Structural cracks develop when tensile stresses acting on the member exceed the tensile strength of concrete. Reinforcing steel embedded within the concrete picks up all tensile forces immediately upon cracking. Normal loading generally causes uniformly spaced insignificant or fine cracks in reinforced concrete. These are not generally viewed as a problem. Wide cracks accompanied with excessive deflections, or any flexural cracks found in prestressed beams, suggest that the bridge has been overloaded. Foundation movement or settlement can also cause flexural cracks in superstructure or substructure elements.

Nonstructural cracks do not generally affect the load-carrying capacity of the member. All concrete develops small, shallow, nonstructural cracks due to drying and shrinkage during the curing process. After curing, concrete creep (increased deflections or shortening under sustained loads) and seasonal temperature changes expand and contract the concrete, causing further random cracks. These long-term effects can have more serious consequences should movable bearings become locked up, restraining concrete movement and increasing the crack widths. A nominal amount of reinforcing steel placed transverse and longitudinal to the member controls widths and lengths of shrinkage and temperature cracks.

### *Crack Orientation*

Depending on the cause of cracking, cracks can travel in several directions within a structural member. Their patterns may be described as follows:

1. **Map cracking** – nonstructural temperature/shrinkage cracks which travel randomly within the member. Several usually occur within any given area, giving the surface an appearance of a road map.
2. **Random cracks** - individual meandering cracks, usually found on decks.
3. **Transverse cracks** – cracks oriented perpendicular to the bridge centerline. May be structural flexural cracks on slab bridges or nonstructural temperature/shrinkage cracks on bridge decks.
4. **Longitudinal cracks** – cracks oriented parallel to the bridge centerline or horizontal members such as beams, girders, slabs, decks, or parapets.
5. **Horizontal cracks** – cracks oriented transversely to vertical members such as structural flexural cracks in pier shafts, pier columns, walls, and abutments.
6. **Vertical cracks** – cracks oriented vertically to vertical members such as pier shafts, columns, walls, and abutments.
7. **Diagonal cracks** – cracks angled with respect to the member centerline, commonly structural shear cracks.
8. **D-cracks** – letter “D” shaped cracks found at the edge of deck or slab joints.
9. **Radial cracks** – cracks oriented in a circular pattern; may indicate a punching shear type failure in a bridge deck.

### Delaminations

Delamination is the separation of concrete at or near the level of the reinforcing steel, and is caused by reinforcing steel corrosion. Rust, the corrosion product of steel, has a volume approximately 7 to 10 times that of the original steel. Since concrete has only limited tensile strength to counteract this expansive force, it cracks internally in a plane along the layer of reinforcing steel. The presence of delaminations indicates that chlorides, salts, or other corrosive chemicals (generally carried as a solution in water) have been absorbed by or traveled through cracks in the concrete and reached the reinforcing steel.



**Figure 2.1.4.1-5:** Delaminations on Concrete Pier.

Detection of delaminations is often performed using a method called “sounding”. The most common form of sounding on concrete is using hammer tapping. A technique similar to hammer tapping, called chain dragging, is used to detect top of bridge deck delaminations. For each method, a loud popping or hollow sound is generated when the hammer hits or the chain drags over a delaminated area. Thin delaminations are more readily detected than thicker ones, as thicker delaminations will begin to sound more like undamaged concrete. Sometimes slight surface discolorations, surface cracks or rust stains indicate the presence of a delamination. Delaminations should be outlined with a lumber crayon or spray paint for monitoring the deterioration rate or for removal marking.

One high-tech method for delamination detection is infrared thermography. It is mostly used for large area deck investigations or high traffic situations. A truck-mounted infrared camera detects concrete defects by reading differences in deck surface temperatures. These temperature differences are generated because a crack within the concrete is a location of heat transfer discontinuity. Defects are then recorded on videotape and mapped on a bridge deck plan sheet. Because this method relies on temperature differentials, certain weather conditions must be met in order to properly and accurately carry out this testing. For other methods for determining concrete delamination please refer to Part 5 in the manual.

If it can be performed safely, removal of small delaminated areas may be done during an inspection. Removing the delamination allows the base concrete to dry out, slowing down the reinforcing steel corrosion process. Additionally, removing concrete in a controlled manner eliminates the possibility of the delamination suddenly falling onto the public or private property. Large areas of delamination, however, should be removed as a maintenance action.

### Spalls

When a delamination is removed or falls off of the base concrete, the resulting depression is called a spall. Spalls are typically circular or oval in shape, often exposing the surface of the corroded reinforcing steel. Causes of spall formation include freeze/thaw action from trapped water, friction from thermal movement, expansive effects from reinforcing steel corrosion, and impact fractures.



**Figure 2.1.4.1-6:** Spalled Concrete on Pier Cap.

### Reinforcing/Prestressing Steel Corrosion

The high alkaline environment of concrete temporarily protects the underlying reinforcing steel from corrosion. As the structure ages, however, chlorides from deicing salts, carbon dioxide, and other potentially corrosive atmospheres may reach the steel reinforcement through diffusion or cracks in the concrete cover. These chemicals, along with moisture and oxygen, form an electrolytic cell that corrodes the steel. As the corrosion advances, it expands, delaminating and spalling the concrete.

Heavy reinforcement corrosion can lead to a structural capacity loss in a member. As corrosion advances, the cross-sectional area of the reinforcing steel is reduced. Since the reinforcing steel must resist the same load, its stresses increase. Excessive section loss may lead to yielding or fracture during an overload. Fortunately, however, there are usually several reinforcing steel bars carrying the tensile loads in any one member. This results in redundancy and a lesser likelihood that a total member failure will occur. Corrosion of prestressing strands, however, is typically more detrimental than reinforced concrete. This is due to the higher stresses already existing in the strands. As the strand corrodes the strength

of the prestressed component is drastically reduced. Forensic studies done after a beam failure in 2005, determined that lightly corroded prestressed strands experienced a 20 percent reduction in tensile capacity where heavily pitted strands experienced up to a 29 percent reduction in tensile capacity.



**Figure 2.1.4.1-7:** Reinforcing Steel Corrosion.

#### Efflorescence and Leaching

Efflorescence, informally referred to as leaching, is a white deposit on the concrete surface caused by the crystallization of calcium carbonate from the cement paste and other recrystallized carbonate and chloride compounds. Water traveling through the concrete dissolves these salts and usually deposits them along cracks where the water exits. Efflorescence indicates that water and dissolved chemicals are able to pass through and contaminate the concrete.

Light efflorescence does not affect the compressive strength of the concrete paste. Heavy efflorescence, which is sometimes accompanied with rust stains from reinforcing steel corrosion, indicates a reduction in the compressive strength of the concrete and reduction in the structural member's overall strength.



**Figure 2.1.4.1-8:** Heavy Efflorescence on an Abutment and Slab.

#### Chloride Contamination

Concrete is typically exposed to chlorides, especially in Wisconsin, from deicing salts. Chlorides can also be found in acid rain or in some cases contaminated water during concrete mixing. Chloride ions attack and destroy the passivation layer surrounding reinforcing steel. With the passivation layer removed the reinforcing steel is vulnerable to corrosion. Using a practice no longer allowed, in the 1960's salt was added to concrete during mixing to prevent water from freezing. This caused accelerated corrosion in rebar which ultimately led to concrete cracking.

#### Carbonation

Carbonation is the reaction between carbon dioxide in the atmosphere and the compounds in cured concrete. Carbon dioxide reacts with cement reducing the alkalinity. If the extents of the carbonation reaction extend to or beyond the reinforcing steel, the lowered alkalinity jeopardizes the passivation layer surrounding the reinforcing steel. Once compromised the steel is vulnerable to corrosion. While a slow process, cracking in concrete allows carbon dioxide to penetrate further into the concrete.

#### Scaling

Scaling, also known as surface breakdown is the gradual loss of surface aggregates and cement paste caused by the chemical degradation of the cement bond. It is classified by ACI as light, medium, severe, or very severe. Light scaling indicates cement paste loss of up to 1/4 inch deep accompanied with surface exposure of coarse aggregates. Medium scaling indicates cement paste loss of from 1/4 inch to 1/2 inch deep, exposing the sides of the coarse aggregates. Severe scaling indicates cement paste loss of from 1/2 inch to 1 inch deep with clear exposure of the coarse aggregates. Finally, very severe scaling indicates a loss of coarse aggregate with depths greater than 1 inch. Reinforcing steel may be exposed.



**Figure 2.1.4.1-9:** Scaling on the Underside of a Concrete Box Girder Due to Fire.

Typically located along the gutter lines of the deck, scaling is common when deicing chemicals are used. Pondered salt water along the gutter, caused by clogged drains or scuppers, is the usual culprit for the chemical attacks. Other bridge components can sometimes be subjected to scaling by way of sulfate compounds found in soil and water. Fire damage, distinguished by a blackened concrete surface, can also cause scaling, since temperatures above 700 degrees Fahrenheit will weaken the cement paste.

#### Pop-outs

Pop-outs are small conical shaped depressions in the concrete surface caused by coarse aggregates which expand during moisture absorption. Shale is one common expansive aggregate, although in Wisconsin, cherts are generally responsible. Pop-outs may also be caused by reactive aggregates and high alkali cement. Pop-outs can normally be discerned by seeing the aggregate particle's fractured surface in the bottom of the depression. Pop-outs themselves are not a structural concern, although the pop-outs may eventually cause a rougher ride or help to speed the rate at which water can reach the underlying reinforcing steel.



**Figure 2.1.4.1-10:** Pop-out on Concrete Deck.

#### Honeycombs (Poor Consolidation)

Caused by congested reinforcing steel or improper concrete vibration during construction, honeycombs are voids within the concrete mass. Small honeycombs are not detrimental to the strength of the member, whereas large honeycombs may be structurally significant. Severe honeycombing may even leave some of the reinforcing steel within the member uncovered.

Only voids adjacent to the concrete surface are inspected by visual means. Current construction practice is to fill large surface voids with mortar.

#### Collision Damage

Trucks, over-height vehicles, derailed trains, and marine traffic may strike and damage concrete piers, abutments, or girders. A large section of concrete may be cracked or chipped off a structural member, exposing reinforcing steel or prestressing strands. If damaged sections are similar to spalls, patching may be used as a repair method. Damaged prestressed beams with exposed or broken strands can be repaired, but generally the beams are replaced. Very serious impacts can knock out pier columns or girders.

#### Abrasion and Wear

Concrete disintegrates over time with continuous external mechanical forces acting on its surfaces. Surface abrasion is caused by the erosive action of silt or sand found in fast-flowing rivers, streams, or surf zones. It is usually associated with piers, pilings, and abutments. Freeze thaw can accelerate abrasion damage. Wear is the scraping effect on the deck, curb, and parapets due to snow plows, street sweepers and friction caused by daily tire traffic. Severe wear is noted as revealed polished aggregate. This can create a safety concern on bridge decks if the deck is wetted.



### Fire Damage

Though concrete is considered a fire-resistant material, fire can cause some deterioration. This will mainly be seen as a discoloration on the concrete surface, but pop-outs, scaling, delaminations, and spalls may be caused by the intense heat expanding the aggregate and reinforcing steel.

### Overload Damage

Overload damage is caused from overstressing a structural component. Unlike cracking defects which are typically gradual over time, bridge components experiencing overloading may suffer serious structural cracking in as soon as a single loading. A concrete element that has undergone overloading may exhibit sagging, spalling or working flexural cracks at tension areas and/or diagonal shear cracking near support points.

#### 2.1.4.2 Steel

Carbon steel is often referred to simply as steel and has been a widely-used building material since the later part of the 19<sup>th</sup> century. It has many advantages, including a high strength/weight ratio, ductility, elasticity, reliability, and versatility. Steel is differentiated from iron by the inclusion of carbon and other alloying elements. Many standard cross-sectional steel shapes are produced by rolling mills, such as angles, channels, and wide flange sections. Nonstandard shapes may be created by welding, bolting, or riveting together combinations of flat plates and/or smaller rolled sections.

#### **Physical Properties**

Steel weighs approximately 490 pounds per cubic foot. The chemical composition of steel varies widely depending on the type of steel. Carbon steel is a combination of iron, carbon (0.15 percent to 1.7 percent of carbon by weight), manganese (up to 1.65 percent), silicone, and copper (both up to 0.60 percent). For improved mechanical properties, weldability, and corrosion resistance, high-strength, low-alloy steels are produced. These steels may include the alloying elements used for carbon steels, plus others such as columbium, vanadium, chromium, and nickel. Still higher strength steels are available by using higher percentages of alloying elements and heat-treatments. These are known as quenched and tempered alloy steels, and they are not commonly used for bridge structures.

Unprotected structural steel will readily corrode or rust. Painting and galvanizing (the application of a sacrificial coating of zinc) are the most common methods used to protect steel against atmospheric corrosion. Some steels, known as weathering steels, oxidize to produce a dense protective coating (patina) which inhibits further corrosion. When used in the proper environment, these steels require no painting and develop an even-textured, dark red-brown appearance.

#### **Mechanical Properties**

Steel is a material used for its high tensile and compressive strengths. Depending on the steel type, yield strengths (the greatest stress a material can withstand without being permanently deformed) most commonly range from 33,000 pounds per square inch to





50,000 pounds per square inch. Tensile and compressive yield strengths are the same. Shear strength is about 60 percent of its yield strength.

When stressed below its yield point, steel is elastic, and a loaded beam will readily spring back into shape once the load is removed. Should high loads or impacts be applied which produce stresses beyond yield, steel is ductile and can withstand excessive deformations without failure. However, steel may become brittle due to the effects of welding, heat treatment, fatigue or very low temperatures.

Fatigue is a material failure under cyclic (repeated) loading. It only affects parts of a member's cross-section subject to varying tensile stresses or stress reversals (alternating compressive and tensile stresses). Steel strength is reduced if it is subject to a large number of stress fluctuations or reversals. This strength reduction depends on the number of load cycles, the magnitude of the stress fluctuation, and the type of detail involved. The strength reduction is small for base metal. Reductions in allowable strengths may be required when discontinuities (such as changes in cross section, cuts, tack welds, and rough edges) exist. Small discontinuities may be removed or improved by grinding to a smooth profile.

### **Steel Deterioration**

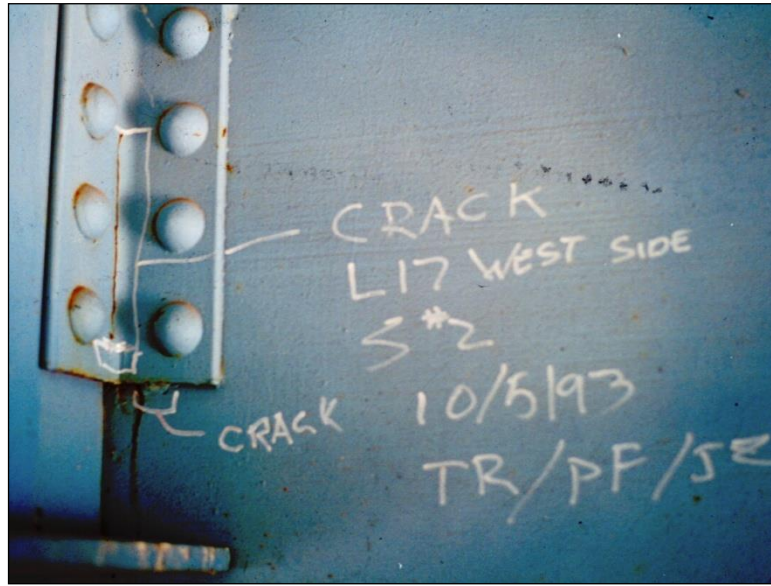
Steel can experience many types of defects. Steel's susceptibility to fatigue damage makes reporting these defects all the more critical. The following information is a brief overview of causes of fatigue cracking in steel. An excellent resource for a more complete discussion of fatigue, as well as for example photographs and diagrams, is the *Manual for Inspecting Bridges for Fatigue Damage Conditions* by Yen, Huang, Lai, and Fisher.

### Fatigue Cracks

Fatigue cracks are of primary concern since their growth can lead to sudden catastrophic failures. It is therefore extremely important for an inspector to understand where fatigue cracks are likely to occur and know the signs that indicate a crack.

Fatigue is material failure or fracture under a sufficient number of stress fluctuations. The stress fluctuations are caused by repeated member loading, such as trucks repeatedly driving over a bridge day in and day out. Each load cycle causes a stress loading and unloading in the primary supporting members. The stress generated by this cyclic loading is much lower than the steel's ultimate, or breaking, stress. Eventually, the steel will begin to crack. For example, consider a steel wire capable of suspending a permanent 100-pound weight just prior to breaking. This same wire may only be able to suspend a 75-pound weight, applied and removed several thousands of times, before it would finally break. Bending a paper clip back and forth several times until it breaks is an example of a fatigue failure.

Fatigue crack development depends on several factors. These factors include load frequency, stress type, stress range, and detail type.



**Figure 2.1.4.2-1:** Fatigue Crack through Connection Angle and Tack Weld.

#### *Load Frequency*

Steel is more likely to crack under a high number of load applications. Interstate bridges that experience truck loadings on a daily basis are more prone to fatigue damage than rural or local bridges that may not carry truck traffic for days on end. Also, older bridges more than likely have seen a greater number of truckload applications than recently built structures.

Load frequency is generally a concern for highway and railroad bridges where heavy vehicles commonly use the structure. It is generally not a concern for pedestrian bridges where the frequency of design loads is relatively low.

#### *Stress Type*

Fatigue is most often a concern when the type of stress during each load cycle is either tension-tension or reversed (compression-tension). Several bridge members or components thereof are susceptible, including the tension chords, diagonals, verticals of truss bridges, the tension flanges of beam/girder bridges, and hangers of suspended girders or trusses. Beam webs can also be subject to fatigue cracking when cross-frames or diaphragms distort the web out-of-plane.

Cyclic compression-compression stresses can also be a concern, but any cracking in these locations is usually due to residual tensile stresses in the steel from welding or uneven cooling after rolling. Cyclic compressive stress is rarely a concern for bridges.

#### *Stress Range*

Another factor for steel's susceptibility to fatigue is the stress range. Steel is more likely to crack when the range from maximum to minimum stress during each load cycle is high. For example, a detail where the stress varies from -10 kips per square inch compression to 15 kips per square inch tension (stress range = 15 kips per square inch - (-10 kips per square

inch) = 25 kips per square inch) is more prone to fatigue cracking than the same detail which experiences stresses ranging from 10 kips per square inch tension to 30 kips per square inch tension (stress range = 30 kips per square inch - 10 kips per square inch = 20 kips per square inch). Maximum tensile stress is not a consideration when considering fatigue life.

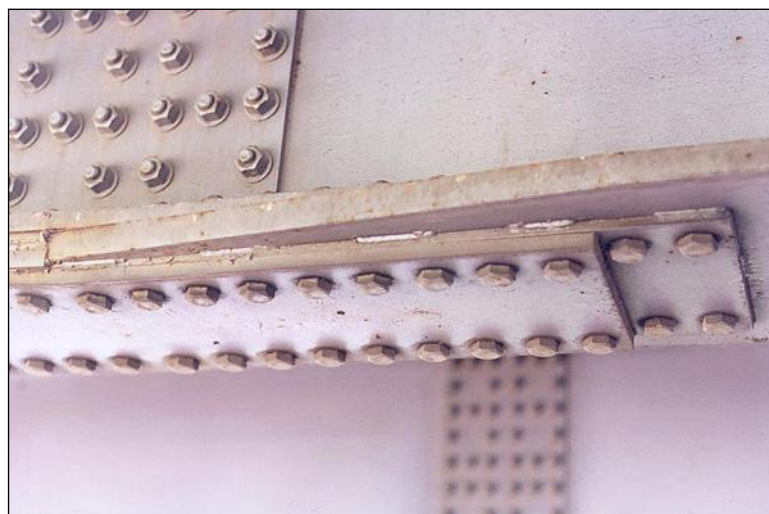
Maximum yield strength is also not a consideration. Steel having yield strength of 50 kips per square inch does not have more fatigue capacity than steel with yield strength of 36 kips per square inch.

#### *Detail Type*

Secondary member attachments, weld flaws, welded cover plate ends, bolt holes, tack welds, etc. create a material discontinuity and introduce an interruption in the stress flow. Each discontinuity acts as a notch in the steel member, creating a sudden rise in the stress level. Smooth transitions are less susceptible to cracking; whereas sharp transitions, such as transverse welds at the end of a cover plate or gouges in the flange, are very susceptible.



**Figure 2.1.4.2-2:** Transverse Weld at a Cover Plate End.



**Figure 2.1.4.2-3:** Tack Welds at a Splice Plate/Bottom Flange Interface.

Notches force the stress flow to suddenly “bend” around a corner. This sudden direction change produces a rise in the stress which may, on the microscopic level, reach yield. Repeated loading to yield will eventually fracture the steel, creating a crack (similar to the repeated bending of a paper clip mentioned above). Once a crack forms, the cross-sectional area of the member is reduced, leading to higher stresses and further crack growth. If the crack is left without arresting the crack, and occurs within a tension or stress reversal zone, the member could eventually tear itself apart.

The AASHTO bridge specifications have categorized several steel bridge details with respect to their susceptibility to fatigue cracking. All were categorized with respect to beam or girder in-plane bending and axial loading of members or member components. See Appendix D for these details.

Several inspection techniques are used to detect fatigue cracks. The most common and most important method is visual examination, as this is usually how cracks are found in the first place. While it would be ideal to examine every square inch of every element experiencing tensile stress variations or stress reversals, this is unnecessary and extremely uneconomical. Since fatigue cracks develop at discontinuities, it is reasonable to inspect local suspect details only. Telltale visual signs suggesting a crack include rust drips (bleeding), rust powder (due to rubbing along the crack), and small, usually rusty cracks. Some cracks could be very large, and in extreme situations they may even open and close under traffic loading. Another sign is a fine line of discoloration in the paint at the toe of a connecting weld, or on the surface of a weld. The *Manual for Inspecting Bridges for Fatigue Damage Conditions* contains several photos and diagrams illustrating these signs. Suspected cracks may be more easily confirmed by using a magnifying glass. All suspect cracks should be reported, and their location marked directly on the member with a permanent felt tipped marker or paint stick.

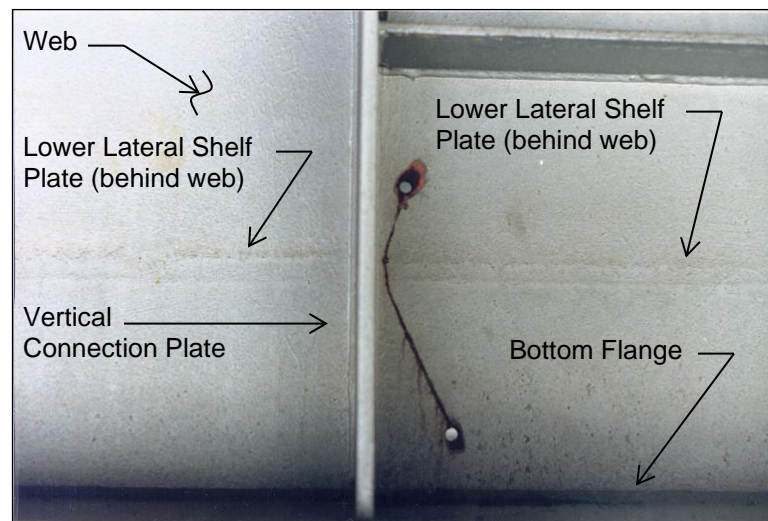
After visual detection, some small cracks may require confirmation through the use of nondestructive evaluation methods. Most commonly, magnetic particle or liquid (dye) penetrant testing is used because these methods are easy to administer, are inexpensive, give fairly quick results, and require fairly low-tech equipment. More advanced nondestructive techniques may be used to establish the extent of a crack within the base metal, since magnetic particle and dye penetrant testing will only reveal crack size at the metal’s surface. The most common high-tech method of examination is ultrasonic testing. Other more expensive methods include acoustic monitoring, eddy current, and radiography (x-ray/gamma ray).

Confirmed cracks should be re-examined during subsequent inspections until the cracks are eliminated or repaired. Shallow cracks may be ground or drilled out. Holes (sometimes referred to as “arrest holes”) may be drilled at the tips of long cracks to eliminate the sharp rise in stress in this area. Longer cracks typically require the drilling of arrest holes plus bolting splice plates to the member.

Although the base metal away from component details is generally not a fatigue concern (such as tension flange areas located between diaphragm connections), crack initiation points may still exist in the form of tack welds, welded flange splices not ground smooth, and notches resulting from traffic impact or fabrication carelessness. These flaws should be examined closely and reported. The flaws should also be re-examined during subsequent

inspections until they are eliminated or repaired. Tack welds or butt welds with the reinforcement left in place can generally be ground smooth, eliminating the defect. Notches are typically ground smooth to form a smooth, tapering transition in the plate.

A detail contributing to the cracking of many fabricated girders is the web-gap. This cracking and associated detail is not related to the in-plane bending details indicated in the AASHTO stress categories. Web-gap cracking is produced by out-of-plane, or sideways, web bending. A web-gap is created when a horizontal gusset plate is notched to fit around a transverse, vertical connection plate. The horizontal gusset plate, used to connect lateral bracing, is then welded directly to the girder web. The small space created between the transverse connection plate and horizontal gusset plate notch is called the web-gap. Forces in the lateral bracing/horizontal gusset plate push and pull on the girder web, causing it to bend sideways (out-of-plane). This bending is restrained due to the stiffness created by the transverse connection plate. As a result, the web is forced to deflect and bend over the very short gap distance, generating extremely high local stresses. After numerous load cycles, a vertical web crack within the web-gap will develop, creating a material discontinuity and notch with respect to in-plane bending. This effect is shown in Figure 2.1.4.2-4. If left without drilling out the crack tips, this crack can grow into the tension flange to create a critical situation.



**Figure 2.1.4.2-4:** Girder Web Gap Fatigue Crack (Note Drilled Crack Arrest Holes at Crack Tips). Note the Outline of the Lower Lateral Shelf Plate Located on the Opposite Side of the Web.

### Corrosion

Corrosion, or rust, is the most visible type of steel deterioration. It is a chemical reaction in which the iron in the steel combines with oxygen and moisture in the air to form ferric oxide and ferric hydroxide. More specifically, it is an electrochemical process between an area having a tendency to corrode (the anode) and an area with a lower tendency to corrode (the cathode). The anode and cathode may be located on the same piece of steel. A liquid electrolyte (water) must be present to allow for the flow of metal ions, and a conductor (the

steel itself) must be present to allow electron flow from the anode to the cathode. Iron in the steel dissolves in the water to form iron ions. These ions react with oxygen in the air to form rust at the anode. Electrons that flow from the anode to the cathode combine with other ions in the water, typically hydrogen ions, to form hydrogen gas. As a result, the cathode is left undamaged.



**Figure 2.1.4.2-5:** Steel Corrosion at Girder Splice.

The corrosion process can be stopped by preventing the electrolyte (water) from coming in contact with the base metal. In most steel bridge structures, this is done by the application of a protective paint coating. In lieu of painting, a zinc galvanizing coating may be applied. Since zinc has a greater tendency to corrode than iron, it becomes the anode and the steel becomes the cathode.

Once the base steel is exposed to the atmosphere, there are several causes for corrosion. The most common cause is the environment, and this primarily affects steel in contact with water or soil. Impurities in water, such as deicing chemicals, bird waste, atmospheric pollutants, and acids in the soil, produce ionic solutions which create more efficient electrolytes. The more efficient the electrolyte, the greater the rate of corrosion.

Other less common causes for corrosion include fretting, stress corrosion, bacteria, and DC currents. Fretting is the rubbing of two closely-fitted steel parts. Pitting and a red deposit occur at the interface. Stress corrosion occurs when a metal is loaded in tension. The tensile stress exposes an increased amount of surface area at the metal's grain boundaries, leading to corrosion and cracking. Waterborne bacteria, heavy clay, contaminated waters, etc., can destroy the steel's protective coating and sometimes corrode the steel itself through a process called microbial induced corrosion. Finally, stray DC currents from sources such as welding equipment, substations, and railway signal systems can also speed the rate of the electrochemical process.

The three commonly recognized stages of corrosion are light, moderate, and heavy. Light or surface rust is a loose form of corrosion usually appearing as a dark orange or light brown

color. Its effect is not serious, as it does not oxidize away a measurable amount of the steel. It can also be observed as light pitting or spotting on the paint surface. Moderate corrosion has a medium to dark brown color and a scaly appearance. Shallow pits may have formed in the steel surface. There is no paint left to protect the steel, and small amounts of section loss may have occurred. Heavy corrosion is easily recognized by its dark brown to almost black color and laminated rust (laminated rust occurring between two plies of plates is referred to as “pack rust”). These rust laminations may be easily removed with a chipping hammer, exposing large deep pits in the steel surface. Heavy corrosion causes reductions in plate thickness that can easily be seen with the naked eye or can even cause through-thickness section loss. Corrosion allowed to reach the heavy stage can present several problems for a steel member.

#### *Loss of Section and Capacity*

If left unchecked, corrosion will remove a significant quantity of a member’s cross-sectional area. This can be serious for members or member components designed to be highly loaded. Regardless if the member is new or severely corroded, the forces within the member remain unchanged. Member stresses, however, can increase significantly.



**Figure 2.1.4.2-6:** Corrosion and Loss of Section - Crushed Beam at Abutment.

For example, suppose a member has an area without corrosion of 3 square inches and carries a load of 60,000 pounds. Stress in the original member is  $60,000 \text{ pounds} \div 3 \text{ square inches}$ , or 20,000 pounds per square inch. If corrosion removes one-third of the original cross-sectional area, leaving only 2 square inches of steel, the remaining stress increased by 50 percent to  $60,000 \text{ pounds} \div 2 \text{ square inches}$ , or 30,000 pounds per square inch.

It is clear that for a given load, stress is inversely proportional to cross-sectional area. Continuing with the procedure above, a 50 percent reduction in area will lead to a stress of 40,000 pounds per square inch. If steel with yield strength of 36,000 pounds per square inch were used for the member, an overstress and possible failure may occur.

### *Creation of Stress Risers*

Corrosion causes surface discontinuities in the form of rough edges and surface pits. Discontinuities act as notches. When stress “flow” is forced to bend around a notch, local stresses in the immediate vicinity are greatly amplified. Under repeated loading, the notch may act as a crack initiation point, and the high stress concentrations coupled with repeated loading will eventually tear the steel apart. As a result, a corroded member is more prone to fatigue damage than members with smooth surfaces without corrosion.

### *Pack Rust*

Corrosion can occur between two plates that are riveted, bolted, or pinned together, such as field splices, bracing connections, cover plates, pin and hanger bars, bearings, etc. If the plates are not clamped tightly together or paint does not properly seal the edge of the faying surface, moisture is able to seep in between the plies. This moisture can remain for extended periods, since it is difficult for this area to dry out quickly. One particular problem area is where rivets or bolts are spaced too far apart and are unable to tightly clamp all surfaces of the plates together. When corrosion begins, it expands to separate the plates, creating prying forces on the fasteners. Advanced corrosion will exhibit stratified rust, plate bending, and popped rivets or bolts.



**Figure 2.1.4.2-7:** Pack Rust Prying Apart Flange Splice Plates.

### *Fixity at Moving Components*

Corrosion that forms at expansion devices such as pins and hangers, sliding plate bearings, and pinned bearings can become so excessive that these devices “lock up”. When this occurs, unintended loads are introduced into the structure which could cause overstresses and possible component failure.

### Overloads

An overload occurs when live loads crossing the bridge are so great that the structural members are stressed beyond their design strength. Compression members or components



may become unstable, or tension members may be stressed beyond their elastic limit. When these events occur, the member will permanently deform, referred to as plastic deformation. In tension components, a sign that an overload has occurred includes an area of “necking down”, where the member is permanently stretched and cross-section is reduced. Other signs are total member elongation or even fracture. For compression members, symptoms of overloading are buckled members that form either a single curved bow or double curved “S” shape. An indication that a compression member component has buckled is acute waviness in the plate.

### Impact Damage

It is not uncommon for older bridges to have lower vertical clearance than bridges built by today’s standards. Some of the bridges may show signs of vehicular or ship impact damage. This damage normally occurs above the roadway or navigable channel on the fascia girder. Indications include dislocated and distorted members and scrape marks on the flange undersides. Distorted members or components may act as stress risers, making a normally sound component a fatigue prone detail.



**Figure 2.1.4.2-8:** Girder Bottom Flange Impact Damage.

### Fire Damage

Unprotected steel has poor resistance to extended heat exposure. Although it is incombustible, it will become significantly weakened by fire. Yield strengths of steels normally used in bridge construction are reduced by about 23 percent at 800 degrees Fahrenheit, 37 percent at 1,000 degrees Fahrenheit, and 63 percent at 1,200 degrees Fahrenheit. Melting points of the many steel alloys vary, but the melting temperature of about 2,800 degrees Fahrenheit for pure iron is a good approximation.



### 2.1.4.3 Timber

Timber has been a widely-used building material for all of recorded human history. It is likely that the first constructed bridge was a tree intentionally felled across a chasm. Timber as a bridge construction material has many advantages, including excellent resistance to fatigue and impact loading, resistance to deicing chemicals and freeze thaw effects, a favorable strength to weight ratio, and ease of construction. Timber is readily available and relatively inexpensive, and it is a renewable resource. Traditionally, solid sawn lumber was used for all bridge components due to the abundance of large, old growth trees. Many of these old growth trees have since been cut down. To compensate, current manufacturing processes allow very large timber members to be created by glue-laminating several smaller pieces together. These members can be assembled into many types of structures including slabs, beams, trusses, arches, trestles, and even suspension bridges.

#### **Physical Properties**

Wood used for bridge construction weighs about 50 pounds per cubic foot, although this value can vary widely, depending upon the wood species and moisture content. It is a hygroscopic material that absorbs and loses moisture as the humidity of the air changes. These moisture content fluctuations cause the wood to expand and shrink. Wood is an orthotropic material, meaning that its physical properties parallel to the grain are different than that perpendicular to the grain. It is resistant to many chemicals. Heavy wood members are even resistant to fire by the formation of a char layer that acts to insulate the underlying sound wood.

One negative aspect of wood is that features related to tree growth, such as knots, splits, checks, and shakes, can adversely affect a member's strength. A second is that high moisture content can negatively affect the wood's strength. Finally, wood without a preservative treatment has limited resistance to decay or insect attack. Fungi, termites, carpenter ants, powder-post beetles, marine borers, and caddis flies are the most common sources for timber deterioration.

#### **Mechanical Properties**

Wood is a material used for its tension, compression, and bending capabilities. Its mechanical properties vary greatly from species to species. Because wood is an orthotropic material, the mechanical properties also vary depending on its principal axes of anatomical symmetry. Ultimate strengths for the most common properties used in design range from 6,600 to 17,500 pounds per square inch for tension parallel to the grain, 1,700 to 10,100 pounds per square inch for compression parallel to the grain, 3,900 to 20,200 pounds per square inch for bending, and 500 to 2,600 pounds per square inch for shear parallel to the grain. Similar properties in wood's other two orthogonal directions (perpendicular to the grain in the radial and tangential directions) will have different ultimate strength values.

For most engineering applications, wood is elastic, and a beam loaded and stressed below its ultimate strength will spring back into shape once the load is removed. Recovery from its deformed loaded shape may not be immediate, and if the load had been in place long-term, recovery will take a longer period of time. Wood is susceptible to creep. Creep is a gradual deformation under a sustained load. Over a period of years, the initial deflection of a wood beam can eventually double under high permanent loading.



Should high dynamic impact loads be applied, wood is a very resilient material. It can sustain loads up to twice the amount that would produce failures if applied statically.

Fatigue is a material failure under cyclic (repeated) loading, affecting only parts of a member's cross-section subject to varying tensile stresses or stress reversals (alternating compressive and tensile stresses). Fatigue damage is not a concern for wood since its fibrous structure is resistant to cyclic loads.

### **Timber Deterioration**

As with any material, timber is susceptible to deterioration and damage. Untreated wood can suffer structural damage due to biological attack. Treated or untreated wood is susceptible to structural damage from mechanical or atmospheric sources, such as vehicle impact, overloads, and cracks due to drying, and from fire.

#### Biologically Induced Damage

Biological damage to wood is caused by living organisms. The main defense against such attacks is by treating the wood with chemical preservatives.

#### *Fungi*

Decay caused by fungi is the primary reason for timber bridge replacement. Brown rot and white rot are the two fungi most responsible for structural damage. They feed upon the cellulose and lignin that make up the wood's cell wall configuration and give it its strength. Brown rot makes the wood dark brown and crumbly. Because its enzymes can diffuse into the wood far from their source, brown rot can weaken the wood substantially in the early stages of its attack. White rot makes the wood white and stringy. Though the enzymes do not migrate into the wood as with brown rot, white rot uses more of the wood cell wall as a food source, causing more severe, localized decay.

Other fungi may be present on a timber member, but do not cause any serious structural damage. However, their presence indicates that conditions are right for the growth of brown or white rot. These "indicator" fungi include molds, which have cottony or powdery appearances and vary from white to black in color. Stains may appear as specks, spots, streaks or patches of varying color on the wood surface. Soft rot does actually attack the wood, but only to just below the surface making the wood soft and spongy.

Conditions must be right for fungi to survive. There must be sufficient oxygen and a minimum of 20 percent moisture present in the wood. Fungi must have a food source, and this is the wood itself. Temperatures must range between 32 degrees and 90 degrees Fahrenheit, with the rate of biological activity being higher at warmer temperatures. Essentially, these are the same conditions required for human survival. Areas on a bridge favorable for fungi growth commonly exist at connections, supports, splices, and the waterline or ground line. Other areas of a bridge usually lack one of the components necessary for fungi survival, such as a lack of oxygen and excessive moisture in submerged timber piles. The only way to stop the natural decay due to fungi is by using wood preservatives, which poison the fungi food source.



### *Parasites*

Wood parasites are insects, mollusks or crustaceans that live within or feed upon the timber member.

**Termites:** Termites are insects recognized for their ability to damage wood and have a northern habitat range within Wisconsin. Termites found in Wisconsin feed on damp wood usually in contact with the ground. Their tunnels contain no exit holes, so a termite-damaged timber may look as good as sound timber. A sharp tap on a timber's surface, however, will easily punch a hole into the termite-damaged interior. Signs of termite activity are mud tubes that run from the ground to the wood member.

Timber damage due to termites on frequently used bridges is rare due to the constant vibrations of daily traffic.

**Carpenter Ants:** Carpenter ants do not feed on wood, but tunnel through a timber's interior for shelter. As with termites, they damage the interior of a timber so that infestation is not readily apparent. They will, however, leave a pile of sawdust at the entrance tunnel, signaling their presence.

**Powder-Post Beetles:** Larvae of powder-post beetles feed on the interior of timbers, creating tunnels and many exit holes. A powdery residue is often packed into these exit holes, indicating their presence.

**Caddisflies:** Caddisflies are insects found in fresh or brackish water. Caddisfly larvae use timber piles for protection by boring holes into the sides of the timber. They are attracted to timber experiencing fungal decay. Since they do not eat the wood, they can also be found in piles treated with creosote.

**Marine Borers:** Marine borers are saltwater-borne parasites and do not affect timber bridges found in Wisconsin.

### Mechanically Induced Damage

Mechanical damage is usually caused by the live loads acting on the bridge.

#### *Overloads*

Overload damage occurs when live loads acting on the bridge are so great that the structural members are stressed beyond their ultimate strength. Compression members may buckle into a single curved bow or double curved "S" shape, crack or even break. Tension and bending members will crack or fracture. Cracks due to overloading will generally occur perpendicular to the grain, splintering the wood. Overloads may not only be caused by traffic but also by foundation settlements.

#### *Impact*

Impact damage, most commonly caused by vehicular collisions, normally occurs above the roadway or navigable channel on the fascia girder. It can also occur on the main load-carrying members of through trusses and arches. Stream debris or ice floes may also impact



bridge members situated within the channel. Indications of impacts include damaged timbers and scrape marks.

### *Abrasion/Mechanical Wear*

Abrasion is most often seen on timber bridge decks and is caused by vehicle tires and snow plows. These forces can cause ruts in the deck that hold water, further weakening the wood. Mechanical wear occurs from fasteners rubbing against their holes at loose connections.

### Atmospheric Related Damage (Weathering)

The weathering effects of moisture, light, and heat can adversely affect the physical properties of wood. Moisture loss in wood can cause dimensional instabilities of a timber, resulting in warps, cracks, and shrinkage.

### *Warping*

Warping of a wood member is caused by uneven drying, allowing one side of the timber to shrink at a different rate than the other. As a result, the member may bow, twist or cup.

### *Cracks*

Moisture loss in a timber will often cause the member to shrink, causing cracks. Cracks create openings into a timber's untreated interior, allowing biological agents to enter and begin the decay process. Cracks may also reduce the timber's strength. Checks are cracks oriented parallel to the grain and perpendicular to the annual growth rings. Splits are advanced checks that extend completely through the member.

Some cracks, called shakes, may form before a tree has been felled. Shakes are oriented parallel to both the grain and annual growth rings.

### *Loose Connections*

Improperly dried wood may shrink during service, resulting in loose connections. Loose connections may allow biological agents to enter the untreated timber interior. Mechanical wear due to the fastener rubbing against the wood may also take place under live load.

### Fire Damage

Though fire can completely consume a small timber member, large timber members often used for bridges offer some resistance to fire. Fire consumes wood at a rate of about 0.05 inch per minute for the first 30 minutes, and about 0.021 inch per minute thereafter. As wood burns, a black char layer is formed. This char helps to insulate the underlying unburned wood, slowing the consumption rate. Large timbers have enough volume to develop this protective char layer, leaving a core of undamaged wood. Though the remaining wood core does not have the strength of the original undamaged timber, it is often enough to prevent a total collapse.



### 2.1.4.4 Other Materials

#### **Stone Masonry**

Stone masonry is rarely used in modern construction as a structural material for bridges. However, it was used extensively for abutments and piers in the 1800s and early 1900s. It was also used during this time to build arch superstructures and culvert structures. Different types of stone were used, depending on local availability. These are most commonly limestone, sandstone, and granite.

Stone masonry is classified as rubble masonry, square-stone masonry or ashlar. Rubble masonry is rough cut stones used for random coursed or roughly coursed construction. Square-stone masonry is roughly squared and dressed and may be laid in random or coursed construction. Ashlar masonry is precisely squared and finely dressed and may be laid in random or coursed construction.

#### Physical Properties

Stone masonry weighs between 135 pounds per cubic foot (sandstones) to 170 pounds per cubic foot (granites). It expands and contracts with increasing and decreasing temperatures, respectively. It may be porous and therefore absorbs moisture. Limestone, common in Wisconsin, tends to be more absorptive than most other stones. Stone is a durable material, and different stone types will each have a different durability.

#### Mechanical Properties

Stone masonry is a material used for its compressive strength. Depending on the material type and where it had been quarried, compressive strengths generally range from 6,000 pounds per square inch (limestones and sandstones) up to 60,000 pounds per square inch (granites). Its tensile strengths are poor, ranging from about 2 to 13 percent of its compressive strength. Mortar is used to form a bedding material for each masonry unit, bond individual stone units together, seal joints against moisture penetration, and seal irregularities on the masonry unit's surface. Mortar itself is almost always weaker than stone.

#### Stone Masonry Deterioration

The three main causes of stone masonry deterioration are splitting, spalling, and weathering.



**Figure 2.1.4.4-1:** Masonry Deterioration/Spalls at an Arch Bearing.

### *Splitting*

Splitting refers to the seams or cracks that may form in rocks. This common type of deterioration may occur due to freezing water within small seams and pores, due to volume changes from seasonal temperature fluctuations, and due to the wedging force of plant roots growing into crevices and joints. Structural overloads may also cause the stone masonry units to split.



**Figure 2.1.4.4-2:** Split Masonry Unit with Failing Mortar Joints.

### *Spalling*

Small pieces of rock which break out or chip off of the stone masonry unit are called spalls. Sources of spalling are the same as those that produce splits. Vehicle impacts may also produce spalls.

### *Weathering*

Weathering is the degeneration of the rock surface into small granules. Causes that chemically attack the stone include lichens and ivy, as well as gasses and solids dissolved in water, including deicing agents. Windborne or waterborne particles can cause abrasion as well.

### **Cast Iron**

Cast iron is a material not used in modern construction as a structural material for bridges. However, it was used for the compression members and bearing castings of very old bridges. Cast iron is produced by pouring molten iron into a mold and letting the metal solidify.



**Figure 2.1.4.4-3: Cast Iron Arch.**

### Physical Properties

Cast iron has a gray color due to the presence of graphite particles distributed throughout the metal. It weighs about 450 pounds per cubic foot. The chemical composition of cast iron varies widely depending on the type. However, the most common gray cast iron is composed mainly of iron, carbon (2.0 percent to 4.0 percent of carbon by weight), and silicone (up to 2.8 percent). Other elements include sulfur, phosphorus, and manganese.

Unprotected cast iron will corrode, but tends to be more corrosion-resistant than steel. It is usually painted to protect against atmospheric corrosion.

### Mechanical Properties

Cast iron is a material used for its high compressive strength. The tensile yield strength of gray cast iron is about the same as its ultimate tensile strength of 20,000 pounds per square





inch to 30,000 pounds per square inch. Its compressive yield strength varies from approximately 80,000 pounds per square inch to 100,000 pounds per square inch.

The free carbon and slag in cast iron make it a brittle material, make it difficult to weld, and gives it poor resistance to shock and impacts. It has poor resistance to fatigue loading, but good damping and machinability properties.

### Cast Iron Deterioration

Types of cast iron deterioration are similar to those found on steel (see Section 2.1.4.2).

### **Wrought Iron**

Wrought iron is a material that is not used in modern construction as a structural material for bridges. In fact, it is no longer produced in the United States. It is, however, still found on many old bridges as tension members. Wrought iron is produced by mechanically rolling or working relatively pure iron into a desired shape, producing a fibrous material with properties in the worked direction similar to steel.

### Physical Properties

Wrought iron weighs about 480 pounds per cubic foot. The chemical composition of wrought iron is mainly of iron, slag (iron silicate, up to 3.0 percent by weight), and phosphorous (approximately 1.2 percent). Other elements include sulfur, manganese, and carbon.

Unprotected wrought iron will corrode, but tends to be more corrosion-resistant than steel. Its fibrous nature produces a tight rust less likely to flake and scale as in structural steels.

### Mechanical Properties

Wrought iron is a material used for its high tensile strength. Its yield strength is about 30,000 pounds per square inch. When wrought iron is worked or rolled, the slag distributed throughout the metal is elongated into fibers. Because of this, it is an anisotropic material, having different mechanical properties with respect to the direction of the slag fibers.

The slag fibers give wrought iron many desirable properties. It surpasses steel in its ductility, fatigue strength, and corrosion resistance. It has good machinability properties and good impact and shock resistance. Wrought iron is also weldable.

### Wrought Iron Deterioration

Types of wrought iron deterioration are similar to those found on steel (see Section 2.1.4.2).

### **Cast Steel**

Cast steel is a material not normally used in fixed bridge construction, but it has been used for tracks in movable bridges. Cast steel is produced by pouring molten metal into a casting mold directly from the steel-making furnace, and letting it solidify.

### Physical Properties

Several types of cast steel exist, including carbon steel, low alloy steel, alloy steel, and stainless steel. Cast steel weighs about 490 pounds per cubic foot. The chemical composition of cast steel varies widely depending on the type. However, carbon steel castings are composed of iron and carbon (0.2 percent to over 0.5 percent of carbon by weight). Unprotected cast steel will corrode.

### Mechanical Properties

Cast steel is a material used for its machinability qualities. The yield strengths of carbon steel castings commonly used for bridges range from 35,000 pounds per square inch to 95,000 pounds per square inch, and tensile strengths range from 60,000 pounds per square inch to 120,000 pounds per square inch. Low alloy and alloy bridge castings are stronger, and can have yield and tensile strengths up to 135,000 pounds per square inch and 140,000 pounds per square inch, respectively

### Cast Steel Deterioration

Types of cast steel deterioration are similar to those found on steel (see Section 2.1.4.2).



**Figure 2.1.4.4-4:** Fatigue Cracks on a Steel Casting.

### **Aluminum**

Aluminum is not normally a material used as a structural material for vehicular bridges. However, it may be found as part of the deck, superstructure or substructure on pedestrian bridges where fatigue is not a concern.



### Physical Properties

Aluminum weighs about 175 pounds per cubic foot. The chemical composition of aluminum varies widely depending on the type. However, the most common aluminum used for structural applications is composed mainly of aluminum, magnesium, silicon, copper, and chromium. Unprotected aluminum is much more corrosion-resistant than steel. Because of this, painting is usually unnecessary to protect it from the atmosphere.

### Mechanical Properties

Aluminum is a material used for its high tensile and compressive strengths. Depending on the aluminum type, yield strengths range from 40,000 pounds per square inch to 48,000 pounds per square inch, giving it a high strength to weight ratio. Tensile and compressive yield strengths are the same. Shear strength is about 60 percent of its yield strength. The modulus of elasticity values of aluminum are approximately one third that of steel. Modulus of elasticity is a material property relating material stress to elongation. Since modulus of elasticity values are inversely proportional to elongations, an aluminum beam will deflect three times as much as a similarly shaped steel beam carrying the same load. In addition, aluminum's fatigue strength is approximately one-third that of steel, making it less desirable when fatigue is a concern.

When stressed below its yield point, aluminum is elastic, and a loaded beam will readily spring back into shape once the load is removed. Should high loads or impacts be applied which produce stresses beyond yield, aluminum is ductile and can withstand excessive deformations without failure. Although weldable, aluminum experiences significant base metal strength reductions of up to one half the yield strength in the vicinity of welds.

### Aluminum Deterioration

With the exception of atmospheric corrosion, types of aluminum deterioration are similar to those found on steel (see Section 2.1.4.2).

### **Composites**

Composites are plastics/resins reinforced with carbon, glass or other fibers. In Wisconsin, their use as main load carrying members for bridges is limited. Wisconsin has several research bridge decks that utilized composites for concrete deck forms, some in combination with deck reinforcement. These can be tracked using the special component feature.

Composites can have a high strength-to-weight ratio, can attain strengths similar to steel, and have excellent corrosion and impact resistance. There are numerous types of plastics available, but their properties can lack consistency from producer to producer. Also, costs are presently very high (although prices may come down as more is being produced).

Composites exhibit viscoelastic (nonlinear) behavior. This means that at any given strain magnitude, temperature changes can produce marked changes in strength and deflection. Similarly, load duration and magnitude affect a composite's strength and deflection. Viscoelastic behavior is less pronounced in composites than in plain, unreinforced plastics/resins.

Though fatigue data does exist for some of the composites, no method is available to characterize fatigue strengths of composites.

### **2.1.5 Classification of Fixed Bridges**

Bridges are classified according to their superstructure type. The use of each type generally depends on the distance the bridge must span, although more than one type can be used for the same span length. Other factors include depth of channel or ravine to be crossed, required underpass clearance, horizontal curvature, and aesthetics.

#### **2.1.5.1 Slab**

Slab bridges are the simplest bridge structures, constructed using reinforced concrete or timber to span distances from 20 feet to about 45 feet. Longer spans are usually continuous, often with a haunch (thickened slab) over the piers. Spans up to 75 feet may be obtained if the slabs are prestressed. The slab acts as a very wide beam spanning between substructure elements. Because live loads are applied directly to their top surfaces, slab bridges (including flat slabs, haunch slabs, and rigid frames) are unique in that the superstructure is the same element as the deck.



**Figure 2.1.5.1-1:** Heavily Deteriorated Single Span Concrete Slab.



**Figure 2.1.5.1-2:** Three-Span Concrete Slab with Haunches.

### 2.1.5.2 Beam/Girder

Beam/girder bridges rely on the use of two or more primary elements acting in bending to support the deck and traffic. Beam/girder bridges are usually constructed of steel or concrete, although timber is also sometimes used.

The shortest steel bridges are typically constructed using standard hot-rolled “I” shapes, referred to as beams. Spans are generally limited to the range of 20 feet to 90 feet. Longer steel spans require deeper sections that are not produced by rolling mills. For these situations, welded, or historically bolted or riveted “I” shapes fabricated from plates are used. When a shape is built-up by welding, or historically bolting or riveting together plates and structural shapes, it is sometimes referred to as a girder instead of a beam. Still longer spans may consist of steel plates built-up into a four-sided rectangular or trapezoidal closed shape, known as a box girder. Due to the box girder’s inherent resistance to the effects of torsion, box girders are commonly used for horizontally curved spans. Box girders are capable of reaching very long span lengths.



**Figure 2.1.5.2-1:** Steel Multiple Girder Bridge.



**Figure 2.1.5.2-2:** Prestressed Concrete Multiple Girder Bridge.

Many types of concrete beam bridges exist, since concrete can be cast into many different shapes. The earliest examples are cast-in-place structures, usually of single spans. The rectangular beams and deck were typically cast simultaneously, forming “T” beams with the deck acting as the top flange. On many older structures, the fascia beams protrude above the deck. These beams are part of the superstructure and double as bridge parapets.

Prestressed concrete girders, cast at an off-site plant and delivered to the site, gained acceptance in the 1950s. By compressing the girder with steel tendons prior to the application of dead load, internal tensile stresses in the concrete are greatly reduced or eliminated. This technology has allowed concrete to span much farther than conventionally reinforced concrete. Prestressed girders come in a variety of geometric cross-sections, including “I”, “C”, “T”, “Bulb-T”, and closed box shapes.



For longer spans or horizontally curved structures, post-tensioned concrete boxes may be used. Rather than being prestressed at a plant, the girders are either cast-in-place, or segments thereof are precast at a plant and lined up to form a girder on site. Both contain ducts through which post-tensioning rods or tendons are passed. The rods/tendons are then pulled into tension, compressing the girder.

Rectangular timber beams may be either sawn or glue-laminated and are used for fairly short span bridges. Solid sawn beams are most often associated with older structures built during a time when large timber members were plentiful. To create the same size or larger beams nowadays, multiple strips of wood are glued together to build up a laminated, or glulam, member.

### 2.1.5.3 Truss

A truss is a structure whose members are arranged to form triangles. Each member is classified as either a top chord, bottom chord, vertical or diagonal. Most, but not all, trusses have vertical members. The mechanics of this arrangement is such that each member is acting as either a pure tension or pure compression member. Two parallel trusses (rarely more than two) form the main load-carrying system of a bridge superstructure. Each may be thought of as a very deep beam with holes cut into the web, the top chord acting as the top flange, and the bottom chord acting as the bottom flange. Thus, under positive bending, the top chord is in compression, and the bottom chord is in tension. The reverse is true if the truss undergoes negative bending. A truss' diagonal and vertical members usually have one end connected to the top chord and the other to the bottom chord. The diagonal members deliver the “shear” loads of the imaginary deep beam to the supports by means of tension or compression, depending on their orientation within the truss.

Truss bridges are mostly constructed using steel members, while very old trusses used timber and wrought iron. Loads are delivered to trusses by way of the deck bearing on stringers (longitudinal beams), which in turn bear on floor beams (transverse beams). The floor beams frame into the sides of the trusses, usually at the panel points. Timber trusses are used only for fairly short spans. Simply supported steel trusses were used for spans from about 100 feet upwards to 800 feet. Cantilevered and continuous spans ranged from 500 to 1,500 feet.



Figure 2.1.5.3-1: Parker Truss Bridge.



Figure 2.1.5.3-2: King Post Truss Bridge.





**Figure 2.1.5.3-3:** Pratt Truss Bridge.

#### 2.1.5.4 Arch

Arch bridges generally transmit their loads to the ground by diagonally pushing on their supports, rather than bearing vertically as with slabs, beams or trusses. To resist this push, or thrust, buttresses are built at the arch ends, or the ends are tied together with a tension member in a manner similar to an archer's bow. Arches resist a combination of compression, bending, and shear. The relative magnitude of each depends upon the shape of the arch. True arches are parabolic in shape and are subjected only to compressive forces. For practical reasons, most arches are not designed or built as true parabolas and therefore must transmit bending and shear, in addition to compression.

Tied arch bridges are similar to arches with one significant variant. Rather than the diagonal thrusting forces being absorbed by the foundations, tied arches transfer the outward thrusting force to ties that run from one end of the arch to the other, like the string in an archer's bow. The ties are entirely in tension. The tied arch foundations, therefore, only carry the dead and transient loads.

Arches have been used for a wide range of bridge spans, from under 50 feet up to 1,700 feet. Almost all types of construction materials have been used to build arches, including stone masonry, wood, cast iron, steel, and concrete. They may be comprised of two or more parallel ribs or of a single curved member called a barrel. Arch ribs can be constructed with steel, concrete, or wood. Usually, only stone masonry and concrete are used to form barrel arches.

The space between the flat deck and curved arch is called the spandrel. Open spandrel arches use columns placed within the spandrel to transfer the live loads and deck dead loads to the arch ribs. Closed spandrel arches usually use earth fill retained by spandrel walls to transfer the live loads and deck dead loads to barrels. Other closed spandrels do not use earth fill, but leave the spandrel unfilled or vaulted. Deck live and dead loads are delivered to the barrel by way of the spandrel and interior walls.

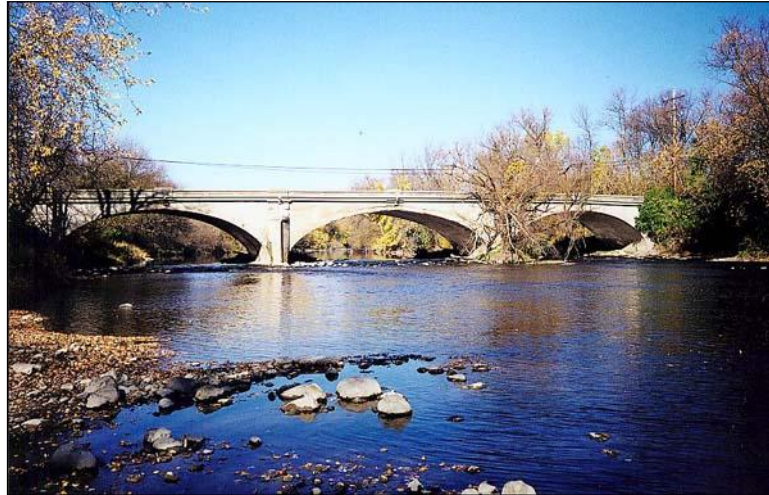


Figure 2.1.5.4-1: Closed Spandrel Concrete Arch Bridge.



Figure 2.1.5.4-2: Steel Open Spandrel Arch.

### 2.1.5.5 Rigid Frame

Rigid frames are similar to arches in that they transmit their loads to the ground by diagonally pushing on their supports. However, since they consist of horizontal members rigidly connected to the tops of inclined members, they have the advantage of reducing span length

while allowing more head clearance for traffic traveling underneath. Rigid frames primarily resist bending and shear forces, with compression loads occurring mostly in the vertical or slanted legs.

Only steel and concrete are used for rigid frame bridge construction. Steel rigid frames are usually multi-span structures known as “K-frames”, with main spans ranging from 50 feet to 200 feet. They are built of welded plate girder construction and require a minimum of two frames placed parallel to the roadway to carry the deck and live loads. Concrete rigid frames can be built as single or multi-span structures, with a main span of each up to 50 feet in length. Single span concrete rigid frames are commonly slab type structures, similar to barrel arches. Multi-span bridges are usually built of multiple frames similar to steel rigid frames.



**Figure 2.1.5.5-1:** Steel Rigid Frame.

#### 2.1.5.6 Cable-Stayed

Cable stayed bridges have superstructures supported by diagonal cable tension members. Each cable stay is connected to a pylon (tower) located at the main pier. Superstructures may be built of steel or concrete.



**Figure 2.1.5.6-1:** Cable-Stayed Pedestrian Bridge.

The cable stays act as spring supports, causing the superstructure to act as a multi-span bending member. Since the cables are sloped relative to the roadway, the cable stays also introduce compressive forces into the superstructure. Compression forces are also introduced into the pylon at each cable stay connection point. Because of the possible unequal live loading from span to span, variable cable stay forces also cause the pylon to bend. Back stay cables, either anchored to the approach spans or anchorage block on land, help to balance the forces of the main span cables, thereby minimizing pylon bending.

Cable stayed bridges are not very common in Wisconsin. Currently, there are only a handful of structures that are used as either pedestrian bridges or vehicular bridges. When used for highway bridges, they can be used for spans from 200 feet to 2,000 feet.

### 2.1.5.7 Suspension

Suspension bridges are uncommon in Wisconsin, currently existing only for pedestrian structures. When used for highway bridges, suspension bridges can span distances in excess of 1,800 feet. They use vertical cable hangers to suspend the superstructure from two or more main cables. The main cables are draped over towers and terminate at heavy anchor blocks. The main suspension cables can have diameters exceeding 3 feet for long roadway spans. The main cables exert large compressive loads on the tops of the towers and may introduce some bending due to unequal live loading from span to span.

The distance between adjacent hanger cables is relatively small, and therefore only a relatively shallow superstructure is required for strength. However, this results in a very flexible structure, giving rise to large deflections. Because of this, deep stiffening trusses, girders, or box girders are normally used to more evenly distribute the live loads among the hangers, thereby reducing deflections. Stiffening trusses and girders for highway suspension bridges are normally built of steel.



**Figure 2.1.5.7-1:** Pedestrian Suspension Bridge.