PDHonline Course S206 (8 PDH)

Bridge and Culvert Basics

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2012

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Bridge and Culvert Basics

1.1 Introduction

A bridge engineer must be familiar with the terminology and elementary theory of bridge mechanics and materials. This course presents the terminology needed to properly identify and describe the individual elements that comprise a bridge. First the major components of a bridge are introduced. Then the basic member shapes and connections of the bridge are presented ending with the purpose and function of the major bridge components are described in detail.

1.2 NBIS Structure Length

According to the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* the minimum length for a structure carrying traffic loads is 20 feet. The structure length is measured as shown on Figure 1.1

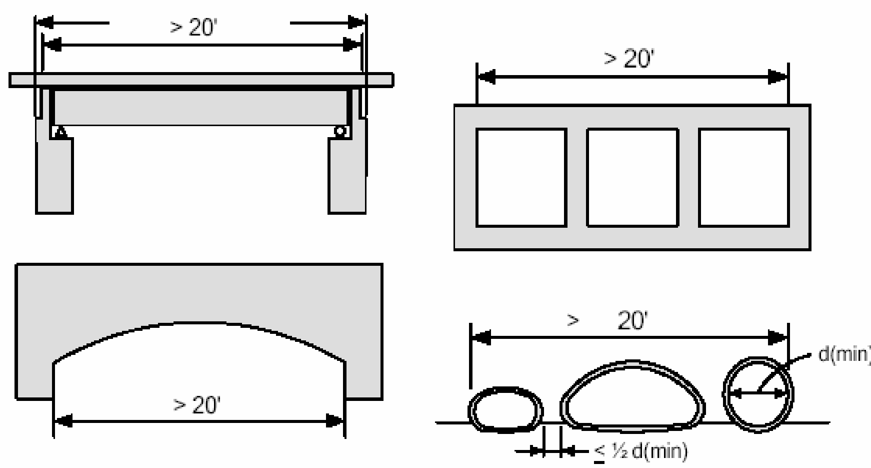


Figure 1.1 NBIS Structure Length

23 CFR Part 650.305 Definitions gives the definition of a bridge as it applies to the NBIS regulations. From the NBIS regulations, a bridge is defined as follows: a structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet between undercopings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes; it may also include multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening

1.3 Major Bridge Components

A thorough and complete design is dependent upon the bridge engineer's ability to identify and understand the function of the major bridge components and their elements. Most bridges can be divided into three basic parts or components (see Figure 1.1A):

- Deck
- Superstructure
- Substructure

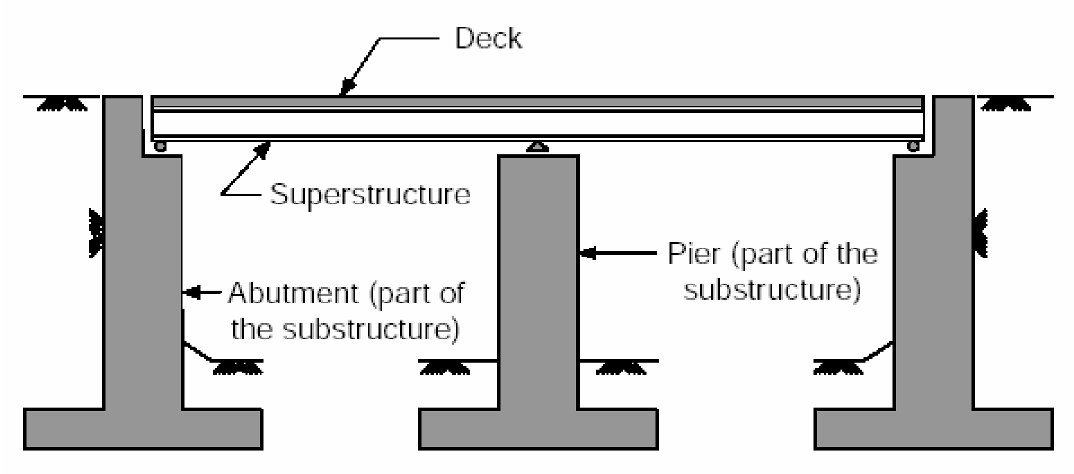


Figure 1.1A Major Bridge Components

1.4 Basic Member Shapes

The ability to recognize and identify basic member shapes requires an understanding of the timber, concrete, and steel shapes used in the construction of bridges

Every bridge member is designed to carry a unique combination of tension, compression, and shear. These are considered the three basic kinds of member stresses. Bending loads cause a combination of tension and compression in a member. Shear stresses are caused by transverse forces exerted on a member. Therefore, certain shapes and materials have distinct characteristics in resisting the applied loads. For a review of bridge loadings and member responses, see section 2.

Timber Shapes

Timber members are found in a variety of shapes (see Figure 1.2). The sizes of timber members are generally given in nominal dimensions (such as in Figures 1.2 and 1.3). However, timber members are generally seasoned and surfaced from the rough sawn condition, making the actual dimension about 1/2 to 3/4 inches less than the nominal dimension.

The physical properties of timber enable it to resist both tensile and compressive stresses. Therefore, it can function as an axially-loaded or bending member. Timber bridge members are made into three basic shapes:

- Planks
- Beams
- Piles

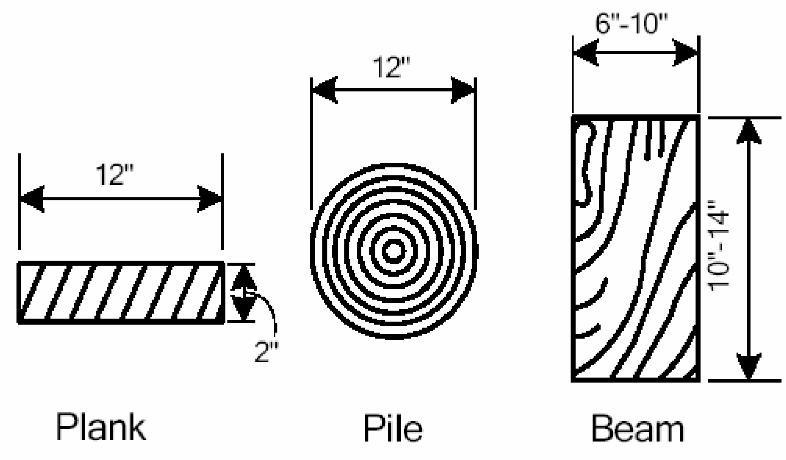


Figure 1.2 Timber Shapes

Planks

Planks are characterized by elongated, rectangular dimensions determined by the intended bridge use. Plank thickness is dependent upon the distance between the supporting points and the magnitude of the vehicle load. A common dimension for timber planks is a 2" x 12", nominal or rough sawn. Dressed lumber dimensions would be 1 1/2" x 11 1/4" (see Figure 1.2).

Planks are most often used for bridge decks on bridges carrying light or infrequent truck traffic. While some shapes and materials are relatively new, the use of timber plank decks has existed for centuries. Timber planks are advantageous in that they are economical, lightweight, readily available, and easy to erect.

Beams

Timber beams have more equal rectangular dimensions than do planks, and they are sometimes square. Common dimensions include 10 inches by 10 inches square timbers, and 6 inches by 14 inches rectangular timbers.

As the differences in the common dimensions of planks and timber beams indicate, beams are larger and heavier than planks and can support heavier loads, as well as span greater distances. As such, timber beams are used in bridge superstructures and substructures to carry bending and axial loads.

Timbers can either be solid sawn or glued-laminated. Glued-laminated timbers are advantageous in that they can be fabricated from smaller, more readily available pieces. Glued lamination also allows larger rectangular members to be formed without the presence of natural defects such as knots. Glued-laminated timbers are normally manufactured from well-seasoned laminations and display very little shrinkage after they are fabricated.

Piles

Timber can also be used for piles. Piles are normally round, slender columns that support the substructure footing or partially form the substructure. Piles may be partially above ground or completely buried.

Concrete Shapes

Concrete is a unique material for bridge members because it can be formed into an infinite variety of shapes. Concrete members are used to carry axial and bending loads. Since bending results in a combination of compressive and tensile stresses, concrete bending members are typically reinforced with either reinforcing steel (producing reinforced concrete) or with prestressing steel (producing prestressed concrete) in order to carry the tensile stresses in the member.

Cast-in-Place Flexural Shapes

The most common shapes of reinforced concrete members are (see Figure 1.3):

- Slabs/Decks
- Rectangular beams
- Tee beams
- Channel beams

Bridges utilizing these shapes and mild steel reinforcement have been constructed and were typically cast-in-place (CIP). Many of the designs are obsolete, but the structures remain in service. Concrete members of this type are used for short and medium span bridges.

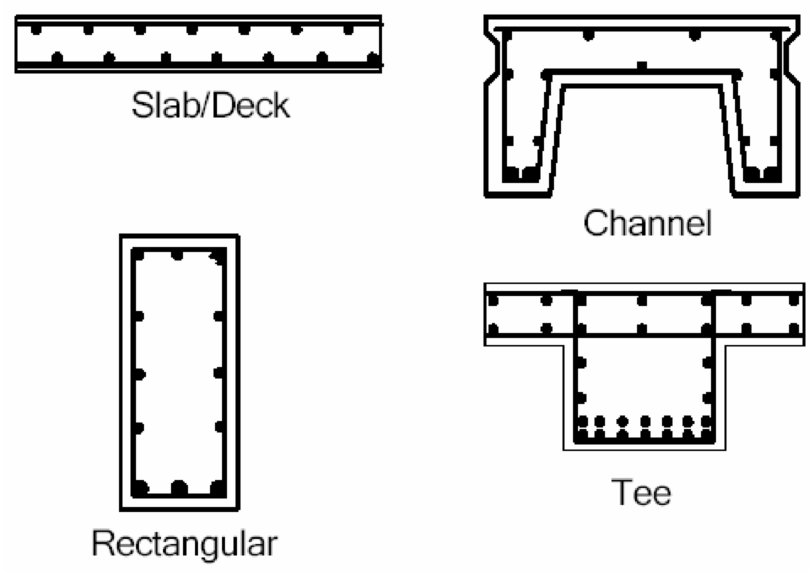


Figure 1.3 Reinforced Concrete Shapes

Concrete slabs are used for concrete decks and slab bridges. On concrete decks, the concrete spans the distance between superstructure members and is generally 7 to 9 inches thick. On slab bridges, the slab spans the distance between piers or abutments, forming an integral deck and superstructure. Slab bridge elements are usually 12 to 24 inches thick.

Rectangular beams are used for both superstructure and substructure bridge elements. Concrete pier caps are commonly rectangular beams which support the superstructure.

Bridge use for tee beams is generally limited to superstructure elements. Distinguished by a "T" shape, tee beams combine the functions of a rectangular beam and slab to form an integral deck and superstructure.

Bridge use for channel beams is limited to superstructure elements. This particular shape is precast rather than cast-in-place. Channel beams are formed in the shape of a "C" and placed legs down when erected. They function as both superstructure and deck and are typically used for shorter span bridges.

Precast Flexural Shapes

The most common shapes of prestressed concrete members are (see Figure 1.4):

- I-beams
- Bulb-tees
- Box beams
- Box girders
- Voided slabs

These shapes are used for superstructure members.

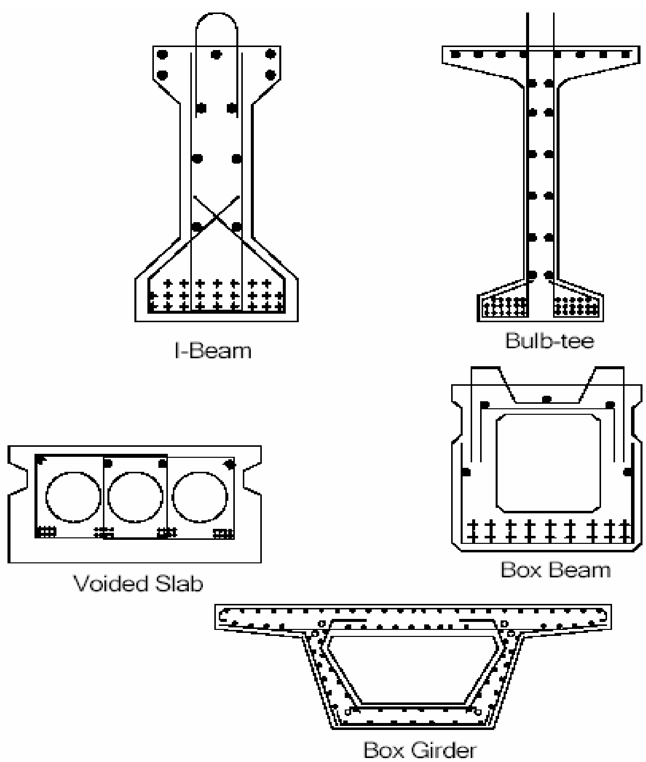


Figure 1.4 Prestressed Concrete Shapes

Prestressed concrete beams can be precast at a fabricator's plant using high compressive strength concrete. Increased material strengths, more efficient shapes, the prestress forces and closely controlled fabrication allow these members to carry greater loads. Therefore, they are capable of spanning greater distances and supporting heavier live loads. Bridges using members of this type and material have been widely used in the United States since World War II.

Prestressed concrete is generally more economical than conventionally reinforced concrete because the prestressing force lowers the neutral axis, putting more of the concrete section into compression. Also, the prestress steel is very high strength, so fewer pounds of steel are needed (see Figure 1.5).

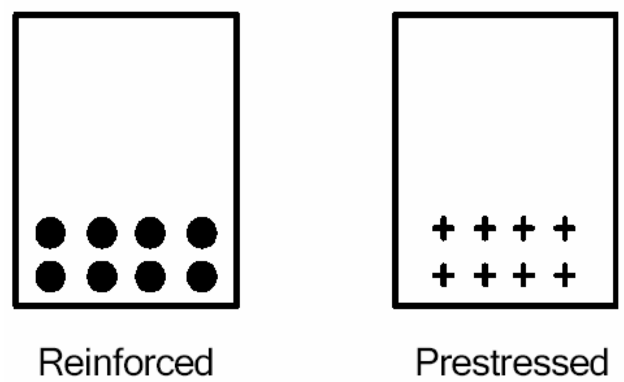


Figure 1.5 Mild Steel Reinforced Concrete vs. Precast Prestressed Concrete

I-beams, distinguished by their "I" shape, function as superstructure members and support the deck. This type of beam can be used for spans as long as 150 feet.

Bulb-tee beams are distinguished by their "T" shapes, with a bulb-shaped section (similar to the bottom flange of an I-beam) at the bottom of the vertical leg of the tee. This type of beam can be used for spans as long as 180 feet.

Box beams, distinguished by a square or rectangular shape, usually have a beam depth greater than 17 inches. Box beams can be adjacent or spread, and they are typically used for short and medium span bridges.

Box girders, distinguished by their trapezoidal or rectangular box shapes, function as both deck and superstructure. Box girders are used for long span or curved bridges and can be precast and erected in segments or cast in place.

Voided slabs, distinguished by their rectangular shape and their interior voids, are generally precast units supported by the substructure. The interior voids are used to reduce the dead load. Voided slabs can be used for spans of 30 to 80 feet.

Axially-Loaded Compression Members

Concrete axially-loaded compression members are used in bridges in the form of:

- Columns
- Arches
- Piles

Because these members also carry varying bending forces, they contain steel reinforcement.

Columns are straight members which can carry axial load, horizontal load, and bending and are used as substructure elements. Columns are commonly square, rectangular, or round.

An arch can be thought of as a curved column and is commonly used as a superstructure element. Concrete superstructure arches are generally square or rectangular in cross section.

Piles are slender columns that support the substructure footing or partially form the substructure. Piles may be partially above ground but are usually completely buried (see Figure 1.6).

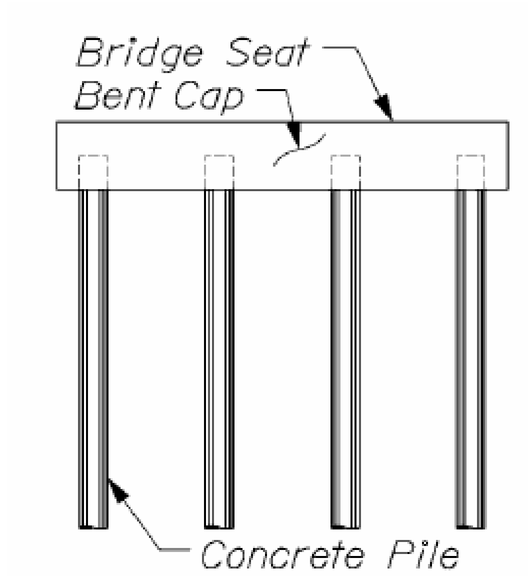


Figure 1.6 Concrete Pile Bent

Iron Shapes

Iron was used predominately as a bridge material between 1850 and 1900. Stronger and more fire resistant than wood, iron was widely used to carry the expanding railroad system during this period.

There are two types of iron members: cast iron and wrought iron. Cast iron is formed by casting, whereas wrought iron is formed by forging or rolling the iron into the desired form.

Cast Iron

Historically, cast iron preceded wrought iron as a bridge material. The method of casting molten iron to form a desired shape was more direct than that of wrought iron.

Casting allowed iron to be formed into almost any shape. However, because of cast iron's brittleness and low tensile strength, bridge members of cast iron were best used to carry axial compression loads. Therefore, cast iron members were usually cylindrical or box-shaped to efficiently resist axial loads.

Wrought Iron

In the late 1800's, wrought iron virtually replaced the use of cast iron. The two primary reasons for this were that wrought iron was better suited to carry tensile loads and advances in rolling technology made wrought iron shapes easier to obtain and more economical to use. Advances in technology made it possible to form a variety of shapes by rolling, including:

- Rods and wire
- Bars
- Plates
- Angles
- Channels
- Beams

Steel Shapes

Steel bridge members began to be used in the United States in the late 1800's and, by 1900, had virtually replaced iron as a bridge material. The replacement of iron by steel was the result of advances in steel making. These advances yielded a steel material that surpassed iron in both strength and elasticity. Steel could carry heavier loads and better withstand the shock and vibration of ever-increasing live loads. Since the early 1900's, the quality of steel has continued to improve. Stronger and more ductile A36, A572, and A588 steels have replaced early grades of steel, such as A7.

Due to their strength, steel bridge members are used to carry axial forces as well as bending forces. Steel shapes are generally either rolled or built-up.

Rolled Shapes

Rolled steel shapes commonly used on bridges include (see Figure 1.7):

- Bars and plates
- Angles
- Channels
- S Beams
- W Beams

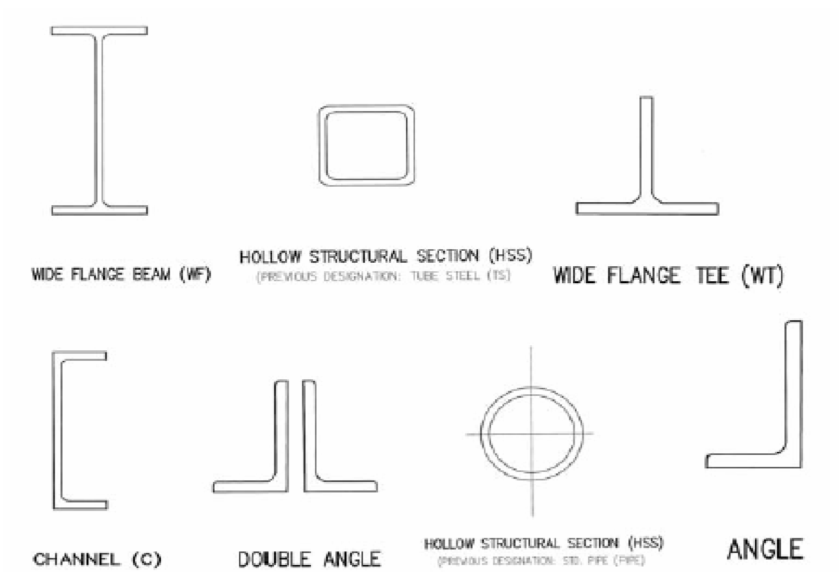


Figure 1.7 Common Rolled Steel Shapes

The standard weights and dimensions of these shapes can be found in the American Institute of Steel Construction (AISC) *Manual of Steel Construction.*

Bars and plates are formed into flat pieces of steel. Bars are normally considered to be up to 8 inches in width. Common examples of bars include lacing bars on a truss and steel eyebars. Plates are designated as flat plates if they are over 200 mm (8 inches) in width. A common example of a plate is the gusset plate on a truss. Bars and plates are dimensioned as follows: width x thickness x length. Examples of bar and plate dimensions include:

- Lacing bar: 2" x 3/8" x 1'-3"
- Gusset plate: 21" x 1/2" x 4'-4"

Angles are "L"-shaped members, the sides of which are called "legs". Each angle has two legs, and the width of the legs can either be equal or unequal. When dimensioning angles, the two leg widths are given first, followed by the thickness and the length. Examples of angle dimensions include:

- L 4" x 4" x 1/4" x 3'-2"
- 2L's 5" x 3" x 3/8" x 1'-1"

Angles range in size from 1"x1"x1/4" to 8"x8"x1-1/8". Angles range in weight from less than 1 pound per foot to almost 60 pounds per foot.

Angles, and plates are commonly connected to form bracing members (see Figure 1.8).

Channels are squared-off "C"-shaped members and are used as diaphragms, struts, or other built-up members. The top and bottom parts of a channel are called the flanges. Channels are dimensioned by the depth (the distance between outside edges of the flanges) in mm or inches, the weight in kg per m or pounds per foot, and the length in mm or inches. Examples of channel dimensions include:

- C 230 x 22 x 2895 mm (C 9 x 15 x 9'-6")
- C 310 x 31 x 3416 mm (C 12 x 20.7 x 11'-2-1/2")

When measuring a channel, it is not possible to know how much the channel section weighs. In order to determine the weight, the engineer must review the flange width and the web depth. From this information, you can then determine the true channel designation through the use of reference books.

Standard channels range in depth from 3 inches to 15 inches, and weights range from less than 5 pounds per foot to 50 pounds per foot. Nonstandard sections (called miscellaneous channels or MC) are rolled to depths of up to 24 inches, weighing up to 60 pounds per foot.

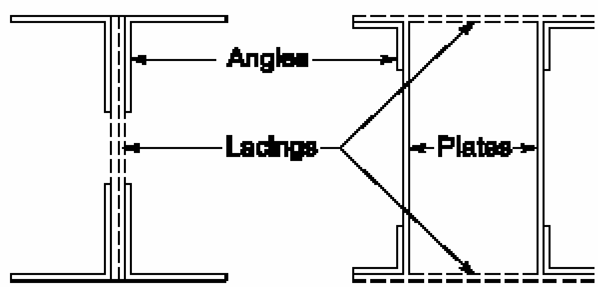


Figure 1.8 Bracing Members Made from Angles, and Plates

Beams are “I”-shaped sections used as main load-carrying members. The load-carrying capacity generally increases as the member size increases. The early days of the iron and steel industry saw the various manufacturers rolling beams to their own standards. It was not until 1896 that beam weights and dimensions were standardized when the Association of American Steel Manufacturers adopted the American Standard beam. Because of this, I-beams are referred to by many designations, depending on their dimensions and the time period in which the particular shape was rolled. Today all I-beams are dimensioned according to their depth, weight, and length.

Examples of beam dimensions include:

- S1 5x50 - an American Standard (hence the “S”) beam with a depth of 15 inches and a weight of 50 pounds per foot
- W18x76 - a wide (W) flange beam with a depth of 18 inches and a weight of 76 pounds per foot

Some of the more common designations for rolled I-beams are:

- S = American Standard beam
- W = Wide flange beam
- WF = Wide flange beam
- CB = Carnegie beam
- M = Miscellaneous beam
- HP = H-pile

When determining the size of an I-beam, the engineer needs to measure the depth, the flange width and thickness, and the web thickness (if possible). With this information, you can then determine the beam designation from reference books.

These beams normally range in depth from 3 to 36 inches and range in weight from 6 to over 300 pounds per foot. There are some steel mills that can roll beams up to 44 inches deep.

Built-up Shapes

Built-up shapes offer a great deal of flexibility in designing member shapes. As such, they allow the bridge engineer to customize the members to their use. Built-up shapes are fabricated by either riveting or welding techniques.

The practice of riveting steel shapes began in the 1800's and continued through the 1950's. Typical riveted shapes include girders and boxes.

Riveted girders are large I-beam members fabricated from plates and angles. These girders were fabricated when the largest rolled beams were still not large enough as required by design (see Figure 1.9).

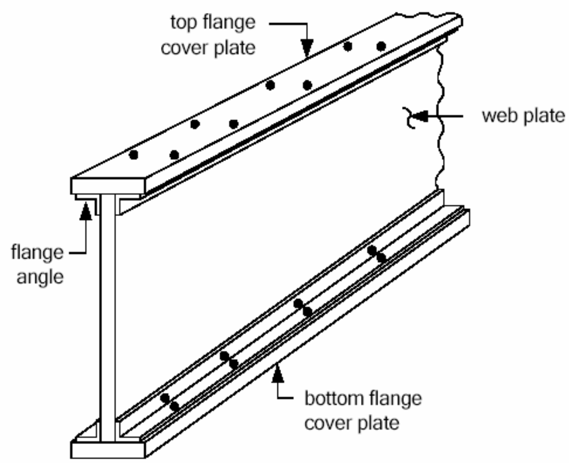


Figure 1.9 Riveted Plate Girder

Riveted boxes are large rectangular shapes fabricated from plates, angles, or channels. These boxes are used for cross-girders, truss chord members, and substructure members (see Figure 1.10).

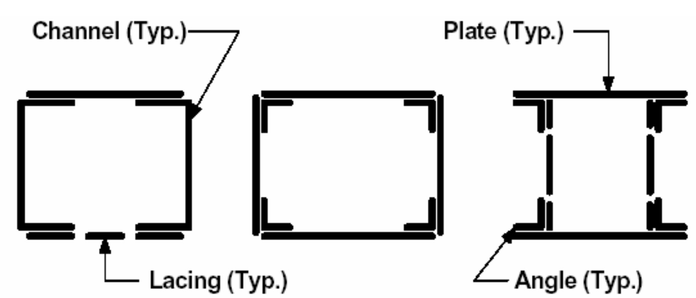


Figure 1.10 Riveted Box Shapes

As technology improved, the need for riveting was replaced by high strength bolts and welding. Popular since the early 1960's, welded steel shapes also include girders and boxes.

Welded girders are large I-beam members fabricated from plates. They are referred to as welded plate girders and have replaced the riveted girder (see Figure 1.11).

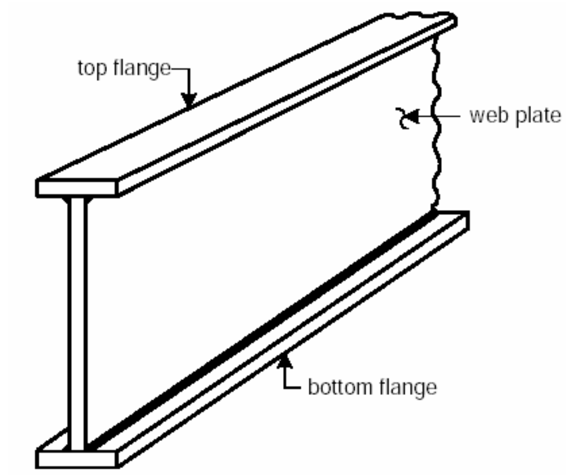


Figure 1.11 Welded I-Beam

Welded boxes are large, rectangular-shaped members fabricated from plates.

Welded boxes are commonly used for superstructure girders, truss members, and cross girders. Welded box shapes have replaced riveted box shapes (see Figure 1.12).

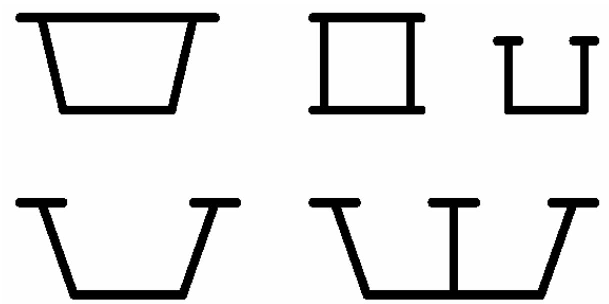


Figure 1.12 Welded Box Shapes

Cables

Steel cables are tension members and are used in suspension, tied-arch, and cable-stayed bridges. They are used as main cables and hangers of these bridge types (see Figure 1.13).

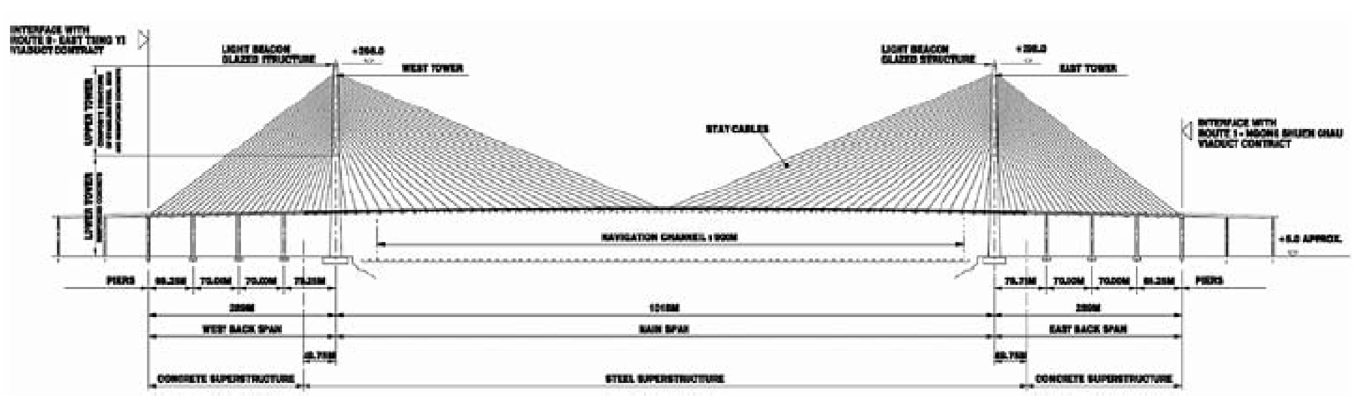


Figure 1.13 Cable-Supported Bridge

1.5 Connections

Rolled and built-up steel shapes are used to make stringers, floor beams, girders, and truss members. These members require structural joints, or connections, to transfer loads between members. There are several different types of bridge member connections:

- Pin connections
- Riveted connections
- Bolted connections
- Welded connections
- Pin and hanger connections
- Splice connections

Pin Connections

Pins are cylindrical beams produced by forging, casting, or cold-rolling. The pin sizes and configurations are as follows (see Figure 1.14):

- A small pin, 1-1/4 to 4 inches in diameter, is usually made with a cotter pin hole at one or both ends
- A medium pin, up to 10 inches in diameter, usually has threaded end projections for recessed retainer nuts
- A large pin, over 10 inches in diameter, is held in place by a recessed cap at each end and is secured by a bolt passing completely through the caps and pin

Pins are often surrounded by a protective sleeve, which may also act as a spacer to separate members. Pin connections are commonly used in eyebar trusses, hinged arches, pin and hanger assemblies, and bearing supports (see Figure 1.15).

The major advantages of using pin connection details are the design simplicity and the ability for free end rotation. The design simplicity afforded by pin connections reduces the amount and complexity of design calculations. By allowing for free end rotation, pin connections reduce the level of stress in the member.

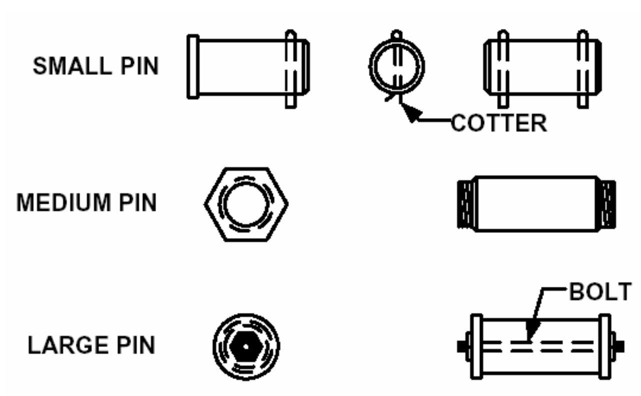


Figure 1.14 Sizes of Bridge Pins

The major disadvantages of pin connection details are the result of vibration, pin wear, unequal eyebar tension, unseen corrosion, and poor inspectability. Vibrations increase with pin connections because they allow more movement than more rigid types of connections. As a result of increased vibration, moving parts are subject to wear.

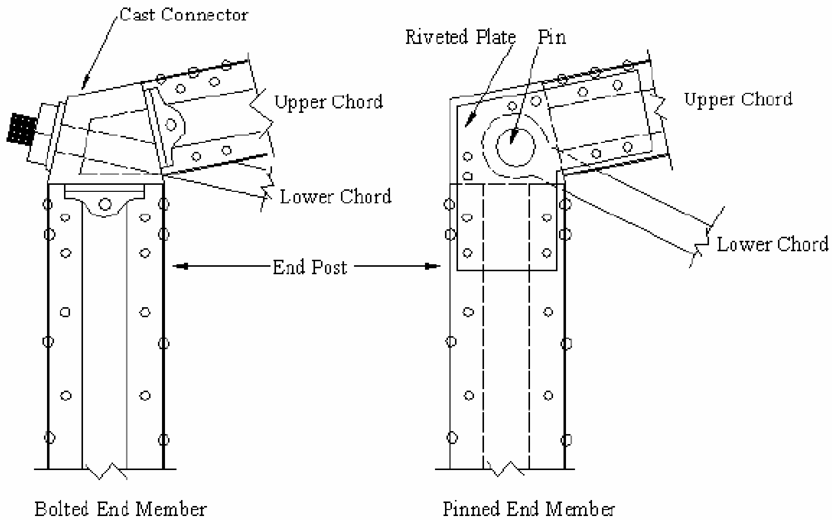


Figure 1.15 Bolted and Pin Connected Truss Members

Pin connections are used both in trusses and at expansion joints. Both truss and girder suspended spans or cantilever joints that permit expansion are susceptible to freezing or fixity of the pinned joints. This results in changes in the structure and undesirable stresses when axially-loaded members become bending members.

Some pins connect multiple eyebars. Since the eyebars may have different lengths, they may experience different levels of tension.

Riveted Connections

The rivet was the primary fastener used in the early days of iron and steel bridges.
The use of high strength bolts replaced rivets by the early 1960's.

The standard head is called a high-button or acorn-head rivet. Flat-head and countersunk-head rivets were also used in areas of limited clearance, such as an eyebar pin connection (see Figure 1.16).

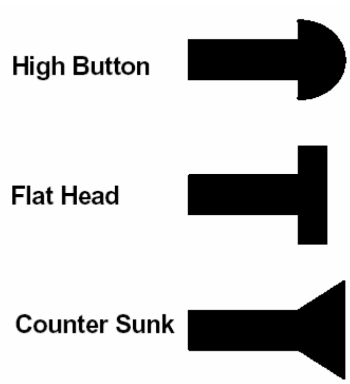


Figure 1.16 Types of Rivet Heads

There are two grades of rivets typically found on bridges:

- ASTM A502 Grade 1 (formerly ASTM A141) low carbon steel
- ASTM A502 Grade 2 (formerly ASTM A 195) high strength steel

The rivet sizes most often used on bridges were 3/4, 7/8, or 1- inch shank diameters. Rivet holes were generally 2 mm (1/16-inch) larger than the rivet shank. While the hot rivet was being driven, the shank would increase slightly, filling the hole. As the rivet cooled, it would shrink in length, clamping together the connected elements.

When there is a vibration on one head of the rivet while hitting the other rivet head with a hammer, this generally indicates that the rivet is loose. This method may not work with sheared rivets clamped between several plates.

Bolted Connections

Research into the use of high strength bolts began in 1947. The first specifications for the use of bolts were subsequently published in 1951. The economic and structural advantages of bolts over rivets led to their rapid use by bridge engineers. Bridges constructed in the late 1950's may have a combination of riveted (shop) and bolted (field) connections (see Figure 1.17).

Structural bolts consist of three basic material designations:

- ASTM A307 low carbon steel
- ASTM A325M (ASTM A325 (AASHTO M 164)) high strength steel
- ASTM A490M (ASTM A490 (AASHTO M 253)) high strength alloy steel

For further information on the bolts listed above or any other material properties visit the American Society for Testing and Materials International website at: www.astm.org .

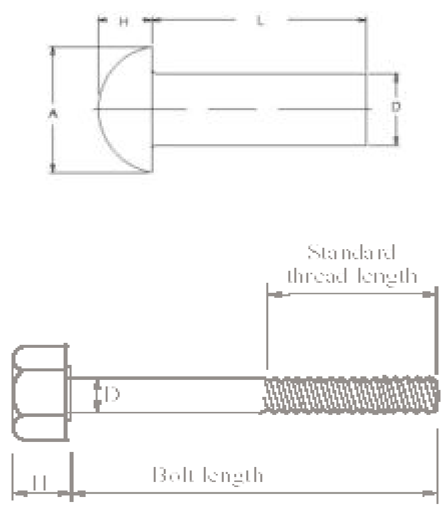


Figure 1.17 Shop Rivet and Bolt

The most commonly used bolts on bridges are 3/4, 7/8, and 1- inch in diameter. Larger bolts are often used to anchor the bearings. Bolt holes are typically 1/16-inch larger than the bolt. However, oversized and slotted holes are also permissible.

The strength of high strength bolts is measured in tension. However, the use of high strength bolts on bridges involves many variables. The installation of new high strength bolts often requires the use of a torque wrench. The torque is dependent on factors such as bolt diameter, bolt length, connection design (bearing or friction), use of washers, paint and coatings, parallelism of connected parts, dirt, rust, and corrosion.
The engineer must use standard tables and formulas relating tension to torque when determining how and where high strength bolts are to be installed.

Welded Connections

Pins, rivets, and bolts are examples of mechanical fasteners forming non-rigid joints. A welded connection is not mechanical but rather is rigid one-piece construction. A properly welded joint, in which two pieces are fused together, is as strong as the joined materials.

Similar to mechanical fasteners, welds are used to make structural connections between members and also to connect elements of a built-up member. Welds have also been used in the fabrication and erection of bridges as a way to temporarily hold pieces together prior to field riveting, bolting, or welding. Small temporary erection welds, known as tack welds, can cause serious fatigue problems to certain bridge members (see Figure 1.18). Welding is also used as a means of sealing joints and seams from moisture.

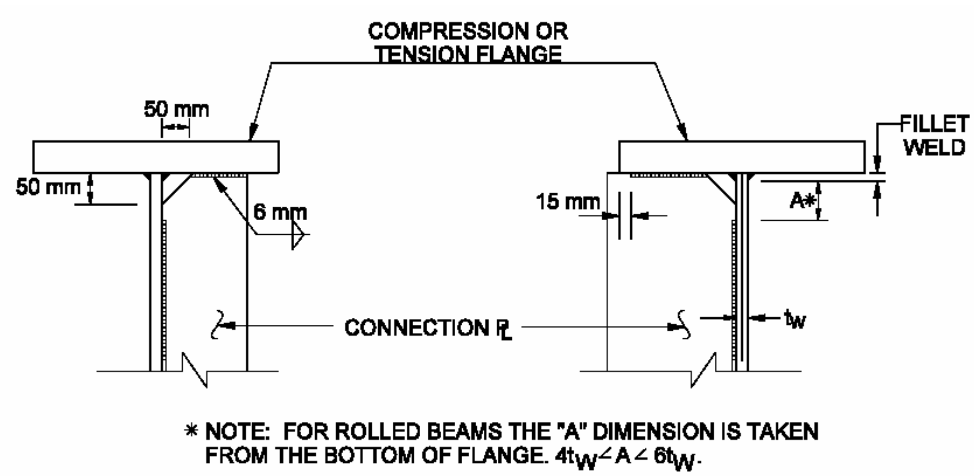


Figure 1.18 Weld on a Flange Member

Pin and Hanger Connections

The first specification for using welds on bridges appeared in 1936. Welding eventually replaced rivets for fabricating built-up members. Welded plate girders, hollow box-like truss members, and shear connectors for composite decks are just a few of the advances attributed to welding technology.

A pin and hanger connection is a type of hinge consisting of two pins and a hanger. Pin and hanger connections are used in an articulated (continuous bridge with hinges) or a suspended span configuration. The location of the connection varies depending on the type of bridge. In I-beam bridges, a hanger is located on either side of the webs (see Figure 1.19). In suspended span truss bridges, each connection has a hanger which is similar in shape to the other truss members (with the exception of the pinned ends).

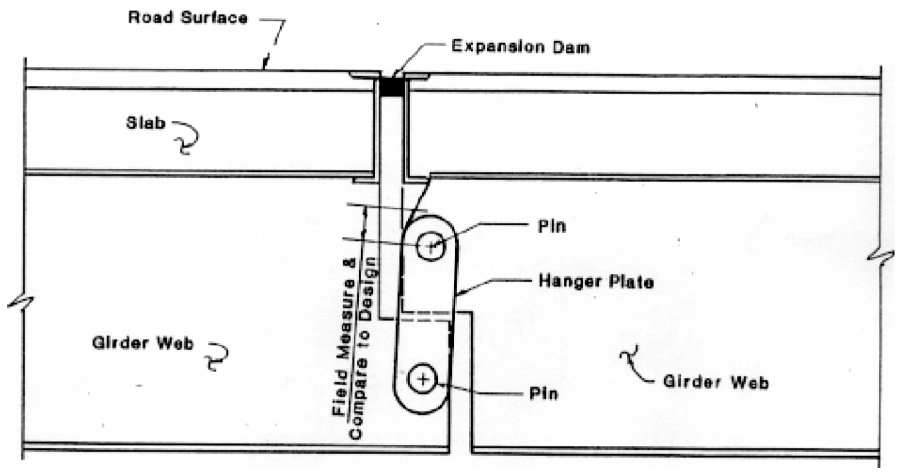


Figure 1.19 Pin and Hanger Connection

Pin and hanger connections must be carefully installed. A potential problem can occur if corrosion of the pin and hanger causes the connection to "freeze," inhibiting free rotation.

This condition does not allow the pin to rotate and results in additional stresses in the pin and hanger and adjacent girder. The failure of a pin and hanger connection can cause a partial or complete failure of a bridge.

Splice Connections

A splice connection is the joining of two sections of the same member, either in the fabrication shop or in the field. This type of connection can be made using rivets, bolts, or welds. Bolted splices are common in multi-beam superstructures due to the limited allowable shipping lengths (see Figure 1.20). Welded flange splices are common in large welded plate girders as a means of fabricating the most economical section.

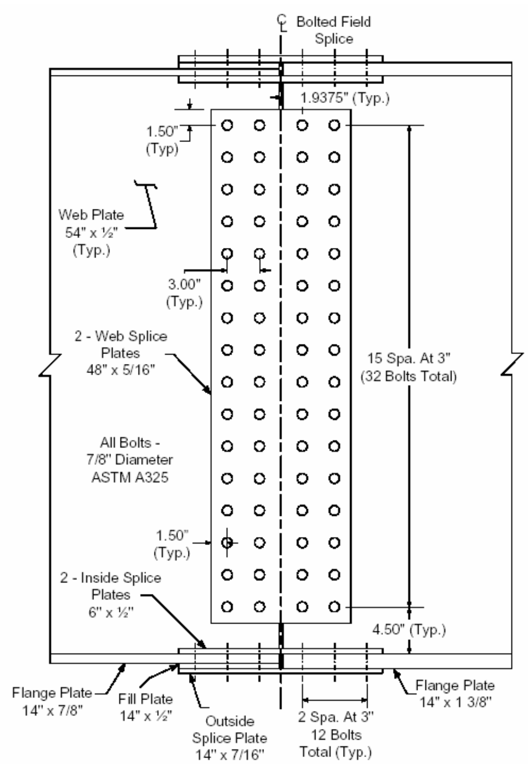


Figure 1.20 Bolted Field Splice

1.6 Decks

The deck is the component of a bridge to which the live load is directly applied.

Deck Purpose

The purpose of the deck is to provide a smooth and safe riding surface for the traffic utilizing the bridge (see Figure 1.21).

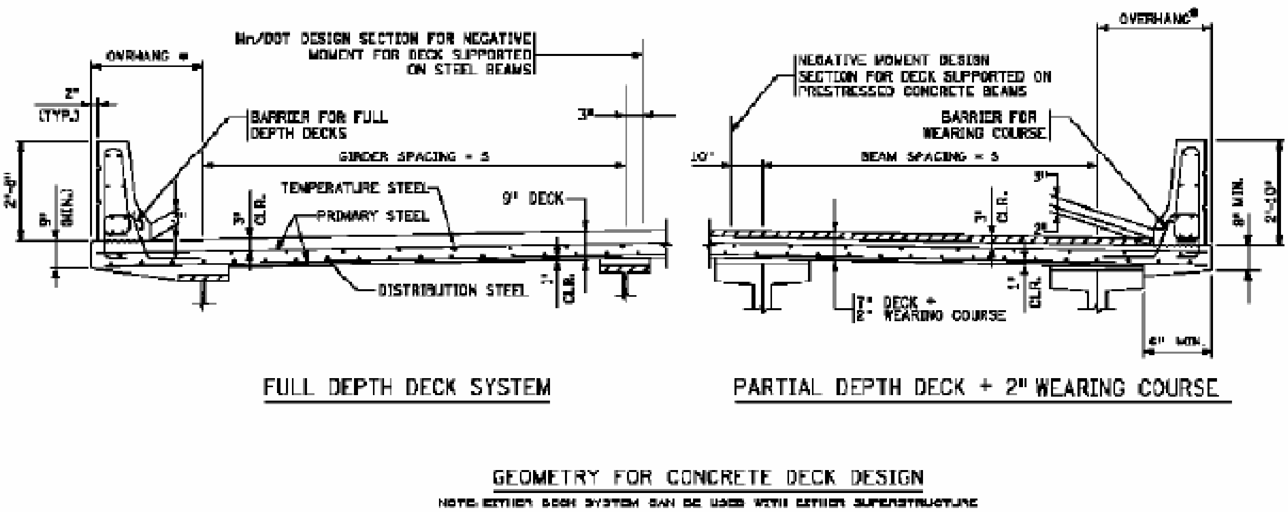


Figure 1.21 Bridge Deck with a Smooth Riding Surface

Deck Function

The function of the deck is to transfer the live load and dead load of the deck to other bridge components. In most bridges, the deck distributes the live load to the superstructure. However, on some bridges (e.g., a concrete slab bridge), the deck and superstructure are one unit which distributes the live load directly to the bridge supports.

- Composite decks - act together with their supporting members and increase superstructure capacity (see Figures 1.22)
- Non-composite decks - are not integral with their supporting members and do not contribute to structural capacity of the superstructure

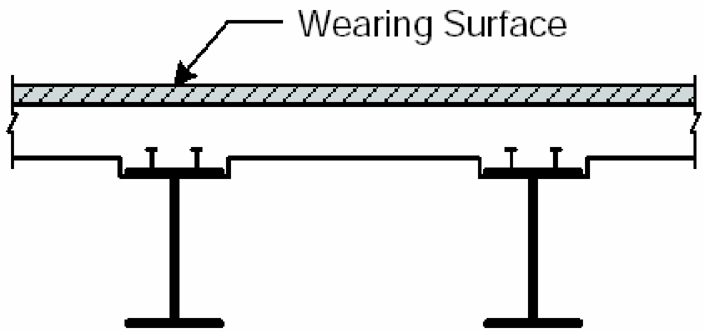


Figure P.1.22 Composite Deck and Steel Superstructure

Deck Materials

There are three common materials used in the construction of bridge decks:

- Timber
- Concrete
- Steel

Timber Decks

Timber decks are normally referred to as decking or timber flooring, and the term is limited to the roadway portion which receives vehicular loads.

Five basic types of timber decks are:

- Plank deck (see Figure 1.23)
- Nailed laminated deck
- Glued-laminated deck planks
- Stressed-laminated decks
- Structural composite lumber decks

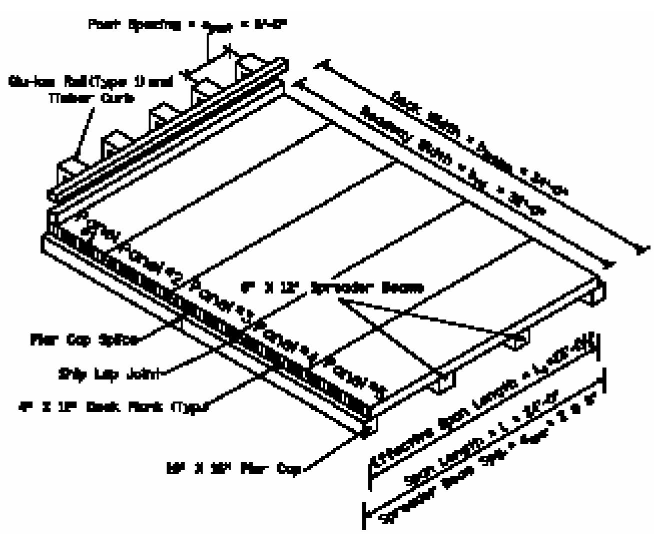


Figure 1.23 Plank Deck

Concrete Decks

Concrete permits casting in various shapes and sizes and has provided the bridge designer and the bridge builder with a variety of construction methods. Because concrete is weak in tension, it is used together with reinforcement to resist the tensile stresses (see Figure 1.21).

There are several common types of concrete decks:

- Reinforced cast-in-place (CIP) - removable or stay-in-place forms
- Precast
- Precast, prestressed deck panels
- Precast prestressed deck panels with cast-in-place topping

Steel Decks

Steel decks are decks composed of either solid steel plate or steel grids (see Figure 1.24).

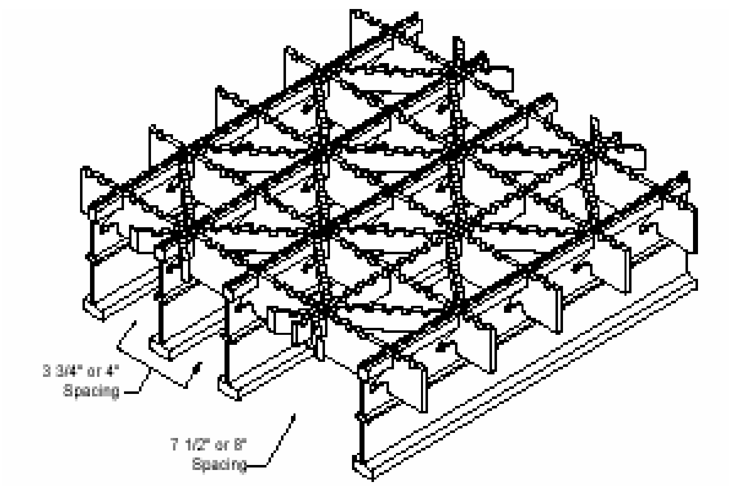


Figure 1.24 Steel Grid Deck

There are four common types of steel decks:

- Corrugated steel flooring
- Orthotropic deck
- Grid Deck - open, filled, or partially filled
- Buckle plate deck (still exist on some older bridges but are no longer used)

Fiber Reinforced Polymer (FRP) Decks

With the rise of technological development, innovative material such as carbonfiber-reinforced polymer (FRP) bridge decking has begun replacing existing highway bridge decks. Though FRP material is more expensive than conventional bridge materials such as concrete, it has several other advantages. These include lighter weight for efficient transport, better resistance to earthquakes, and easier installation. FRP bridge decking is also not affected by water or de-icing salts, which corrode steel and deteriorate concrete (see Figure 1.25).

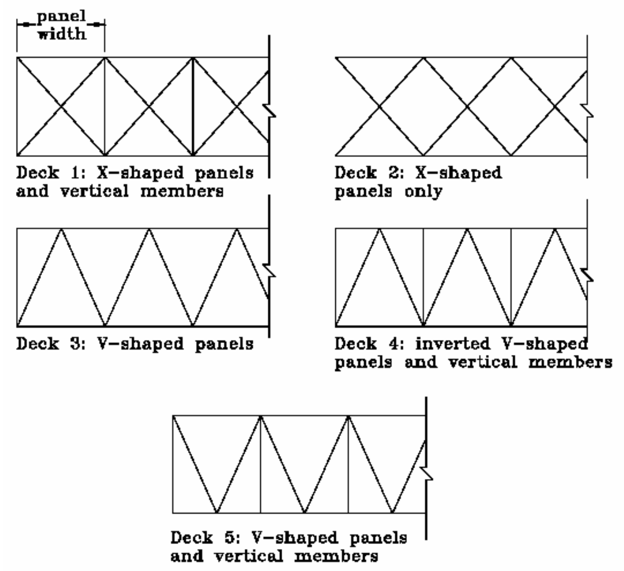


Figure 1.25 Fiber Reinforced Polymer (FRP) Decks

Wearing Surfaces

Constant exposure to the elements makes weathering a significant cause of deck deterioration. In addition, vehicular traffic produces damaging effects on the deck surface. For these reasons, a wearing surface is often applied to the surface of the deck. The wearing surface is the topmost layer of material applied upon the deck to provide a smooth riding surface and to protect the deck from the effects of traffic and weathering.

A timber deck may have one of the following wearing surfaces:

- Timber planks
- Asphalt/Bituminous

Concrete decks may have wearing surfaces of:

- Concrete
- Latex modified concrete (LMC)
- Low slump dense concrete (LSDC)
- Asphalt or bituminous (see Figure 1.26)
- Epoxy overlay with broadcast aggregate

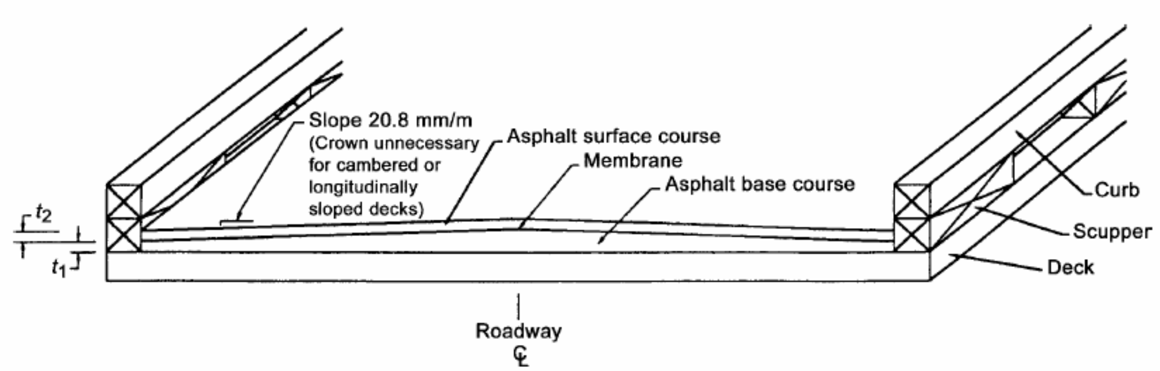


Figure 1.26 Asphalt Wearing Surface on a Concrete Deck

Steel decks may have wearing or riding surfaces of:

- Serrated steel
- Concrete
- Asphalt

Deck Joints, Drainage, Appurtenances, Signing and Lighting

Deck Joints

The primary function of a deck joint is to accommodate the expansion, contraction, and rotation of the superstructure. The joint must also provide a smooth transition from an approach roadway to a bridge deck, or between adjoining segments of bridge deck.

There are two major categories of deck joints:

- Open joints
- Closed joints

Open Joints

Open joints allow water and debris to pass through them. There are two types of unsealed joints:

- Formed joints
- Plate joints (see Figure 1.27)

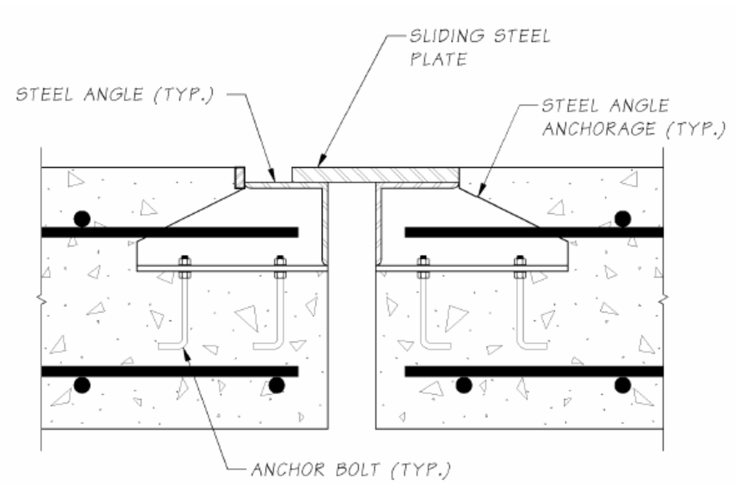


Figure 1.27 View of a Plate Joint

Closed Joints

Closed joints are designed so water and debris do not pass through them. There are seven types of closed joints:

- Poured joint seal
- Compression seal (see Figure 1.28)
- Cellular seal (closed cell foam)
- Sliding plate joint
- Prefabricated elastomeric seal – plank, sheet, or strip seal (see Figure 1.29)
- Modular elastomeric seal
- Asphaltic expansion joint

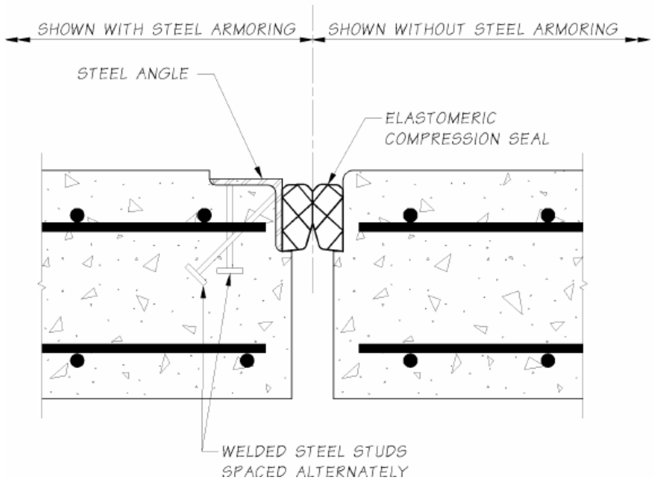


Figure 1.28 View of an Compression Seal

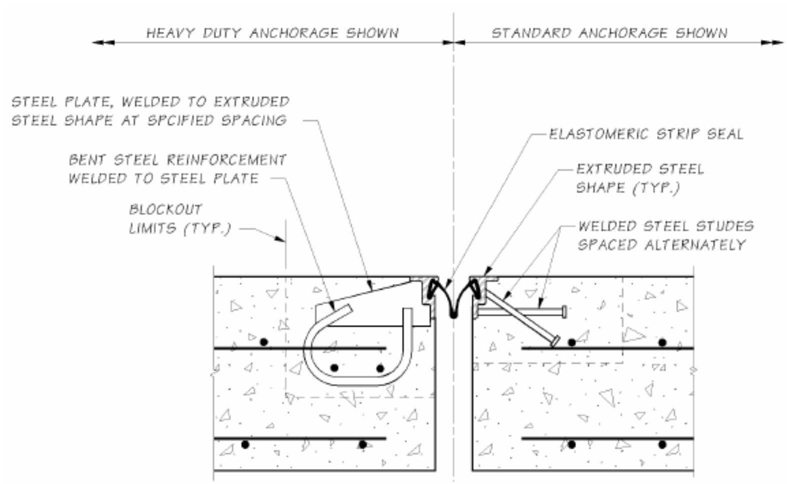


Figure 1.29 Strip Seal

Drainage Systems

The primary function of a drainage system is to remove water from the bridge deck, from under unsealed deck joints and from behind abutments and wingwalls.

Deck Drainage System

A deck drainage system has the following components:

- Deck drains (see figure 29A)
- Outlet pipes - to lead water away from drain
- Downspouts pipes - to transport runoff to storm sewers
- Cleanout plugs - for maintenance

Joint Drainage System

A joint drainage system is typically a separate gutter or trough used to collect water passing through a finger plate or sliding plate joint.

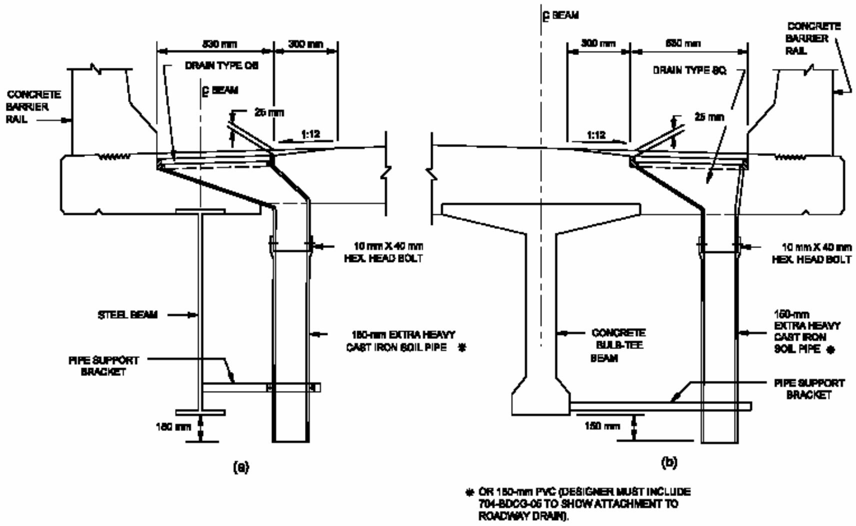


Figure 1.29A Deck drain

Combining all these drainage components forms a complete deck drainage system. Substructure Drainage Systems Substructure drainage allows the fill material behind an abutment or wingwall to drain any accumulated water. Substructure drainage is accomplished with weep holes or substructure drain pipes.

Deck Appurtenances

The proper and effective use of deck appurtenances minimizes hazards for traffic on the highways as well as waterways beneath the bridge.

Bridge Barriers

Bridge barriers can be broken down into two categories:

- Bridge railing - to guide, contain, and redirect errant vehicles
- Pedestrian railing - to protect pedestrians

Examples of railing include:

- Timber plank rail
- Steel angles and bars
- Concrete pigeon hole parapet
- Combination bridge-pedestrian aluminum or steel railing
- New Jersey barrier - a very common concrete barrier (see Figure 1.30)

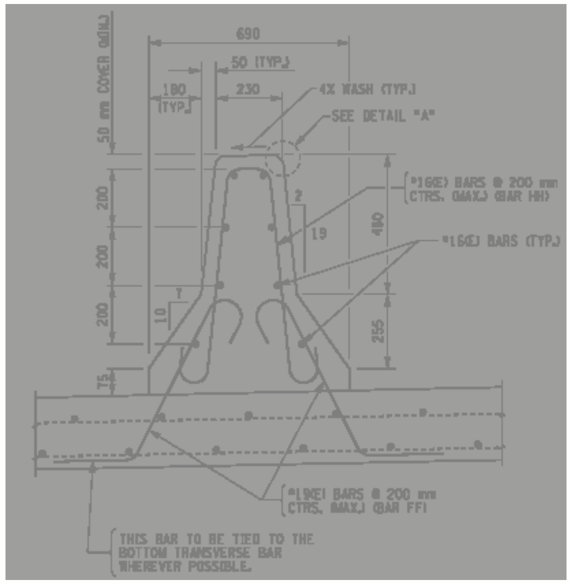


Figure 1.30 New Jersey Barrier

Sidewalks and Curbs

The function of sidewalks and curbs is to provide access to and maintain safety for pedestrians. Curbs serve to lessen the chance of vehicles crossing onto the sidewalk and endangering pedestrians.

Signing

Signing serves to inform the motorist about bridge or roadway conditions that may be hazardous.
Several signs likely to be encountered are:

- Weight limit (see Figure 1.31)
- Speed traffic marker
- Vertical clearance
- Lateral clearance
- Narrow underpass

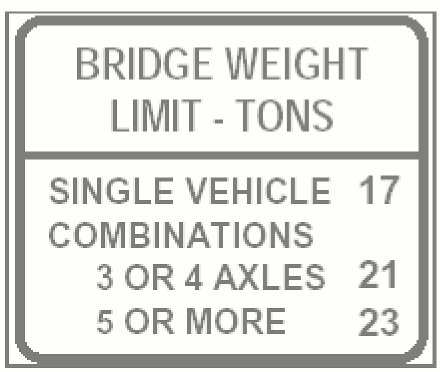


Figure 1.31 Weight Limit Sign

Lighting

Types of lighting that may be encountered on a bridge include the following (see Figure 1.32):

- Highway lighting
- Traffic control lights
- Aerial obstruction lights
- Navigation lights
- Signing lights

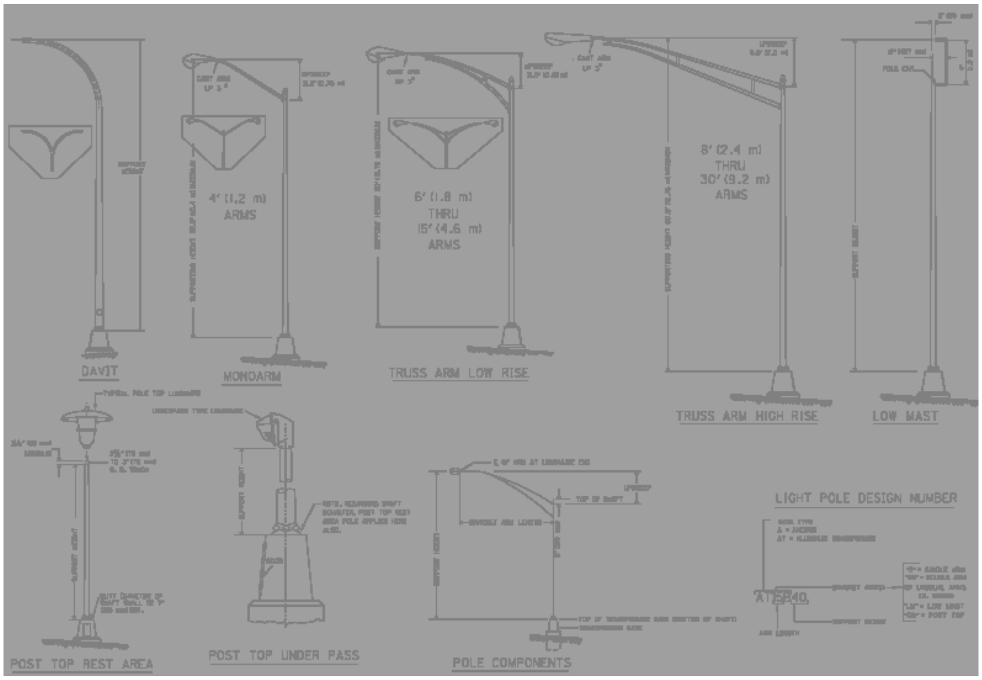


Figure 1.32 Bridge Lighting

1.7 Superstructure

Superstructure Purpose

The basic purpose of the superstructure is to carry loads from the deck across the span and to the bridge supports. The superstructure is that component of the bridge which supports the deck or riding surface of the bridge, as well as the loads applied to the deck.

Superstructure Function

The function of the superstructure is to transmit loads. Bridges are named for their type of superstructure. Superstructures may be characterized with regard to their function (i.e., how they transmit loads to the substructure). Loads may be transmitted through tension, compression, bending, or a combination of these three.

There are three common materials used in the construction of bridge superstructures:

- Timber
- Concrete

- Steel

Primary Elements

Most superstructures are made up of two basic elements:

- Floor system - Receives traffic loads from the deck and distributes them to the main supporting elements (see Figure 1.33)
- Main supporting elements - Transfer all loads to the substructure units

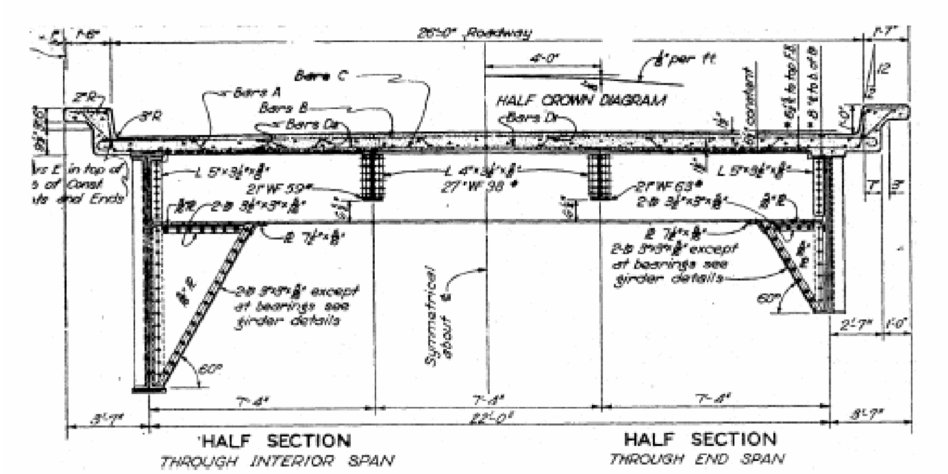


Figure 1.33 Floor System

Secondary Elements

Secondary elements are elements which do not normally carry traffic loads directly. Typical secondary elements are:

- Diaphragms
- Cross or X-bracing
- Lateral bracing
- Sway-portal bracing

Superstructure Types

There are three basic types of bridges (see Figure 1.34):

- Beam
- Arch
- Cable-supported

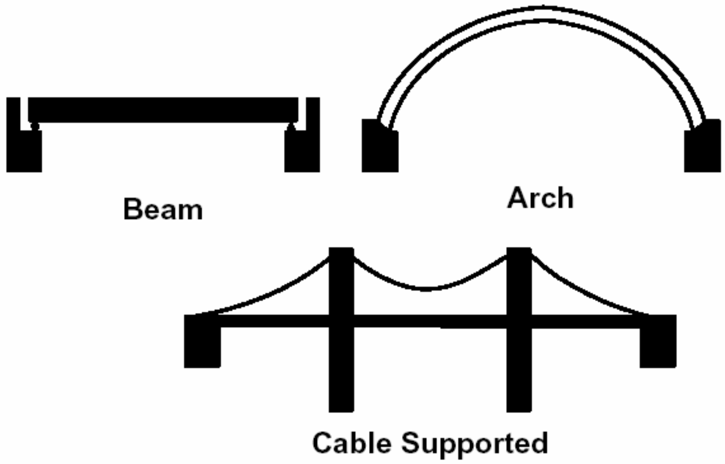


Figure 1.34 Three Basic Bridge Types

Beam Bridges

In the case of beam bridges, loads from the superstructure are transmitted vertically to the substructure.

Examples of beam bridges include:

- Slabs (concrete) (see Figure 1.35)
- Beams (timber, concrete, or steel)
- Girders (concrete or steel)
- Trusses (timber or steel)

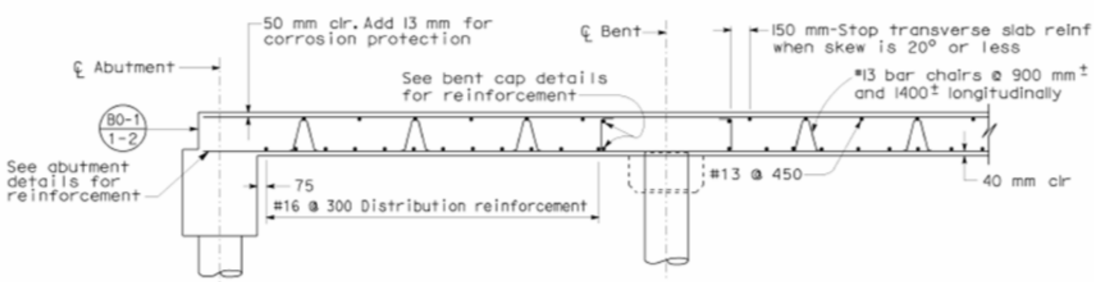


Figure 1.35 Slab Bridge

In the case of arch bridges, the loads from the superstructure are transmitted diagonally to the substructure. True arches are in pure compression. Arch bridges can be constructed from timber, concrete, or steel

Cable-Supported Bridges

In the case of cable-supported bridges, the superstructure loads are resisted by cables which act in tension. The cable forces are then resisted by the substructure anchorages and towers. Cable-supported bridges can be either suspension or cable-stayed (see Figures 1.36 and 1.37).

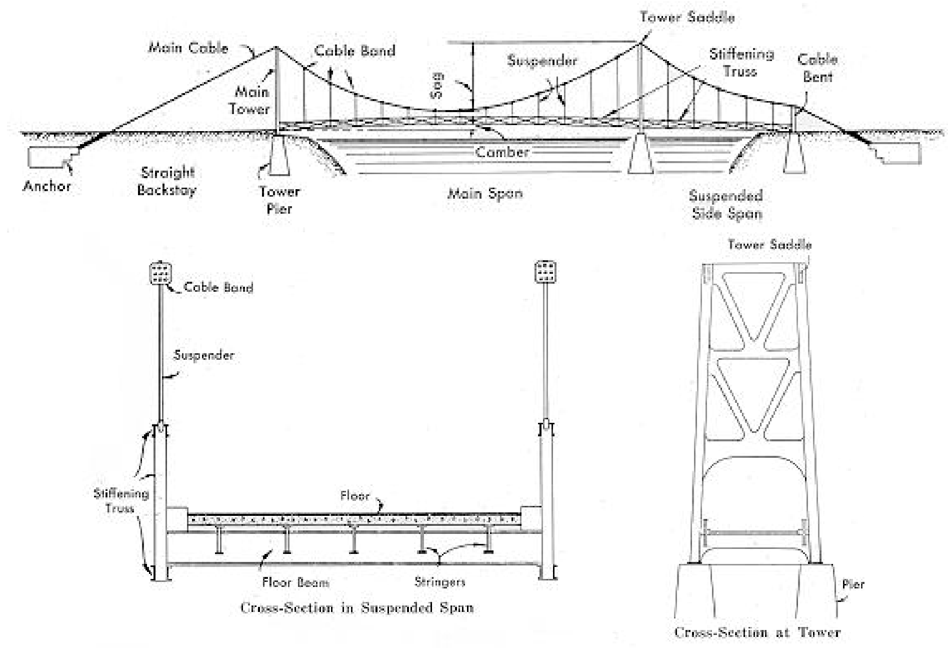


Figure 1.36 Steel Suspension Bridge

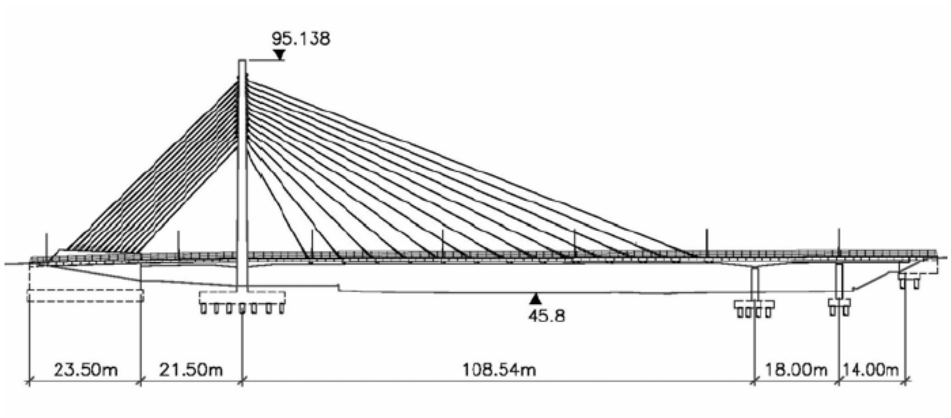


Figure 1.37 Cable-stayed Bridge

Movable Bridge

Movable bridges are constructed across designated "Navigable Waters of the United States," in accordance with "Permit Drawings" approved by the U.S. Coast Guard. The purpose of a movable bridge is to provide the appropriate channel width and underclearance for passing water vessels when fully opened.

Movable bridges can be classified into three general groups:

- Bascule (see Figure P.1.38)
- Swing
- Lift

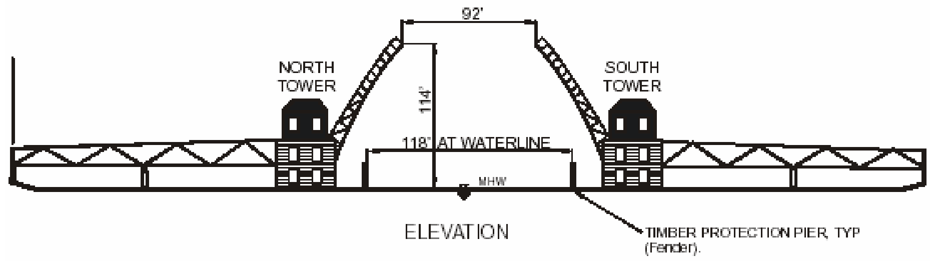


Figure 1.38 Bascule Bridge

Floating Bridges

Although uncommon, some states have bridges that are not supported by a substructure. Instead, they are supported by water. The elevation of the bridge will change as the water level fluctuates.

Culverts

A culvert is primarily a hydraulic structure, and its main purpose is to transport water flow efficiently.
Culverts are often viewed as small bridges, being constructed entirely below and independent of the roadway surface. However, culverts do not have a deck, superstructure, or substructure (see Figure 1.39).

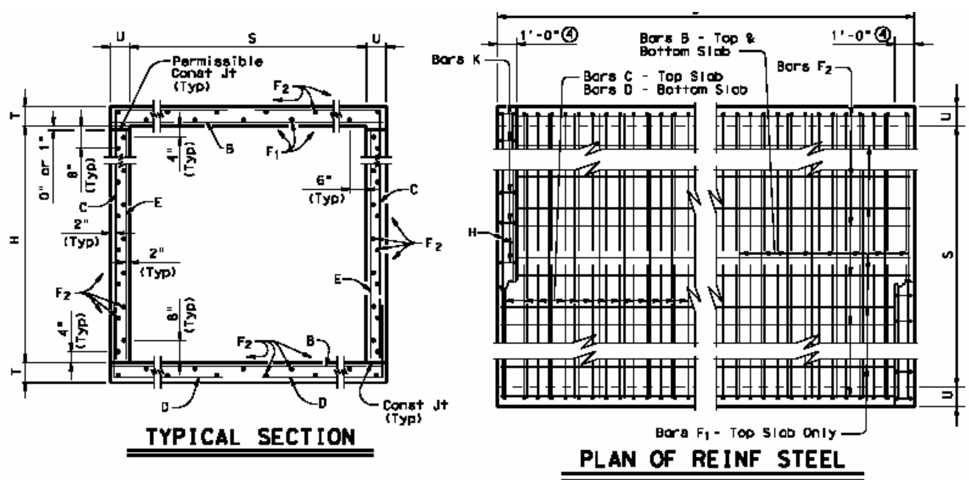


Figure 1.39 Concrete Box Culvert

1.8 Bearings

Definition

A bridge bearing is a superstructure element which provides an interface between the superstructure and the substructure.

Primary Function

There are three primary functions of a bridge bearing:

- Transmit all loads from the superstructure to the substructure
- Permit longitudinal movement of the superstructure due to thermal expansion and contraction
- Allow rotation caused

by dead and live load deflection

Bearings that do not allow for translation or movement of the superstructure are referred to as fixed bearings.

Bearings that allow for the displacement of the structure are known as expansion bearings. Both fixed and expansion bearings permit rotation.

Basic Elements

A bridge bearing can be broken down into four basic elements (see Figure 1.40):
- Sole plate
- Masonry plate
- Bearing or bearing surfaces
- Anchorage

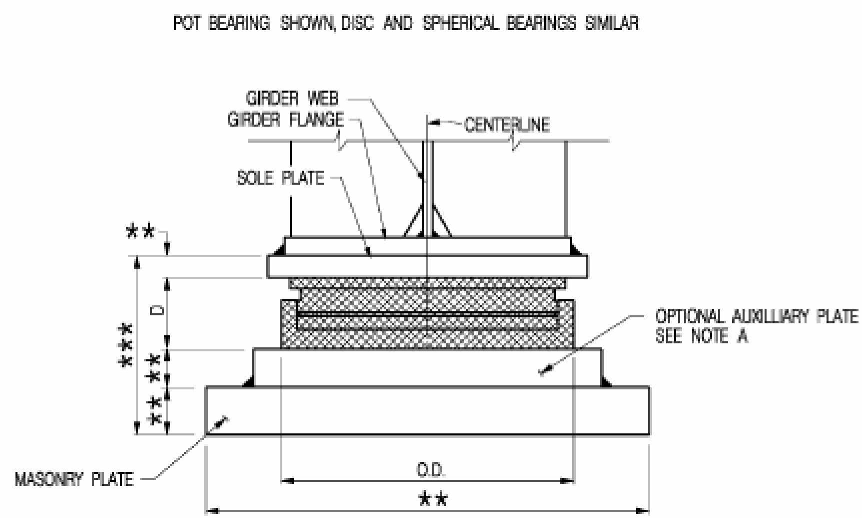


Figure 1.40 Typical Bearing Showing Four Basic Elements

Bearing Types

Various bearing types have evolved out of the need to accommodate superstructure movement and rotation:
- Sliding plate bearings
- Roller bearings
- Rocker bearings
- Pin and link bearings
- Elastomeric bearings
- Pot bearings (see Figure 1.40)
- Restraining bearings
- Isolation bearings

1.9 Substructure

The substructure is the component of a bridge which includes all the elements which support the superstructure.

Substructure Purposes

The purpose of the substructure is to transfer the loads from the superstructure to the foundation soil or rock. Typically the substructure includes all elements below the bearings. The loads are then distributed to the earth through the footing.

Substructure Function

Substructure units function as both axially-loaded and bending members. These units resist both vertical and horizontal loads applied from the superstructure and roadway embankment. Substructures are divided into two basic categories:

- Abutments (see Figure 1.41)
- Piers and bents

Abutments provide support for the ends of the superstructure and retain the roadway approach embankment.

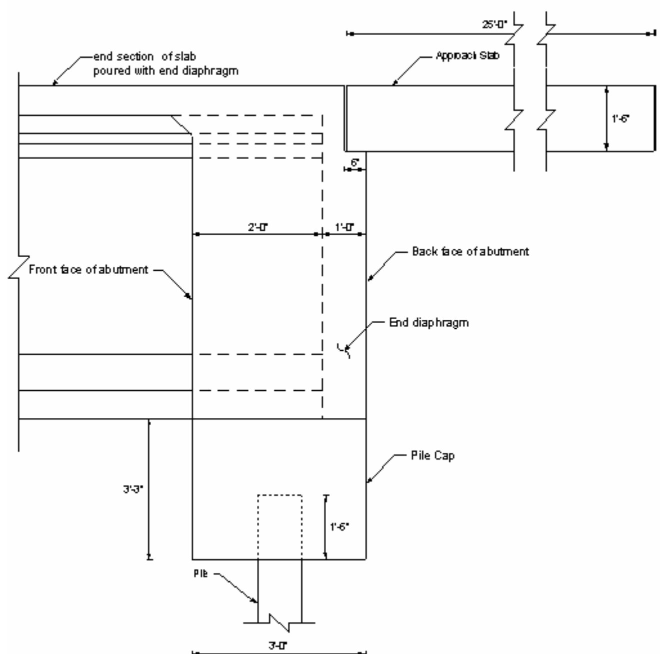


Figure 1.41 Concrete Abutment

Basic types of abutments include:

- Cantilever or full height abutment - extends from the grade line of the roadway or waterway below, to that of the road overhead.
- Stub, semi-stub, or shelf abutment - located within the topmost portion of the end of an embankment or slope. In the case of a stub, less of the abutment stem is visible than in the case of the full height abutment. Most new construction uses this type of abutment. These abutments may be required to be supported on deep foundations (see Figure 1.42).
- Spill-through or open abutment - consists of columns and has no solid wall, but rather is open to the embankment material. The approach embankment material is usually rock (see Figure 1.43).

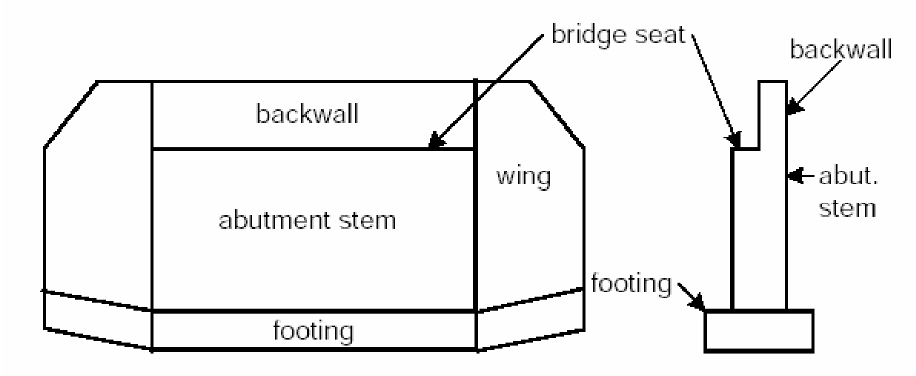


Figure 1.42 Stub Abutment

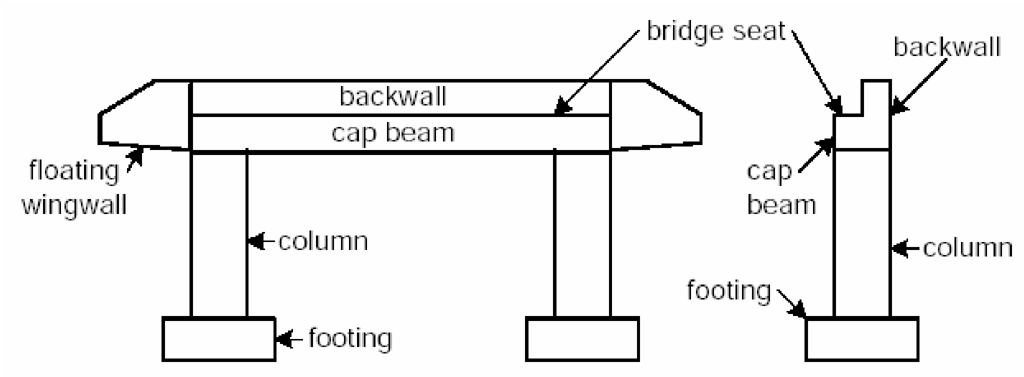


Figure 1.43 Open Abutment

Piers and Bents

A pier has only one footing at each substructure unit (the footing may serve as a pile cap). A bent has several footings or no footing, as is the case with a pile bent.

There are four basic types of piers:

- Solid shaft pier
- Column pier
- Column pier with web wall
- Cantilever or hammerhead pier (see Figure 1.44)

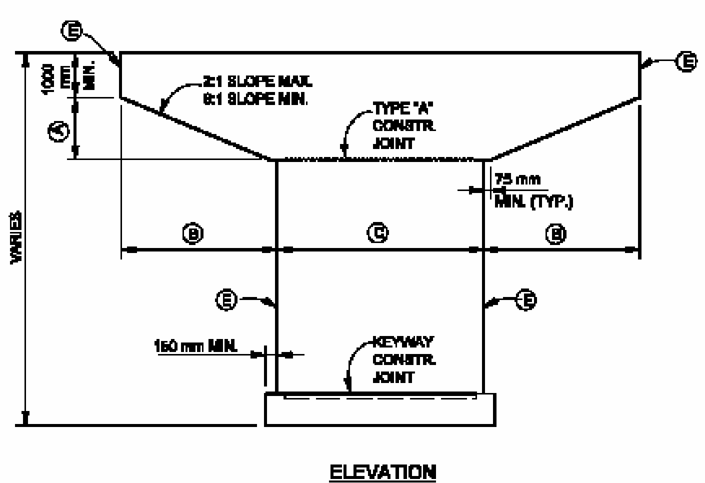


Figure 1.44 Hammerhead pier

There are two basic types of bents:

- Column bent
- Pile bent (see Figure 1.45)

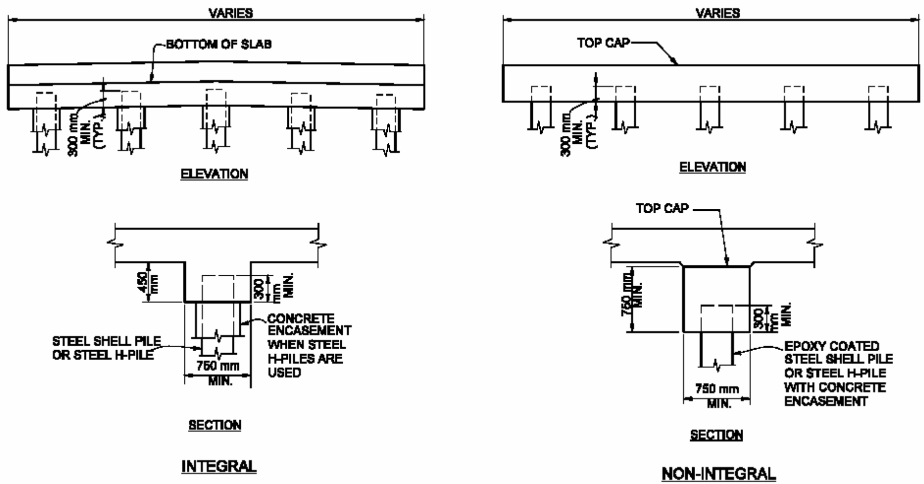


Figure 1.45 Pile Bent

2 Bridge Mechanics

2.1 Introduction

Mechanics is the branch of physical science that deals with energy and forces and their relation to the equilibrium, deformation, or motion of bodies. A bridge engineer will primarily be concerned with statics, or the branch of mechanics dealing with solid bodies at rest and with forces in equilibrium.

The two most important reasons to study bridge mechanics are:

- To understand how bridge members function
- To recognize the impact a defect may have on the load-carrying capacity of a bridge component or element

2.2 Bridge Design Loadings

A bridge is designed to carry or resist design loadings in a safe and economical manner. Loads may be concentrated or distributed depending on the way in which they are applied to the structure.

A concentrated load, or point load, is applied at a single location or over a very small area. Vehicle loads are considered concentrated loads.

A distributed load is applied to all or part of the member, and the amount of load per unit of length is generally constant. The weight of superstructures, bridge decks, wearing surfaces, and bridge parapets produce distributed loads. Secondary loads, such as wind, stream flow, earth cover and ice, are also usually distributed loads.

Highway bridge design loads are established by the American Association of State Highway and Transportation Officials (AASHTO). For many decades, the primary bridge design code in the United States was the AASHTO *Standard Specifications for Highway Bridges* (*Specifications),* as supplemented by agency criteria as applicable.

During the 1990's AASHTO developed and approved a new bridge design code, entitled *AASHTO LRFD Bridge Design Specifications.* It is based upon the principles of Load and Resistance Factor Design (LRFD).

Load and Resistance Factor Rating (LRFR) consists of three methods: design load rating, legal load rating, and permit load rating. Each serves a specific purpose in the evaluation of bridge safety or serviceability.
Bridge design loadings can be divided into three principal categories:

- Dead loads
- Primary live loads
- Secondary loads

Dead Loads

Dead loads do not change as a function of time and are considered full-time, permanent loads acting on the structure. They consist of the weight of the materials used to build the bridge (see Figure P.2.1). Dead load includes both the self-weight of structural members and other permanent external loads. They can be broken down into two groups, initial and superimposed.

Initial dead loads are loads which are applied before the concrete deck is hardened, including the beam itself and the concrete deck. Initial deck loads must be resisted by the non-composite action of the beam alone.

Superimposed dead loads are loads which are applied after the concrete deck has hardened (on a composite bridge), including parapets and any anticipated future deck pavement. Superimposed dead loads are resisted by the beam and the concrete deck acting compositely.

Dead load includes both the self-weight of the structural members and other permanent external loads.

Example of self-weight:

A 20 foot long beam weighs 50 pounds per linear foot. The total weight of the beam is 1000 pounds. This weight is called the self-weight of the beam.

Example of an external dead load:

If a utility such as a water line is permanently attached to the beam in the previous example, then the weight of the water line is an external dead load. The weight of the water line plus the self weight of the beam comprises the total dead load.

Total dead load on a structure may change during the life of the bridge due to additions such as deck overlays, parapets, utility lines, and inspection catwalks.

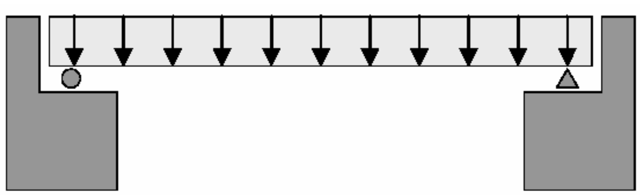


Figure 2.1 Dead Load on a Bridge

Primary Live Loads

A live load is a temporary dynamic load applied to a structure. In bridge applications, the primary live loads are moving vehicular loads (see Figure 2.2).

To account for the affects of speed, vibration, and momentum, highway live loads are typically increased for impact. Impact is expressed as a fraction of the live load, and its value is a function of the span length.

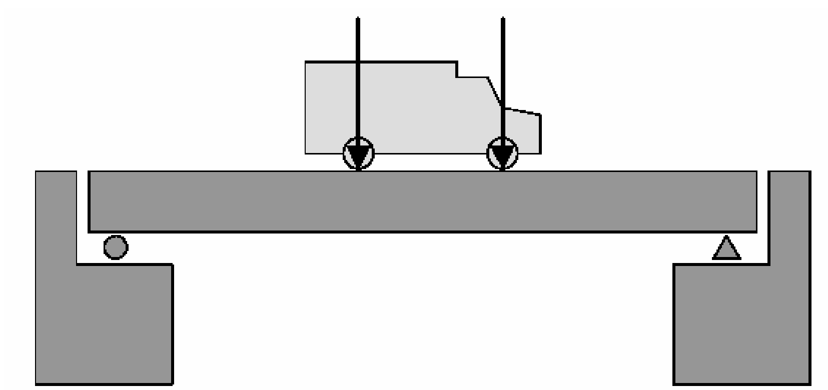


Figure 2.2 Vehicle Live Load on a Bridge

AASHTO Truck Loadings

Standard vehicle live loads have been established by AASHTO for use in bridge design and rating. There are two basic types of standard truck loadings described in the current *AASHTO Specifications.* A third type of loading is used for AASHTO Load and Resistance Factor Design and Rating.

The first type is a single unit vehicle with two axles spaced at 14 feet and designated as a highway truck or "H" truck (see Figure 2.3). The weight of the front axle is 20% of the gross vehicle weight, while the weight of the rear axle is 80% of the gross vehicle weight. The "H" designation is followed by the gross tonnage of the particular design vehicle. The AASHTO LRFD design vehicular live load, designated HL-93, is a modified version of the HS-20 highway loadings from the *AASHTO Standard Specifications.*

Example of an H truck loading:

H20-35 indicates a 20 ton vehicle with a front axle weighing 4 tons, a rear axle weighing 16 tons, and the two axles spaced 14 feet apart. This standard truck loading was first published in 1935. The 1935 truck loading used a train of trucks that imitated the railroad industry's standards.

As trucks grew heavier during World War II, AASHTO developed the new concept of hypothetical trucks. These fictitious trucks are used only for design and do not resemble any real truck on the road. The loading is now performed by placing one truck, per lane, per span. The truck is moved along the span to determine the point where it produces the maximum moment. The current designation is H20-44 published in 1944.
The second type of standard truck loading is a two unit, three axle vehicle comprised of a highway tractor with a semi-trailer. It is designated as a highway semi-trailer truck or "HS" truck (see Figure 2.4).

The tractor weight and wheel spacing is identical to the H truck loading. The semi-trailer axle weight is equal to the weight of the rear tractor axle, and its spacing from the rear tractor axle can vary from 14 to 30 feet. The "HS" designation is followed by a number indicating the gross weight in tons of the tractor only.

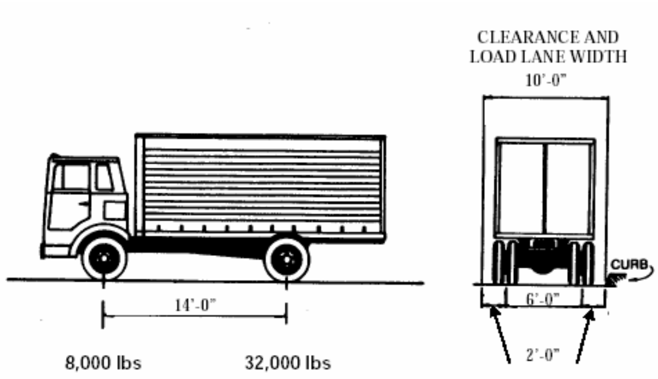


Figure 2.3 AASHTO H20 Truck

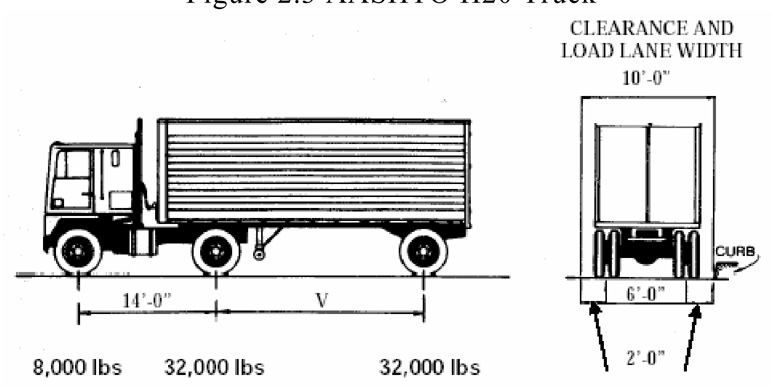


Figure 2.4 AASHTO HS20 Truck

Example of an HS truck loading:

HS20-44 indicates a vehicle with a front tractor axle weighing 4 tons, a rear tractor axle weighing 16 tons, and a semitrailer axle weighing 16 tons. The tractor portion alone weighs 20 tons, but the gross vehicle weight is 36 tons. This standard truck loading was first published in 1944.

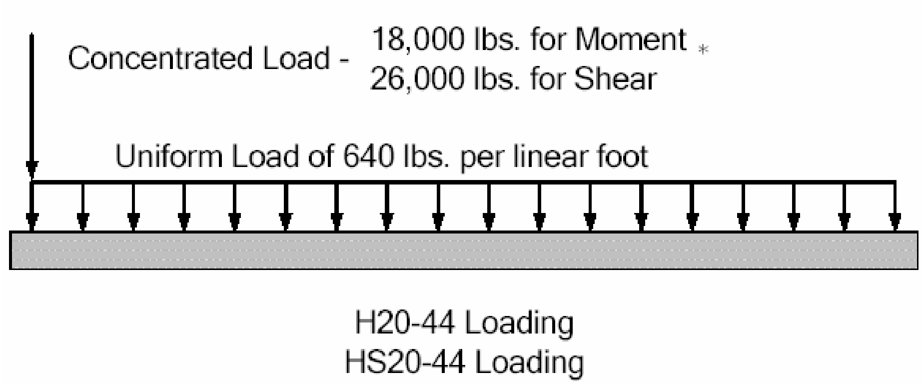
In specifications prior to 1944, a standard loading of H1 5 was used. In 1944, the policy of affixing the publication year of design loadings was adopted. In specifications prior to 1965, the HS20-44 loading was designated as H20-S 16-44, with the S 16 identifying the gross axle weight of the semi-trailer in tons.

The H and HS vehicles do not represent actual vehicles, but can be considered as "umbrella" loads. The wheel spacings, weight distributions, and clearance of the Standard Design Vehicles were developed to give a simpler method of analysis, based on a good approximation of actual live loads. These loads are used for the design of bridge members. Depending on such items as highway classification, truck usage and span classification, for example, an appropriate design load is chosen to determine the most economical member. Bridge posting is determined by performing a rating analysis using the current member condition of an in-service bridge.

AASHTO Lane Loadings

In addition to the standard truck loadings, a system of equivalent lane loadings was developed in order to provide a simple method of calculating bridge response to a series, or "train" of trucks. Lane loading consists of a uniform load per linear foot of traffic lane combined with a concentrated load located on the span to produce the most critical situation in the structure (see Figure 2.5).

For design and load capacity rating analysis, an investigation of both a truck loading and a lane loading must be made to determine which produces the greatest stress for each particular member. Lane loading will generally govern over truck loading for longer spans. Both the H and HS loadings have corresponding lane loads.



* Use two concentrated loads for negative moment in continuous spans (Refer to *AASHTO Bridge Design Specifications,* 2005 Interim; Article 3.6.1.3)

Figure 2.5 AASHTO Lane Loadings.

LRFD Live Loads

Under HS-20 loading as described earlier, the truck or lane load is applied to each loaded lane. Under HL-93 loading, the design truck or tandem is combined with the lane load and applied to each loaded lane.

The LRFD design truck is exactly the same as the AASHTO HS-20 design truck. The LRFD design tandem, on the other hand, consists of a pair of 12 tons axels spread at 25 kip axles spaced 4 feet apart. The transverse wheel spacing of all of the trucks is 6 feet.

The magnitude of the HL-93 lane load is equal to that of the HS-20 lane load. The lane load is 0.64 kips per linear foot longitudinally and it is distributed uniformly over a 10 foot width in the transverse direction. The difference between the HL-93 lane load and the HS-20 lane load is that the HL-93 lane load does not include a point load. The HL-93 design load consists of a combination of the design truck or design tandem, and design lane load (see Figure 2.6).

Finally, for LRFD live loading, the dynamic load allowance, or impact, is applied to the design truck or tandem but is not applied to the design lane load. It is typically 33 percent of the design vehicle.

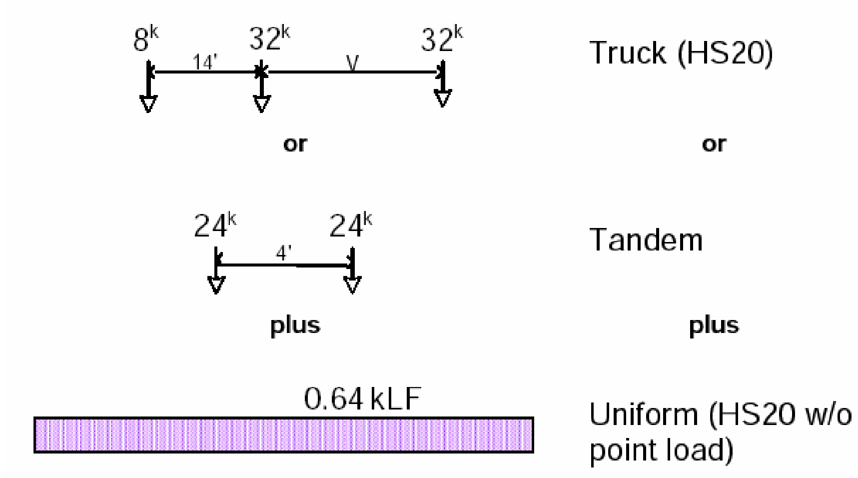


Figure 2.6 AASHTO LRFD Loading

Alternate Military Loading

The Alternate Military Loading is a single unit vehicle with two axles spaced at 4 feet and weighing 12 tons each. It has been part of the AASHTO *Specifications* since 1977. Bridges on interstate highways or other highways which are potential defense routes are designed for either an HS20 loading or an Alternate Military Loading (see Figure 2.7).

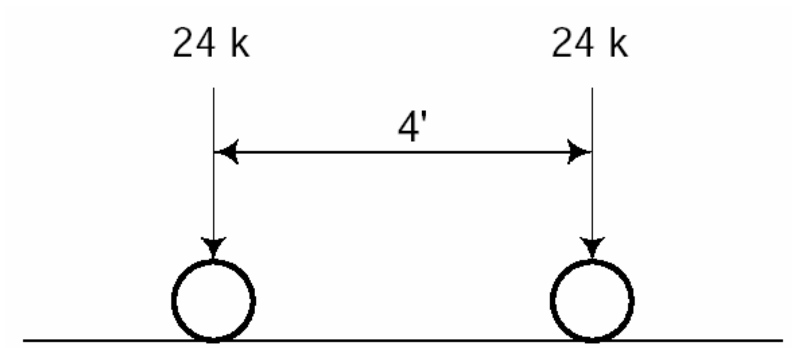


Figure 2.7 Alternate Military Loading

Permit Vehicles

Permit vehicles are overweight vehicles which, in order to travel a state's highways, must apply for a permit from that state. They are usually heavy trucks (e.g., combination trucks, construction vehicles, or cranes) that have varying axle spacings depending upon the design of the individual truck. To ensure that these vehicles can safely operate on existing highways and bridges, most states require that bridges be designed for a permit vehicle or that the bridge be checked to determine if it can carry a specific type of vehicle. For safe and legal operation, agencies issue permits upon request that identify the required gross weight, number of axles, axle spacing, and maximum axle weights for a designated route.

Secondary Loads

In bridge applications, the secondary loads are temporary dynamic loads and consist of the following:

- **Buoyancy** - the force created due to the tendency of an object to rise when submerged in water
- **Centrifugal force -** an outward force that a live load vehicle exerts on a curved bridge
- **Curb loading -** curbs are designed to resist a lateral force of not less than 500 pounds per linear foot

- **Earth pressure** - a horizontal force acting on earth-retaining substructure units, such as abutments and retaining walls
- **Earthquake -** bridge structures must be built so that motion during an earthquake will not cause a collapse
- **Ice pressure** - a horizontal force created by static or floating ice jammed against bridge components
- **Longitudinal force** - a force in the direction of the bridge caused by braking and accelerating of live load vehicles
- **Railing loading -** railings are provided along the edges of structures for protection of traffic and pedestrians; the maximum transverse load applied to any one element need not exceed 10 kips)
- **Rib shortening -** a force in arches and frames created by a change in the geometrical configuration due to dead load
- **Shrinkage -** applied primarily to concrete structures, this is a multidirectional force due to dimensional changes resulting from the curing process
- **Sidewalk loading -** sidewalk floors and their immediate supports are designed for a pedestrian live load not exceeding 85 pounds per square foot)
- **Stream flow pressure -** a horizontal force acting on bridge components constructed in flowing water
- **Temperature -** since materials expand as temperature increases and contract as temperature decreases, the force caused by these dimensional changes must be considered
- **Wind load on live load** - wind effects transferred through the live load vehicles crossing the bridge
- **Wind load on structure** - wind pressure on the exposed area of a bridge

A bridge may be subjected to several of these loads simultaneously. The AASHTO *Specifications* have established a table of loading groups. For each group, a set of loads is considered with a coefficient to be applied for each particular load. The coefficients used were developed based on the probability of various loads acting simultaneously.

2.3 Bridge Response to Loadings

Each member of a bridge is intended to respond to loads in a particular way. The bridge engineer must understand the manner in which loads are applied to each member in order to evaluate if it functions as intended. Once the engineer understands a bridge member's response to loadings, he will be able to determine the effect the member has on the load-carrying capacity of that member.

Bridge members respond to various loadings by resisting four basic types of forces. These are:

- Axial forces (compression and tension)
- Bending forces (flexure)
- Shear forces
- Torsional forces

In calculating these forces, the analysis is governed by equations of equilibrium.
Equilibrium equations represent a balanced force system and may be expressed as:
where:

$$\sum V = 0$$
$$\sum H = 0$$
$$\sum M = 0$$

$\sum$ = summation of
V = vertical forces
H = horizontal forces
M = moments (bending forces)

Axial Forces

An axial force is a push or pull type of force which acts parallel to the longitudinal axis of a member. An axial force causes compression if it is pushing and tension if it is pulling (see Figure 2.8). Axial forces are generally expressed in English units of pounds or kips, and metric units of Newtons or kilonewtons.

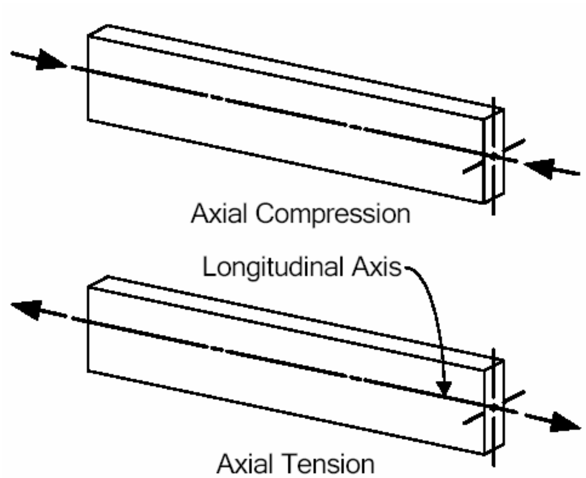


Figure 2.8 Axial Forces

Examples of axial forces:

A man sitting on top of a fence post is exerting an axial force that causes compression in the fence post. A group of people playing tug-of-war exerts an axial force that causes tension in the rope.

Truss members are common bridge elements which carry axial loads. They are designed for either compression and tension forces. Cables are designed for axial forces in tension.

True axial forces act uniformly over a cross-sectional area. Therefore, axial stress can be calculated by dividing the force by the area on which it acts.

$$f_a = \frac{P}{A}$$

where:

f_a = axial stress
P = axial force
A = cross-sectional area

When bridge members are designed to resist axial forces, the cross-sectional area will vary depending on the magnitude of the force, whether the force is tensile or compressive, and the type of material used.

For tension and compression members, the cross-sectional area must satisfy the previous equation for an acceptable axial stress. However, the acceptable axial compressive stress is generally lower than that for tension because of a phenomenon called buckling.

Bending Forces

Bending forces in bridge members are caused when a load is applied perpendicular to the longitudinal or neutral axis. A moment is commonly developed by the perpendicular loading which causes a member to bend. The greatest bending moment that a beam can resist is generally the governing factor which determines the size and material of the member. Bending moments can be positive or negative and produce both compression and tension forces at different locations in the member (see Figure 2.9). Moments are generally expressed in English units of pound-feet or kip-feet.

Example of bending moment:

When a rectangular rubber eraser is bent, a moment is produced in the eraser. If the ends are bent upwards, the top half of the eraser can be seen to shorten, while the bottom half can be seen to lengthen. Therefore, the moment produces compression forces in the top layers of the eraser and tension forces in the bottom layers.

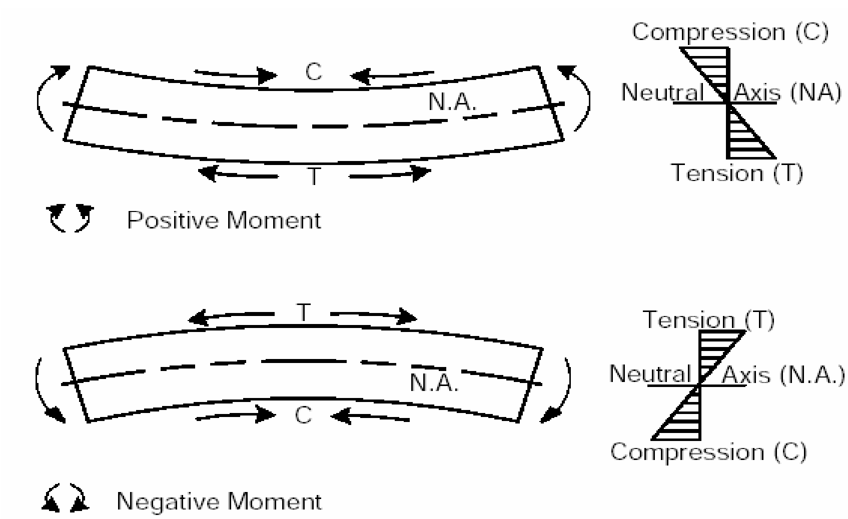


Figure 2.9 Positive and Negative Moment

Beams and girders are the most common bridge elements used to resist bending moments. The flanges are most critical because they provide the greatest resistance to the compressive and tensile forces developed by the moment (see Figure 2.10).

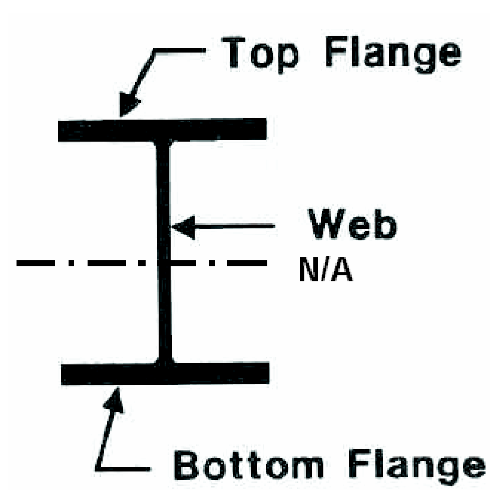


Figure 2.10 Girder Cross Section

Bending stress is normally considered zero at the neutral axis. On a cross section of a member, bending stresses vary linearly with respect to the distance from the neutral axis (see Figures 2.9 and 2.11).

The formula for maximum bending stress is (see Figure 2.11):

$$f_b = \frac{Mc}{I}$$

where:

f_b = bending stress on extreme fiber (or surface) of beam
M = applied moment
c = distance from neutral axis to extreme fiber (or surface) of beam
I = moment of inertia (a property of the beam cross-sectional area and shape)

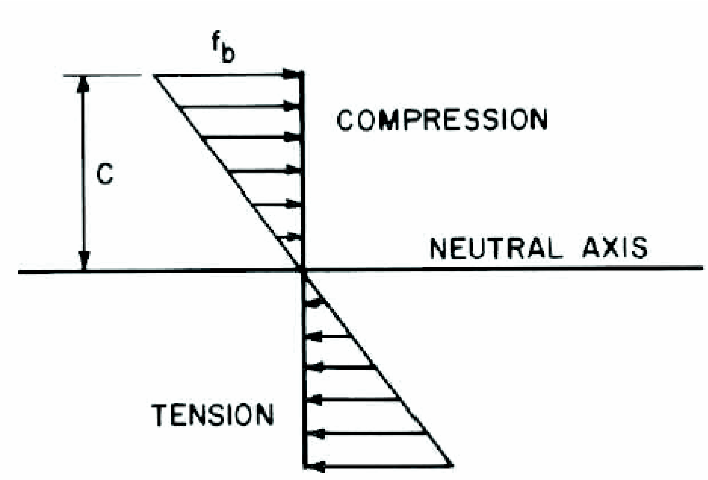


Figure 2.11 Bending Stresses

Shear Forces

Shear is a force, which results from equal but opposite transverse forces, which tend to slide one section of a member past an adjacent section (see Figure 2.12). Shear forces are generally expressed in English units of pounds or kips.

Example of shear: When scissors are used to cut a piece of paper, a shear force has caused one side of the paper to separate from the other. Scissors are often referred to as shears since they exert a shear force.

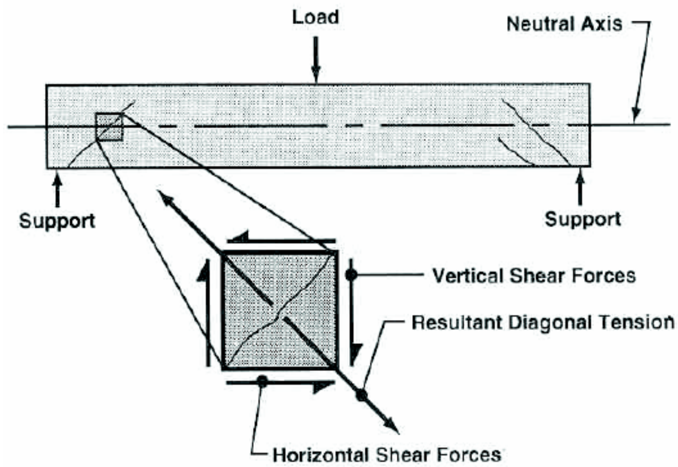


Figure 2.12 Shear Forces in a Member Element

Beams and girders are common shear resisting members. In an I- or T-beam, most of the shear is resisted by the web (see Figure 2.10). The shear stress produced by the transverse forces is manifested in a horizontal shear stress which is accompanied by a vertical shear stress of equal magnitude. The horizontal shear forces are required to keep the member in equilibrium (not moving). Vertical shear strength is generally considered in most design criteria. The formula for vertical shear stress in I- or T-beams is:

$$f_v = \frac{V}{A_W}$$

where:

f_v = shear stress
V = vertical shear due to external loads
A_w = area of web

Torsional Forces

Torsion is a force resulting from externally applied moments which tend to rotate or twist a member about its longitudinal axis. Torsional force is commonly referred to as torque and is generally expressed in English units of pound-feet or kip-feet.

Example of torsion:

One end of a long rectangular steel bar is clamped horizontally in a vise so that the long side is up and down. Using a large wrench, a moment is applied to the other end, which causes it to rotate so that the long side is now left to right. The steel bar is resisting a torsional force or torque which has twisted it 90^0 with respect to its original orientation (see Figure 2.13).

Torsional forces develop in bridge members, which are interconnected and experience unbalanced loadings. Bridge elements are generally not designed as torsional members. However, in some bridge superstructures where elements are framed together, torsional forces can occur in longitudinal members. When these members experience differential deflection, adjoining transverse members apply twisting moments resulting in torsion. In addition, curved bridges are generally subject to torsion (see Figure 2.14).

Figure 2.13 Torsion

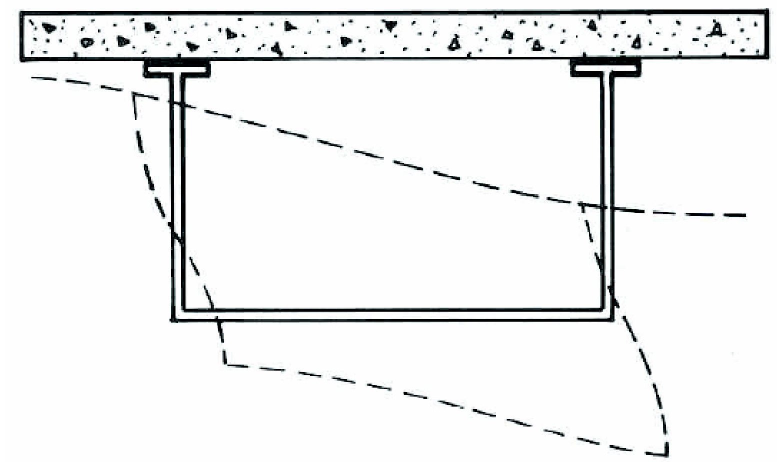


Figure 2.14 Torsional Distortion

Reactions

A reaction is a force provided by a support that is equal but opposite to the force transmitted from a member to its support (see Figure 2.15). Reactions are most commonly vertical forces, but a reaction can also be a horizontal force. The reaction at a support is the measure of force that it must transmit to the ground. A vertical reaction increases as the loads on the member are increased or as the loads are moved closer to that particular support. Reactions are generally expressed in English units of pounds or kips.

Example of reactions:

Consider a bookshelf consisting of a piece of wood supported at its two ends by bricks. The bricks serve as supports, and the reaction is based on the weight of the shelf and the weight of the books on the shelf. As more books are added, the reaction provided by the bricks will increase. As the books are shifted to one side, the reaction provided by the bricks at that side will increase, while the reaction at the other side will decrease.

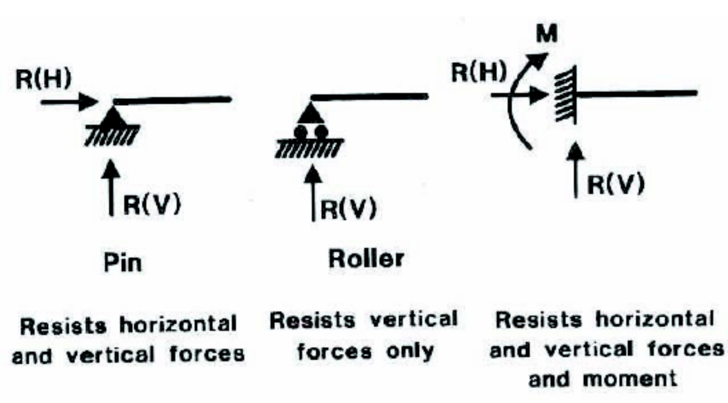


Figure 2.15 Types of Supports

The loads of the entire bridge always equal the reactions provided by the abutments and the piers. However, on a smaller scale, each individual beam and girder also exerts forces, which create reactions provided by its supporting members.

2.4 Material Response to Loadings

Each member of a bridge has a unique purpose and function, which directly affects the selection of material, shape, and size for that member. Certain terms are used to describe the response of a bridge material to loads. A working knowledge of these terms is essential for the bridge engineer.

Force

A force is the action that one body exerts on another body.

Force has two components: magnitude and direction (see Figure 2.16).

The basic English unit of force is called pound (abbreviated as lb.). A common unit of force used among engineers is a kip (K), which is 1000 pounds.

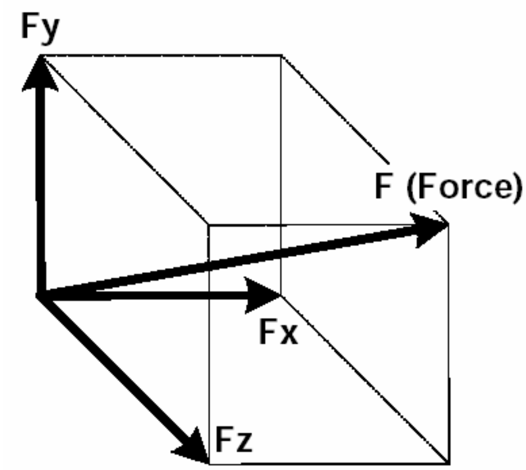


Figure 2.16 Basic Force Components

Stress

Stress is a basic unit of measure used to denote the intensity of an internal force. When a force is applied to a material, an internal stress is developed. Stress is defined as a force per unit of cross-sectional area.

$$\text{Stress (S)} = \frac{\text{Force (F)}}{\text{Area (A)}}$$

The basic English unit of stress is pounds per square inch (abbreviated as psi). However, stress can also be expressed in kips per square inch (ksi) or in any other units of force per unit area. An allowable unit stress is generally established for a given material..

Example of a stress:

If a 30,000 lb. force acts uniformly over an area of 10 square inches, then the stress caused by this force is 3000 psi (or 3 ksi).

Deformation

Deformation is the local distortion or change in shape of a material due to stress.

Strain

Strain is a basic unit of measure used to describe an amount of deformation. It denotes the ratio of a material's deformed dimension to a material's original dimensions. For example, strain in a longitudinal direction is computed by dividing the change in length by the original length.

$$\text{Strain } (\varepsilon) = \frac{\text{Change in Length } (\Delta L)}{\text{Original Length } (L)}$$

Strain is a dimensionless quantity. However, it can also be expressed as a percentage or in units of length per length (e.g., inch/inch).

Example of strain:

If a force acting on a 20 foot long column causes an axial deformation of 0.002 feet, then the resulting axial strain is 0.002 feet divided by 20 feet, or 0.0001 foot/foot. This strain can also be expressed simply as 0.0001 (with no units) or as 0.01%.

Elastic Deformation

Elastic deformation is the reversible distortion of a material. A member is elastically deformed if it returns to its original shape upon removal of a force. Elastic strain is sometimes termed reversible strain because it disappears after the stress is removed. Bridges are designed to deform elastically and return to their original shape after the live loads are removed.

Example of elastic deformation:

A stretched rubber band will return to its original shape after being released from a taut position. Generally, if the strain is elastic, there is a direct proportion between the amount of strain and the applied stress.

Plastic Deformation

Plastic deformation is the irreversible or permanent distortion of a material. A material is plastically deformed if it retains a deformed shape upon removal of a stress. Plastic strain is sometimes termed irreversible or permanent strain because it remains after the stress is removed. Plastic strain is not directly proportional to the given applied stress as is the case with the elastic strain.

Example of plastic deformation:

If a car crashed into a brick wall, the fenders and bumpers would deform. This deformation would remain even after the car is backed away from the wall. Therefore, the fenders and bumpers have undergone plastic deformation.

Creep

Creep is a form of plastic deformation that occurs gradually at stress levels normally associated with elastic deformation. Creep is defined as the gradual, continuing irreversible change in the dimensions of a member due to the sustained application of load. It is caused by the molecular readjustments in a material under constant load. The creep rate is the change in strain (plastic deformation) over a certain period of time.

Example of creep:

If heavy paint cans remain left untouched on a thin wooden shelf for several months, the shelf will gradually deflect and change in shape. This deformation is due to the sustained application of a constant dead load and illustrates the effects of creep.

Thermal Effects

In bridges, thermal effects are most commonly experienced in the longitudinal expansion and contraction of the superstructure. It is possible to disregard deformations caused by thermal effects when members are free to expand and contract. However, there may be members for which expansion and contraction is inhibited or prevented in certain directions. Thermal changes in these members can cause significant frictional stresses and must be considered by the engineer.

Materials expand as temperature increases and contract as temperature decreases. The amount of thermal deformation in a member depends on:

- A coefficient of thermal expansion, unique for each material
- The temperature change
- The member length

Example of thermal effects: Most thermometers operate on the principle that the material within the glass bulb expands as the temperature increases and contracts as the temperature decreases.

Stress-Strain Relationship

For most structural materials, values of stress and strain are directly proportional (see Figure 2.17). However, this proportionality exists only up to a particular value of stress called the elastic limit. Two other frequently used terms, which closely correspond with the elastic limit, are the proportional limit and the yield point.

When applying stress up to the elastic limit, a material deforms elastically. Beyond the elastic limit, deformation is plastic and strain is not directly proportional to a given applied stress. The material property, which defines its stress-strain relationship, is called the modulus of elasticity, or Young's modulus.

Modulus of Elasticity

Each material has a unique modulus of elasticity, which defines the ratio of a given stress to its corresponding strain. It is the slope of the elastic portion of the stress-strain curve.

$$\text{Modulus of Elasticity (E)} = \frac{\text{Stress (S)}}{\text{Strain } (\varepsilon)}$$

The modulus of elasticity applies only as long as the elastic limit of the material has not been reached. The units for modulus of elasticity are the same as those for stress (i.e., psi or ksi).

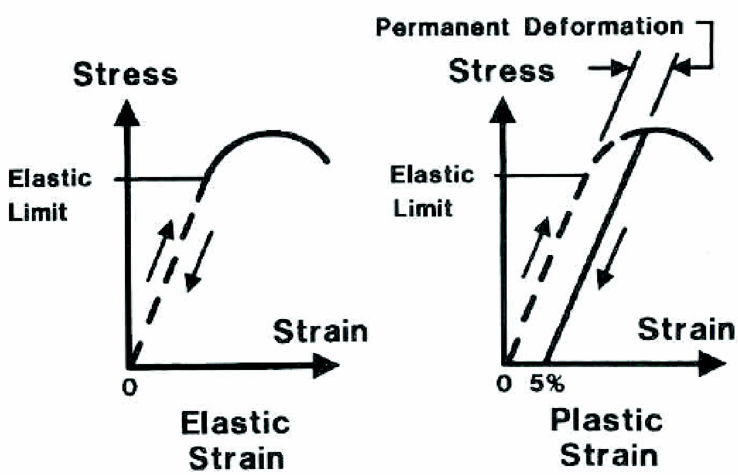


Figure 2.17 Stress-Strain Diagram

Example of modulus of elasticity:

If a stress of 2900 psi is below the elastic limit and causes a strain of 0.0001, then the modulus of elasticity can be computed based on these values of stress and strain.

$$E \quad \frac{2{,}900 \text{ psi}}{0.0001} = 29{,}000{,}000 \text{ psi} = 29{,}000 \text{ ksi}$$

This is approximately equal to the modulus of elasticity for steel. The modulus of elasticity for concrete is approximately 3000 to 4500 ksi, and for commonly used grades of timber it is approximately 1600 ksi.

Overloads

Overload damage may occur when members are overstressed. Overload occurs when the stresses applied are greater than the elastic limit for the material.

Buckling

Buckling is the tendency of a member to crush or bend out of plane when subjected to a compressive force. As the length and slenderness of a compression member increases, the likelihood of buckling also increases.

Compression members require additional cross-sectional area or bracing to resist buckling.

Ductility and Brittleness

Example of buckling:

A paper or plastic straw compressed axially at both ends with an increasing force will eventually buckle.

Elongation

Elongation is the tendency of a member to extend, stretch or crack when subjected to a tensile force. Elongation can be either elastic or plastic.

Example of elongation:

A piece of taffy pulled will stretch in a plastic manner.
Ductility is the measure of plastic (permanent) strain that a material can endure. A ductile material will undergo a large amount of plastic deformation before breaking. It will also have a greatly reduced cross-sectional area before breaking.

Example of ductility:

A baker working with pizza dough will find that the dough can be stretched a great deal before it will break into two sections. Therefore, pizza dough is a ductile material. When the dough finally does break, it will have a greatly reduced cross-sectional area.

Structural materials for bridges that are generally ductile include:

- Steel
- Copper
- Aluminum
- Wood

Brittle, or non-ductile, materials will not undergo significant plastic deformation before breaking. Failure of a brittle material occurs suddenly, with little or no warning.

Example of brittleness:

A glass table may be able to support several magazines and books. However, if more and more weight is piled onto the table, the glass will eventually break with little or no warning. Therefore, glass is a brittle material.

Structural materials for bridges that are generally brittle include:

- Concrete
- Stone
- Cast iron
- Fiber Reinforced Polymer

Fatigue

Fatigue is a material response that describes the tendency of a material to break when subjected to repeated loading. Fatigue failure occurs within the elastic range of a material after a certain number and magnitude of stress cycles have been applied.

Each material has a hypothetical maximum stress value to which it can be loaded and unloaded an infinite number of times. This stress value is referred to as the fatigue limit and is usually lower than the breaking strength for infrequently applied loads.

Ductile materials such as steel and aluminum have high fatigue limits, while brittle materials such as concrete have low fatigue limits. Wood has a high fatigue limit even though it is more like a brittle material than a ductile one.

Example of fatigue:

If a rubber band is stretched and then allowed to return to its original position (elastic deformation), it is unlikely that the rubber band will break. However, if this action is repeated many times, the rubber band will eventually break. The rubber band failure is analogous to a fatigue failure.

Isotropy

A material that has the same mechanical properties regardless of which direction it is loaded is said to be isotropic.

Example of isotropy: Plain, unreinforced concrete, and steel.

2.5 Mechanics of Materials

Materials respond to loadings in a manner dependent on their mechanical properties. In characterizing materials, certain mechanical properties must be defined.

Yield Strength

The ability of a material to resist plastic (permanent) deformation is called the yield strength. Yield strength corresponds to stress level defined by a material's yield point.

Tensile Strength

The tensile strength of a material is the stress level defined by the maximum tensile load that it can resist without failure. Tensile strength corresponds to the highest ordinate on the stress-strain curve and is sometimes referred to as the ultimate strength.

Toughness

Toughness is a measure of the energy required to break a material. It is related to ductility. Toughness is not necessarily related to strength. A material might have high strength but little toughness. A ductile material with the same strength as a non-ductile material will require more energy to break and thus exhibit more toughness. For highway bridges, the CVN (Charpy V-notch) toughness is the toughness value usually used. It is an indicator of the ability of the steel to resist crack propagation in the presence of a notch or flaw. The unit for toughness ft-lbs @ degrees F.

2.6 Bridge Movements

Bridges move because of many factors; some are anticipated, but others are not. Unanticipated movements generally result from settlement, sliding, and rotation of foundations. Anticipated movements include live load deflections, thermal expansions and contractions, shrinkage and creep, earthquakes, rotations, wind drifting, and vibrations. Of these movements, the three major anticipated movements are live load deflections, thermal movements, and rotational movements.

Live Load Deflections

Deflection produced by live loading should not be excessive because of aesthetics, user discomfort, and possible damage to the whole structure.

Limitations are generally expressed as a deflection-to-span ratio. AASHTO generally limits live load bridge deflection for steel and concrete bridges to 1/800 (i.e., 1inch) vertical movement per 67 feet of span length). For bridges that have sidewalks, AASHTO limits live load bridge deflection to 1/1000 (1-inch vertical movement per 83 feet of span length).

Thermal Movements

The longitudinal expansion and contraction of a bridge is dependent on the range of temperature change, length of bridge, and most importantly, materials used in construction. Thermal movements are frequently accommodated using expansion joints and movable bearings. To accommodate thermal movements, AASHTO recommends the designer allow 1-1/4 inches of movement for each 100 feet of span length for steel bridges and 1-3/16 inches of movement for each 100 feet of span length for concrete bridges.

Rotational Movements

Rotational movement in bridges is a direct result of live load deflection and occurs with the greatest magnitude at the bridge supports. This movement can be accommodated using bearing devices that permit rotation.

2.7 Design Methods

Bridge engineers use various design methods that incorporate safety factors to account for uncertainties and random deviations in material strength, fabrication, construction, durability, and loadings.

Allowable Stress Design

The Allowable Stress Design (ASD) or Working Stress Design (WSD) is a method in which the maximum stress a particular member may carry is limited to an allowable or working stress. The allowable or working stress is determined by applying an appropriate factor of safety to the limiting stress of the material. For example, the allowable tensile stress for a steel tension member is 0.55 times the steel yield stress. This results in a safety factor of 1.8. The capacity of the member is based on either the inventory rating level or the operating rating level. AASHTO currently has ten possible WSD group loadings.

Load Factor Design

Load Factor Design (LFD) is a method in which the ultimate strength of a material is limited to the combined effect of the factored loads. The factored loads are determined from the applied loadings, which are increased by selected multipliers that provide a factor of safety. The load factors for AASHTO Group I are 1.3(DL+1.67(LL+I)). AASHTO currently has ten possible LFD group loadings.

Load and Resistance Factor Design

Load and Resistance Factor Design (LRFD) is a design procedure based on the actual strength, rather than on an arbitrary calculated stress. It is an ultimate strength concept where both working loads and resistance are multiplied by factors, and the design performed by assuming the strength exceeds the load. (The load multipliers used in LRFD are not the same multipliers that are used in LFD.)

These design methods are conservative due to safety factors and limit the stress in bridge members to a level well within the material's elastic range, provided that the structural members are in good condition. That is why it is important to accurately report any deficiency found in the members.

2.8 Bridge Ratings

The bridge engineer should understand the principles of bridge load ratings. Bridge load rating methods and guidelines are provided by AASHTO in the *Manual for Condition Evaluation of Bridges, and Manual for Condition Evaluation and LRFR of Highway Bridges.*

A bridge load rating is used to determine the usable live load capacity of a bridge. Each member of a bridge has a unique load rating, and the bridge load rating represents the most critical one. Bridge load rating is generally expressed in units of tons, and it is computed based on the following basic formula:

$$\text{Bridge Rating Factor (RF)} = \frac{C - A_1 D}{A_2 L(1 + I)}$$

where:

RF = the rating factor for the live-load carrying capacity; the rating factor multiplied by the rating vehicle in tons gives the rating of the structure
C = the capacity of the member
D = the dead load effect on the member
L = the live load effect on the member
I = the impact factor to be used with the live load effect
A_1 = factor for dead loads
A_2 = factor for live loads

Bridge load rating for LRFR is computed based on the following basic formula:

$$\text{Bridge Rating Factor (RF)} = \frac{C - (\gamma_{DC})(DC) - (\gamma_{DW})(DW) \pm (\gamma_P)(P)}{(\gamma_L)(LL + IM)}$$

where:

RF = rating factor
C = capacity
DC = dead load effect due to structural components and attachments
DW = dead load effect due to wearing surface and utilities P = permanent load other than dead loads
LL = live load effect
IM = dynamic load allowance
γ_{DC} = LRFD load factor for structural components and attachments
γ_{DW} = LRFD load factor for wearing surfaces and utilities
γ_P = LRFD load factor for permanent loads other than dead loads = 1.0
γ_L = evaluation live-load factor

Both of the formulas above determine a rating factor for the controlling member of the bridge. For either case, the safe load capacity in tons can be calculated as follows:

RT = RFxW

where:

RT = rating in tons for truck used in computing live-load effect
RF = rating factor
W = weight in tons of truck used in computing live-load effect

Note that when LRFR lane loading controls the rating, the equivalent truck weight (W) to be used in calculating the safe load capacity in tons is 40 tons.

Inventory Rating

The inventory rating level generally corresponds to the customary design level of stresses but reflects the existing bridge and material conditions with regard to deterioration and loss of section. Load ratings based on the inventory level allow comparisons with the capacity for new structures and, therefore, results in a live load, which can safely utilize an existing structure for an indefinite period of time. For the allowable stress method, the inventory rating for steel used to be based on 55% of the yield stress. Inventory ratings have been refined to reflect the various material and load types. See the *AASHTO Manual for Condition Evaluation of Bridges.*

The LRFD design level is comparable to the traditional Inventory rating. Bridges that pass HL-93 screening at the Inventory level are capable of carrying AASHTO legal loads and state legal loads within the AASHTO exclusion limits described in the *LRFD Bridge Design Specifications.*

Operating Rating

Load ratings based on the operating rating level generally describe the maximum permissible live load to which the structure may be subjected. Allowing unlimited numbers of vehicles to use the bridge at operating level may shorten the life of the bridge. For steel, the allowable stress for operating rating used to be 75% of the yield stress. Operating ratings have been refined to reflect the various material and load types. See the *AASHTO Manual for Condition Evaluation of Bridges.*

Permit Loading

Special permits for heavy non normal vehicles may occasionally be issued by a governing agency. The load produced by the permit vehicle must not exceed the structural capacity determined by the operating rating.

The second level rating is a legal load rating providing a single safe load capacity for a specific truck configuration. The second level rating is comparable to the traditional Operating rating. Bridges that pass HL-93 screening at the Operating level are capable of carrying AASHTO legal loads, but may not rate for state legal loads especially those that are considerably heavier than AASHTO trucks.

The third level rating is used to check the serviceability and safety of bridges in the review of permit applications. Permits are required for vehicles above the legal load. This third level rating is only applied to bridges with sufficient capacity for AASHTO legal loads. Calibrated load factors by permit type and traffic conditions are specified for checking the effect of the overweight vehicle. Guidance on checking serviceability criteria are also given.

Rating Vehicles

Rating vehicles are truck loads applied to the bridge to establish the inventory and operating ratings. These rating vehicles (see Figure 2.18) include:

- H loading
- HS loading
- HL-93
- Alternate Interstate Loading (Military Loading)
- Type 3 unit
- Type 3-S2 unit
- Type 3-3 unit
- The maximum legal load vehicles of the state

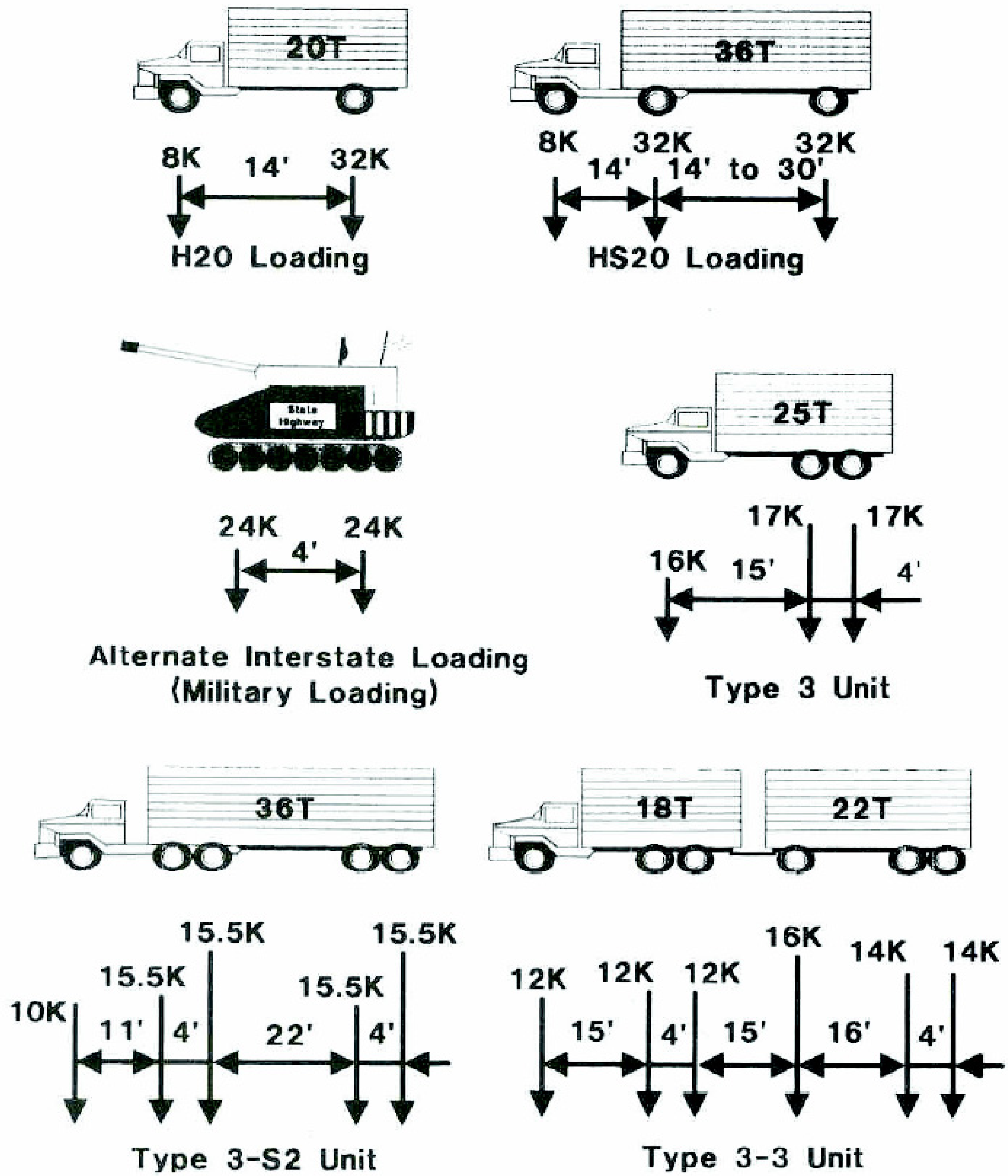


Figure 2.18 Rating Vehicles

The axle spacing and weights of the Type 3 unit, Type 3-S2 unit, and Type 3-3 unit are based on actual vehicles. However, as described previously, the H and HS loadings do not represent actual vehicles.

These standard rating vehicles were chosen based on load regulations of most states and governing agencies. However, individual states and agencies may also establish their own unique rating vehicles.

Bridge Posting

Bridge loads are posted to warn the public of the load capacity of a bridge, to avoid safety hazards, and to adhere to federal law. Federal regulation requires highway bridges on public roads to be inspected every twenty-four months for lengths greater than 20 feet. Federal regulation also requires bridges to be posted when the State's

legal loads exceed the operating rating or equivalent rating factor for the bridge. It is the engineer's responsibility to gather and provide information that can be used to analyze and rate the bridge.
The safe load-carrying capacity of a bridge considers the following criteria:

- Physical condition
- Potential for fatigue damage
- Type of structure/configuration
- Truck traffic data

Bridge postings show the maximum allowable load by law for single vehicles and combinations while still maintaining an adequate safety margin.

Failure to comply with bridge posting may result in fines, tort suits/financial liabilities, accidents, or even death. In addition, bridges may be damaged when postings are ignored.

2.9 Span Classifications

Beams and bridges are classified into three span classifications that are based on the nature of the supports and the interrelationship between spans. These classifications are:

- Simple
- Continuous
- Cantilever

Simple

A simple span is a span with only two supports, each of which is at or near the end of the span (see Figure 2.19).

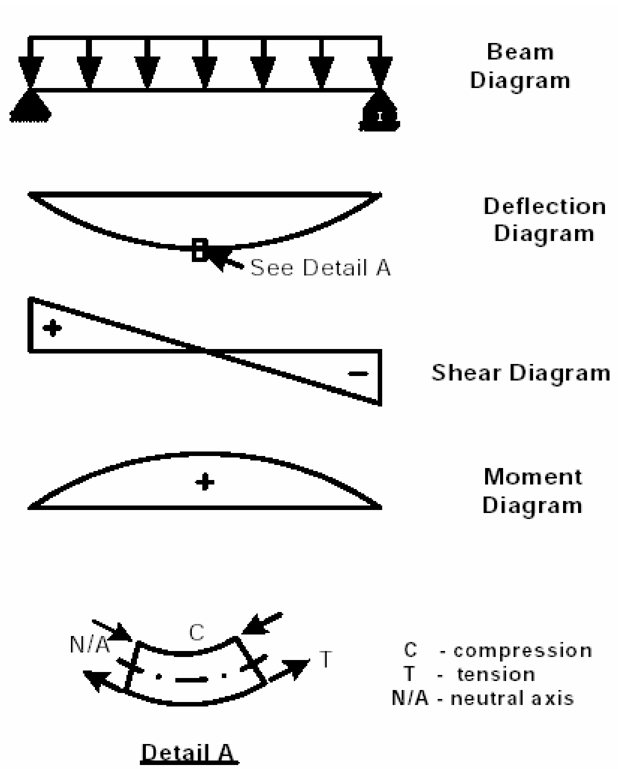


Figure 2.19 Simple Span

A simple span bridge can have a single span supported at the ends by two abutments or multiple spans with each span behaving independently of the others. Some characteristics of simple span bridges are:

When loaded, the span deflects downward and rotates at the supports (i.e., the abutments)

- The sum of the reactions provided by the two supports equals the entire load
- Shear forces are maximum at the supports and zero at or near the middle of the spans
- Bending moment throughout the span is positive and maximum at or near the middle of the span (the same location at which shear is zero); bending moment is zero at the supports
- The part of the superstructure below the neutral axis is in tension while the portion above the neutral axis is in compression

A simple span bridge is easily analyzed using equilibrium equations. However, it does not always provide the most economical design solution.

Continuous

A continuous span is a configuration in which a beam has one or more intermediate supports and the behavior of each individual span is dependent on its adjacent spans (see Figure 2.20).

A continuous span bridge is one which is supported at the ends by two abutments and which spans uninterrupted over one or more piers. Some characteristics of continuous span bridges are:

- When loaded, the spans deflect downward and rotate at the supports (i.e., the abutments and the piers)
- The reactions provided by the supports depend on the span configuration and the distribution of the loads
- Shear forces are maximum at the supports and zero at or near the middle of the spans
- Positive bending moment is greatest at or near the middle of each span
- Negative bending moment is greatest at the intermediate supports (i.e., the piers); the bending moment is zero at the end supports (i.e., the abutments); there are also two locations per intermediate support at which bending moment is zero, known as inflection points
- For positive bending moments, compression occurs on the top portion of the beam and tension occurs on the bottom portion of the beam
- For negative bending moments, tension occurs on the top portion of the beam and compression occurs on the bottom portion of the beam

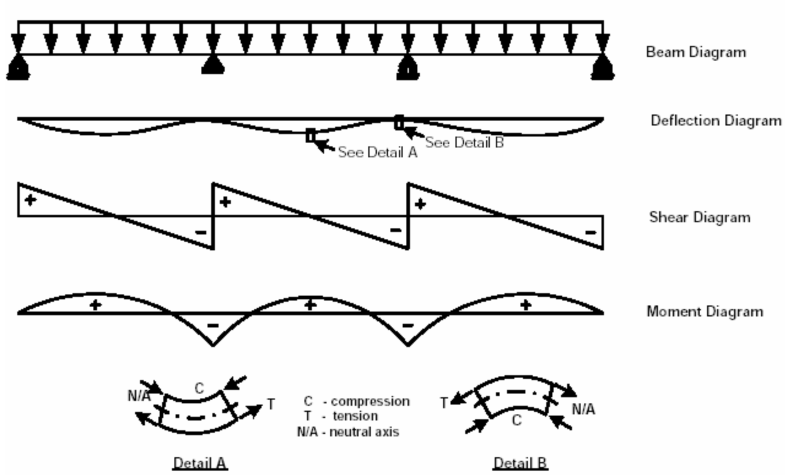


Figure 2.20 Continuous Span

A continuous span bridge allows longer spans and is more economical than a bridge consisting of many simple spans. This is due to its efficient design with members that are shallower. However, a continuous bridge is more difficult to analyze than a simple span bridge and is more susceptible to overstress conditions if the abutments or piers settle.

Cantilever

A cantilever span is a span with one end restrained against rotation and deflection and the other end completely free (see Figure 2.21). The restrained end is also known as a fixed support.

While a cantilever generally does not form an entire bridge, portions of a bridge can behave as a cantilever (e.g., cantilever bridges and bascule bridges). Some characteristics of cantilevers are:

- When loaded, the span deflects downward, but there is no rotation or deflection at the support
- The fixed support reaction consists of a vertical force and a resisting moment
- The shear is maximum at the fixed support and is zero at the free end
- The bending moment throughout the span is negative and maximum at the fixed support; bending moment is zero at the free end

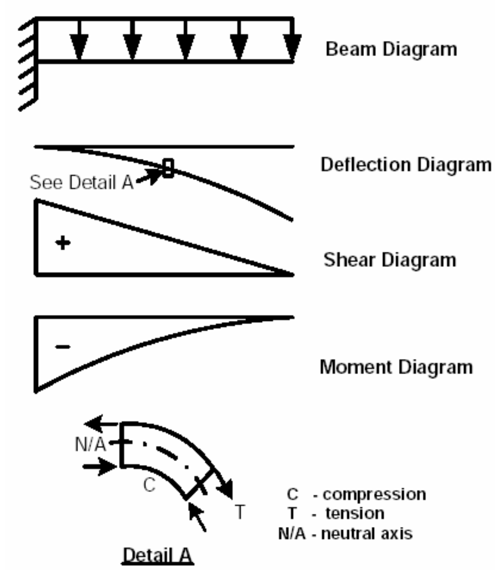


Figure 2.21 Cantilever Span

When cantilever spans are incorporated into a bridge, they are generally extensions of a continuous span. Therefore, moment and rotation at the cantilever support will be dependent on the adjacent span (see Figure 2.22).

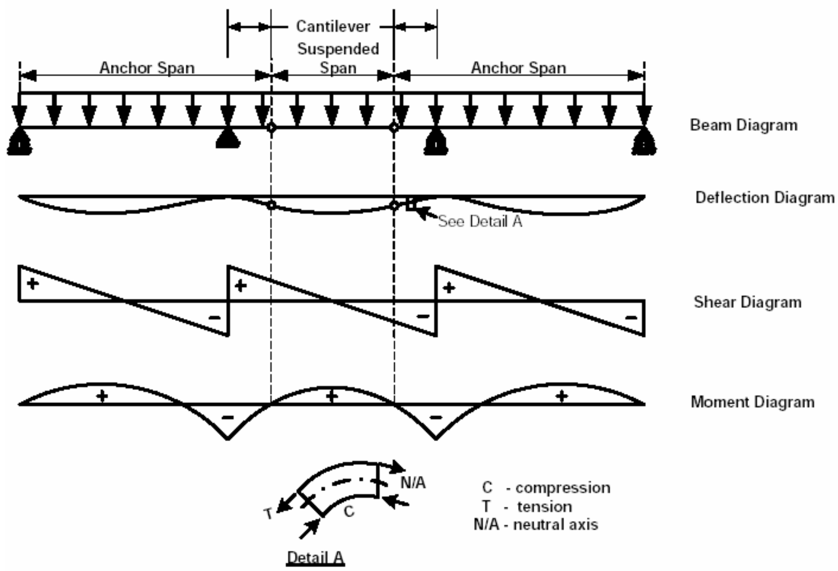


Figure 2.22 Cantilever Bridge

2.10 Bridge Roadway Interaction

Bridges also have two classifications that are based on the relationship between the deck and the superstructure. These classifications are:

- Non-composite
- Composite

Non-composite

A non-composite structure is one in which the superstructure acts independently of the deck. The beams or floor systems alone must resist all of the loads applied to them, including the dead load of the superstructure, deck, and railing, and all of the live loads.

Composite

A composite structure is one in which the deck acts together with the superstructure to resist the loads (see Figure 2.23). The deck material must be strong enough to contribute significantly to the overall strength of the section. The deck material is different than the superstructure material. The most common combinations are concrete deck on steel superstructure and concrete deck on prestressed concrete superstructure. Shear connectors such as studs, spirals, channels, or stirrups that are attached to the superstructure and are embedded in a deck provide composite action. This ensures that the superstructure and the deck will act as a unit by preventing slippage between the two when a load is applied.

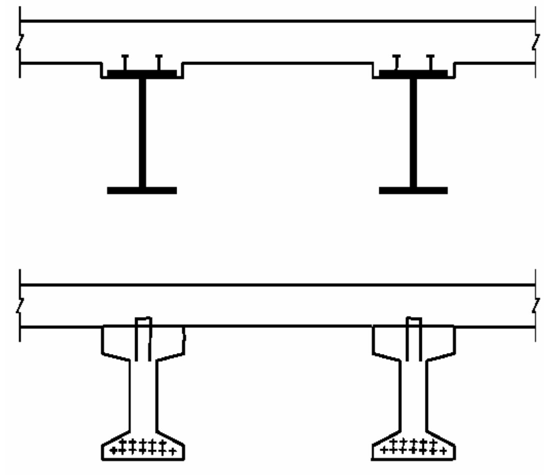


Figure 2.23 Composite Concrete Deck on Steel Beams and Pretressed Concrete Beams

Composite action is achieved only after the concrete deck has hardened. Therefore, some of the dead load (Dead Load 1) must be resisted by the non-composite action of the superstructure alone. These dead loads include the weight of:

- The superstructure itself
- Any diaphragms and cross-bracing
- The concrete deck
- Any concrete haunch between the superstructure and the deck
- Any other loads which are applied before the concrete deck has hardened

Other dead loads, known as superimposed dead loads (Dead Load 2), are resisted by the superstructure and the concrete deck acting compositely. Superimposed dead loads include the weight of:

- Any anticipated future deck pavement
- Parapets
- Railings
- Any other loads which are applied after the concrete deck has hardened

Since live loads are applied to the bridge only after the deck has hardened, they are also resisted by the composite section.

The bridge engineer can identify a simple span, a continuous span, and a cantilever span based on their configuration. However, the bridge engineer can not identify the relationship between the deck and the superstructure while at the bridge site. Therefore, bridge plans must be reviewed to determine whether a structure is non-composite or composite.

Integral

On an integral bridge deck, the deck portion of the beam is constructed to act integrally with the stem, providing greater stiffness and allowing increased span lengths (see Figure 2.24).

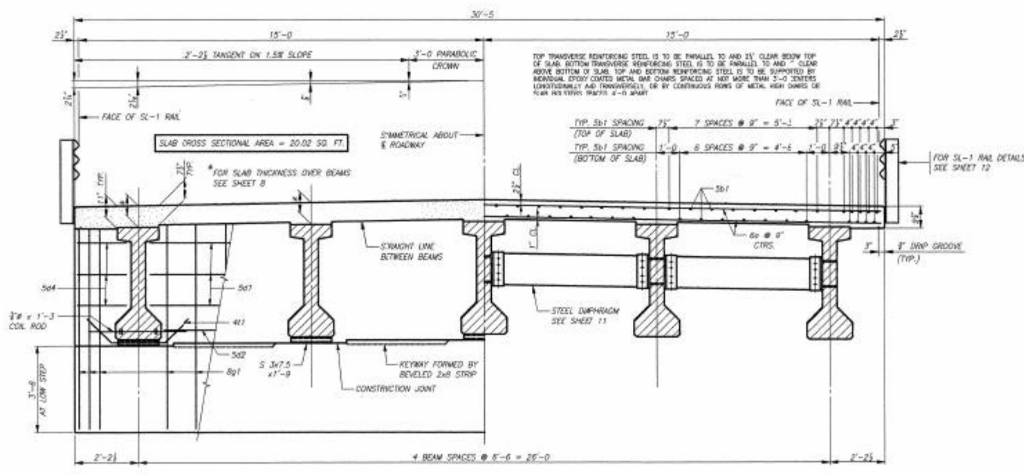


Figure 2.24 Integral Bridge

Orthotropic

An orthotropic deck consists of a flat, thin steel plate stiffened by a series of closely spaced longitudinal ribs at right angles to the floor beams. The deck acts integrally with the steel superstructure. An orthotropic deck becomes the top flange of the entire floor system. Orthotropic decks are occasionally used on large bridges (see Figure 2.25).

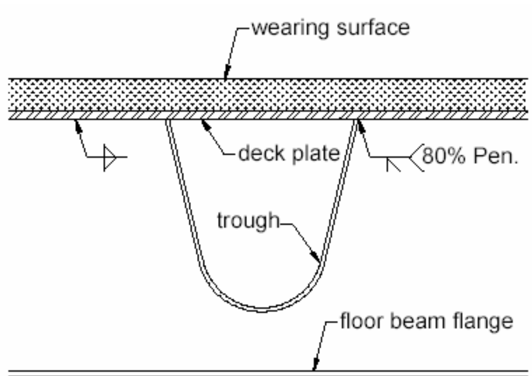


Figure 2.25 Orthotropic Bridge Deck

2.11 Redundancy

Redundancy is the quality of a bridge that enables it to perform its design function in a damaged state.

There are three types of redundancy in bridge design:

- Load Path Redundancy
- Structural Redundancy
- Internal Redundancy

Load Path Redundancy

Bridge designs that are load path redundant have three or more main load-carrying members or load paths between supports. If one member were to fail, load would be redistributed to the other members and bridge failure would not be expected. Bridge designs that are non-redundant have two or fewer main load carrying members or load paths.

Structural Redundancy

Most bridge designs, which provide continuity of load path from span to span are referred to as structurally redundant. Some continuous span two-girder bridge designs are structurally redundant. In the event of a member failure, loading from that span can be redistributed to the adjacent spans and total bridge failure may not occur.

Internal Redundancy

Internal redundancy is when a bridge member contains several elements which are mechanically fastened together so that multiple load paths are formed. Failure of one member element would not cause total failure of the member.

2.12 Foundations

Foundations are critical to the stability of the bridge since the foundation ultimately supports the entire structure. There are two basic types of bridge foundations:

- Shallow foundations commonly referred to as spread footings
- Deep foundations

Spread Footings

A spread footing is used when the bedrock layers are close to the ground surface or when the soil is capable of supporting the bridge. A spread footing is typically a rectangular slab made of reinforced concrete. This type of foundation "spreads out" the loads from the bridge to the underlying rock or well-compacted soil. While a spread footing is usually buried, it is generally covered with a minimal amount of soil. In cold regions, the bottom of a spread footing will be just below the recognized maximum frost line depth for that area (see Figure P.2.29).

Deep Foundations

A deep foundation is used when the soil is not suited for supporting the bridge or when the bedrock is not close to the ground surface. A pile is a long, slender support that is typically driven into the ground but can be partially exposed. It is made from steel, concrete, or timber. Various numbers and configurations of piles can be used to support a bridge foundation. This type of foundation transfers load to sound material well below the surface or, in the case of friction piles, to the surrounding soil (see Figure P.2.30). “Caissons”, “drilled caissons”, and “drilled shafts” are frequently used to transmit loads to bedrock in a manner similar to piles.

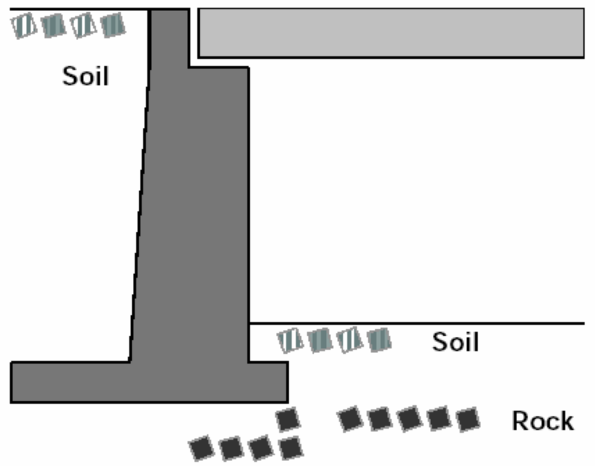


Figure P.2.29 Spread Footing

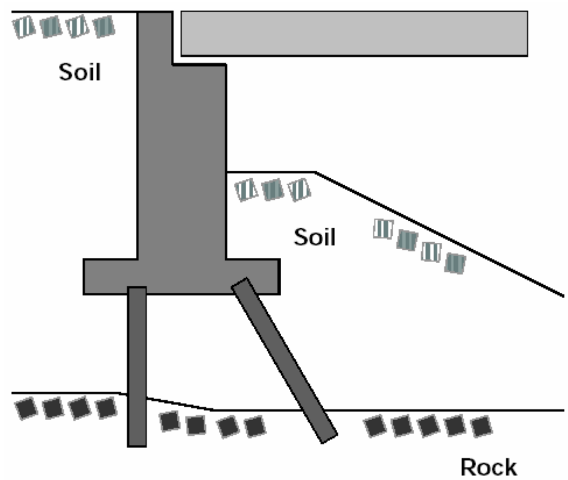


Figure P.2.30 Pile Foundation

Basic Equations of Bridge Mechanics

$$f_a = \frac{P}{A}$$

$$S = \frac{F}{A}$$

$$f_b = \frac{Mc}{I}$$

$$\varepsilon = \frac{\Delta L}{L}$$

$$f_v = \frac{V}{A_w}$$

$$E = \frac{S}{\varepsilon}$$

$$\text{Bridge Load Capacity Rating} = \frac{\text{Allowable Load - Dead Load}}{\text{Rating Vehicle Live Load Plus Impact}} \text{ x Vehicles Weight (Tons)}$$

where:

where:	A	=	area; cross-sectional area
	A_w	=	area of web
	c	=	distance from neutral axis to extreme fiber (or surface) of beam
	E	=	modulus of elasticity
	F	=	force; axial force
	f_a	=	axial stress
	f_b	=	bending stress
	f_v	=	shear stress
	I	=	moment of inertia
	L	=	original length
	M	=	applied moment
	S	=	stress
	V	=	vertical shear force due to external loads
	ΔL	=	change in length
	ε	=	strain

3 Bridge Culvert Characteristics

3.1 Introduction

A culvert is a structure designed hydraulically to take advantage of submergence to increase water carrying capacity. Culverts, as distinguished from bridges, are usually covered with embankment and are composed of structural material around the entire perimeter, although some are supported on spread footings with the streambed serving as the bottom of the culvert. Culverts may qualify to be considered “bridge” length.

Over the years, culverts have traditionally received less attention than bridges. Since culverts are less visible it is easy to put them out of mind, particularly when they are performing adequately. Additionally, a culvert usually represents a significantly smaller investment than a bridge and in the event of a failure usually represents much less of a safety hazard.

Small bridges have been replaced with multiple barrel culverts, box culverts, or long span culverts (see Figure 3.1). There have also been recent advances in culvert design and analysis techniques. Long span corrugated metal culverts with spans in excess of 40 feet were introduced in the late 1960's.

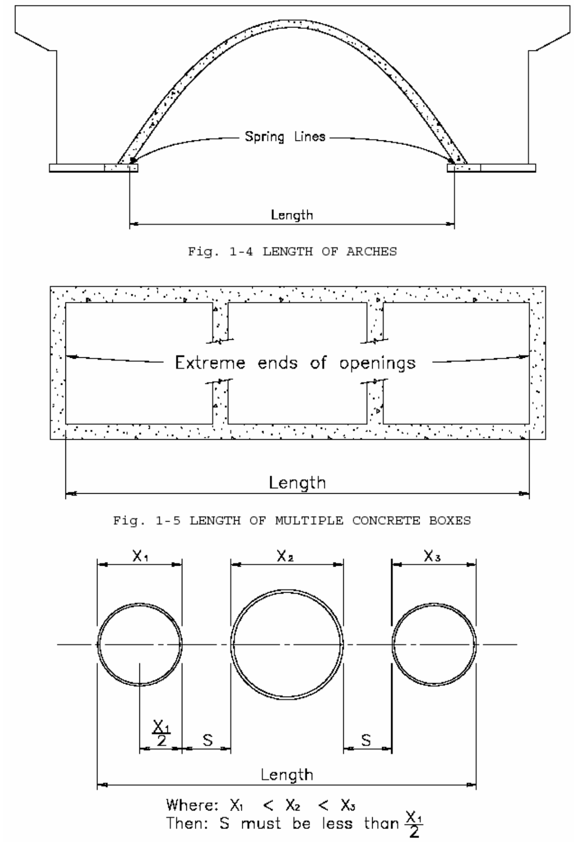


Figure 3.1 Culvert Structure

As a result of these developments, the number, size, complexity, and cost of culvert installations have increased. The failure of a culvert may be more than a mere driving inconvenience. Failure of a major culvert may be both costly and hazardous.

Multiple barrel culvert installations with relatively small pipes meet the definition of a bridge. Structures are evaluated by utilizing standardized inventory appraisal process that is based on rating certain structural and functional features.

Existing road culverts should be inventoried to establish a structural adequacy and to evaluate the potential for roadway overtopping or flooding.

Safety

To insure that a culvert is functioning safely, the engineer should evaluate structural integrity, hydraulic performance, and roadside compatibility.

- Structural Integrity - The failure of major culverts can present a life threatening safety hazard. The identification of potential structural and material problems requires a careful evaluation of indirect evidence of structural distress as well as actual deterioration and distress in the culvert material.
- Hydraulic Performance - When a culvert's hydraulic performance is inadequate, potential safety hazards may result. The flooding of adjacent properties from unexpected headwater depth may occur. Downstream areas may be flooded by failure of the embankment. The roadway embankment or culvert may be damaged because of erosion.
- Roadside Compatibility - Many culverts, like older bridges, present roadside hazards. Headwalls and wingwalls higher than the road or embankment surface may constitute a fixed obstacle hazard. Abrupt

drop-offs over the end of a culvert or steep embankments may represent rollover hazards to vehicles that leave the roadway.

Maintenance Needs

Lack of maintenance is a prime cause of improper functioning culverts and other drainage structures. Regular periodic inspections allow minor problems to be spotted and corrected before they become serious.

Outcomes

The outcome of this section is to provide information necessary to understand and evaluate the significance of defects existing culverts. Therefore, a brief review of how culverts should function structurally and hydraulically is provided, durability concepts is also reviewed.

3.2 Differentiation Between Culverts and Bridges

Traditional definitions of culverts are based on the span length rather than function or structure type. For example, part of the culvert definition is that structures over 20 feet in span parallel to the roadway are usually called bridges; and structures less than 20 feet in span are called culverts even though they support traffic loads directly.

Many structures that measure more than 20 feet along the centerline of the roadway have been designed hydraulically and structurally as culverts. The structural and hydraulic design of culverts is substantially different from bridges, as are construction methods, maintenance requirements, and inspection procedures.

Hydraulic

Culverts are usually designed to operate at peak flows with a submerged inlet to improve hydraulic efficiency. The culvert constricts the flow of the stream to cause ponding at the upstream or inlet end. The resulting rise in elevation of the water surface produces a head at the inlet that increases the hydraulic capacity of the culvert. Bridges may constrict flow to increase hydraulic efficiency or be designed to permit water to flow over the bridge or approach roadways during peak flows. However, bridges are generally not designed to take advantage of inlet submergence to the degree that is commonly used for culverts. The effects of localized flooding on appurtenant structures, embankments, and abutting properties are important considerations in the design and inspection of culverts.

Structural

Culverts are usually covered by embankment material. Culverts must be designed to support the dead load of the soil over the culvert as well as live loads of traffic. Either live loads or dead loads may be the most significant load element depending on the type of culvert, type and depth of cover, and amount of live load. However, live loads on culverts are generally not as significant as the dead load unless the cover is shallow. Box culverts with shallow cover are examples of the type of installation where live loads may be significant.
In most culvert designs the soil or embankment material surrounding the culvert plays an important structural role. Lateral soil pressures enhance the culverts ability to support vertical loads. The stability of the surrounding soil is important to the structural performance of most culverts.

Maintenance

Because culverts usually constrict flow there is an increased potential for waterway blockage by debris and sediment, especially for culverts subject to seasonal flow. Multiple barrel culverts may also be particularly susceptible to debris accumulation. Scour caused by high outlet velocity and turbulence at inlet end is a concern. As a result of these factors, routine maintenance for culverts primarily involves the removal of obstructions and the repair of erosion and scour. Prevention of joint leakage may be critical in culverts bedded in pipeable soils to prevent undermining and loss of support.

Traffic Safety

A significant safety advantage of many culverts is the elimination of bridge parapets and railings. Culverts can usually be extended so that the standard roadway cross section can be carried over the culvert to provide a vehicle recovery area. However, when ends are located near traffic lanes or adjacent to shoulders, guardrails may be used to protect the traffic. Another safety advantage of culverts is that less differential icing occurs. Differential icing is the tendency of water on the bridge deck to freeze prior to water on the approaching roadway. Since culverts are under fill material and do not have a bridge deck, the temperature of the roadway over the culvert is at or near the temperature of the roadway approaching the culvert.

Construction

Careful attention to construction details such as bedding, compaction, and trench width during installation is important to the structural integrity of the culvert. Poor compaction or poor quality backfill around culverts may result in uneven settlement over the culvert and possibly structural distress of the culvert.

Durability

Durability of material is a significant problem in culverts and other drainage structures. In very hostile environments such as acid mine drainage and chemical discharge, corrosion and abrasion can cause deterioration of all commonly available culvert materials.

Inspection

The inspection and assessment of the structural condition of culverts requires an evaluation of not only actual distress but circumstantial evidence such as roadway settlement, pavement patches, and embankment condition.

3.3 Structural Characteristics of Culverts

Loads on Culverts

In addition to their hydraulic functions, culverts must also support the weight of the embankment or fill covering the culvert and any load on the embankment. There are two general types of loads that must be carried by culverts: dead loads and live loads.

Dead Loads

Dead loads include the earth load or weight of the soil over the culvert and any added surcharge loads such as buildings or additional earth fill placed over an existing culvert. If the actual weight of earth is not known, 120 pounds per cubic foot is generally assumed.

Live Loads

The live loads on a culvert include the loads and forces, which act upon the culvert due to vehicular or pedestrian traffic. The highway wheel loads generally used for analysis are shown in Figure 3.2. The effect of live loads decreases as the height of cover over the culvert increases. When the cover is more than two feet, concentrated loads may be considered as being spread uniformly over a square with sides 1.75 times the depth of cover. This concept is illustrated in Figure 3.3 and 3.4. In fact, for single spans, if the height of earth fill is more than 8 feet and exceeds the span length, the effects of live loads can be ignored all together. (see AASHTO)

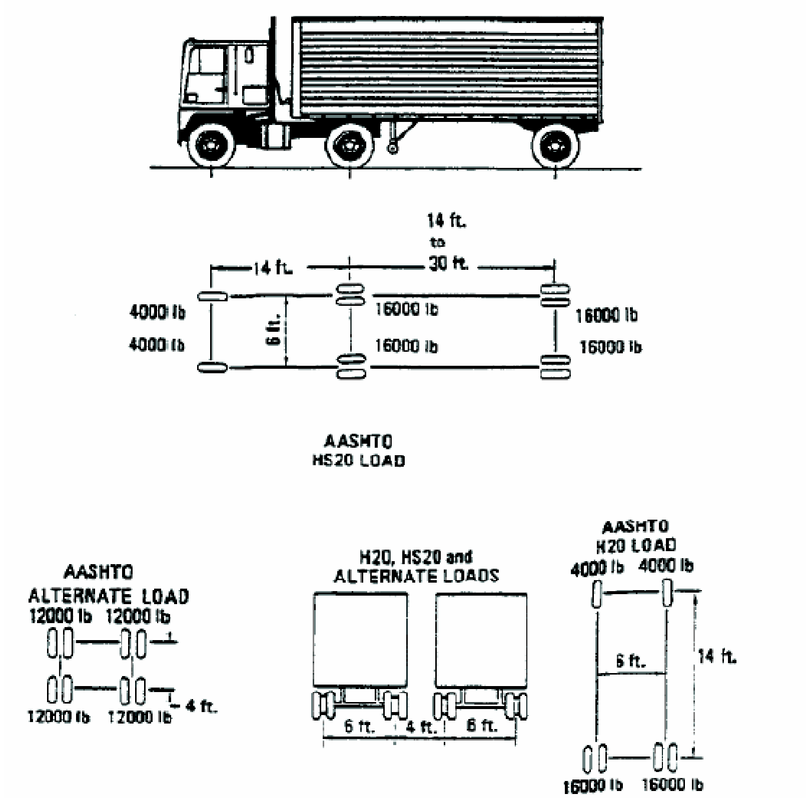


Figure 3.2 AASHTO Live Load Spacing for Highway Structures

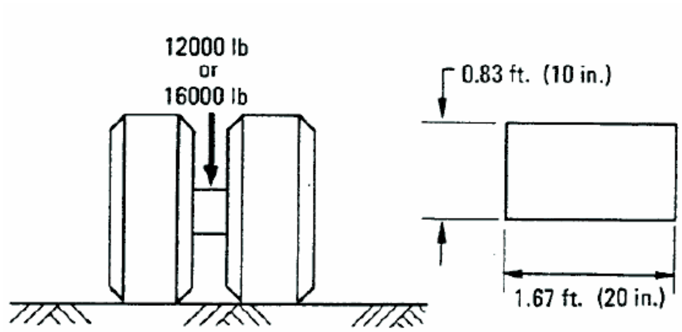


Figure 3.3 Surface Contact Area for Single Dual Wheel

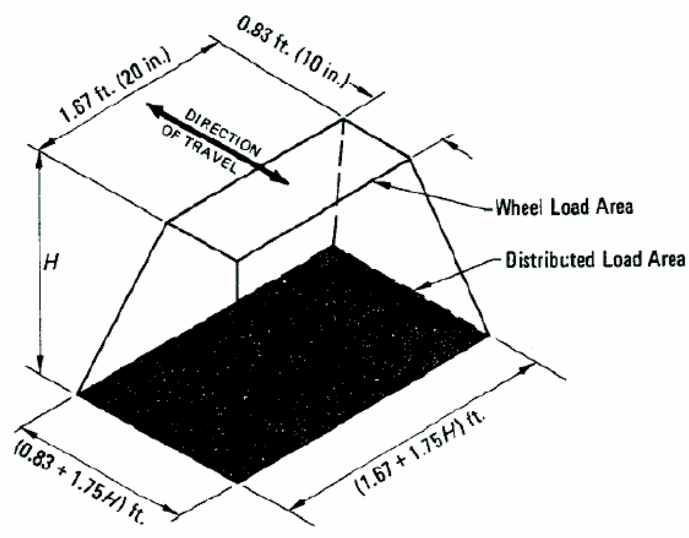


Figure 3.4 Distribution of Live Load (Single Dual Wheel) for Depth of Cover

Categories of Structural Materials

Based upon material type, culverts can be divided into two broad structural categories: rigid and flexible.

Rigid Culverts

Culverts made from materials such as reinforced concrete and stone masonry are very stiff and do not deflect appreciably. The culvert material itself provides the needed stiffness to resist loads. In doing this, zones of tension and compression are created. The culvert material is designed to resist the corresponding stresses.

Flexible culverts

Flexible culverts are commonly made from steel or aluminum. In some states composite materials are used. As stated earlier, flexible culverts rely on the surrounding backfill material to maintain their structural shape. Since they are flexible, they can be deformed significantly with no cracks occurring.

As vertical loads are applied, a flexible culvert will deflect if the surrounding fill material is loose. The vertical diameter decreases while the horizontal diameter increases. Soil pressures resist the increase in horizontal diameter.

For flexible culverts with large openings, sometimes longitudinal and/or circumferential stiffeners are used to prevent excessive deflection.

Construction and Installation Requirements

Circumferential stiffeners are usually metal ribs bolted around the circumference of the culvert. Longitudinal stiffeners may be metal or reinforced concrete. This type of stiffener is sometimes called a thrust beam.
The structural behavior of flexible and rigid culverts is often dependent on construction practices during installation (see Figure 3.5). Items, which require particular attention during construction, are discussed briefly in the following text. This information is provided so that the bridge engineer may gain insight on how certain structural defects affect a culvert.

- Compaction and Side Support - Good backfill material and adequate compaction are of critical importance to flexible culverts. A well-compacted soil envelope is needed to develop the lateral pressures required to maintain the shape of flexible culverts. Well-compacted backfill is also important to the performance of rigid culverts. Poorly compacted soils do not provide the intended lateral support.

- Trench Width - Trench width can significantly affect the earth loads on rigid culverts. It is therefore important that trench widths be specified on the plans and that the specified width not be exceeded without authorization from the design engineer.
- Foundations and Bedding - A foundation capable of providing uniform and stable support is important for both flexible and rigid culverts. The foundation must be able to support the structure at the proposed grade and elevation without concentration of foundation pressures. Foundations should be relatively yielding when compared to side fill. Establishing a suitable foundation requires removal and replacement of any hard spots or soft spots. Bedding is needed to level out any irregularities in the foundation and to insure uniform support. When using flexible culverts, bedding should be shaped to a sufficient width to permit compaction of the remainder of the backfill, and enough loose material should be placed on top of the bedding to fill the corrugations. When using rigid culverts, the bedding should conform to the bedding conditions specified in the plans and should be shaped to allow compaction and to provide clearance for the bell ends on bell and spigot type rigid pipes. Adequate support is critical in rigid pipe installations, or shear stress may become a problem.
- Construction Loads - Culverts are generally designed for the loads they must carry after construction is completed. Construction loads may exceed design loads. These heavy loads can cause damage if construction equipment crosses over the culvert installation before adequate fill has been placed or moves too close to the walls, creating unbalanced loading. Additional protective fill may be needed for equipment crossing points.
- Camber - In high fills the center of the embankment tends to settle more than the areas under the embankment side slopes. In such cases it may be necessary to camber the foundation slightly. This should be accomplished by using a flat grade on the upstream half of the culvert and a steeper grade on the downstream half of the culvert. The initial grades should not cause water to pond or pocket.

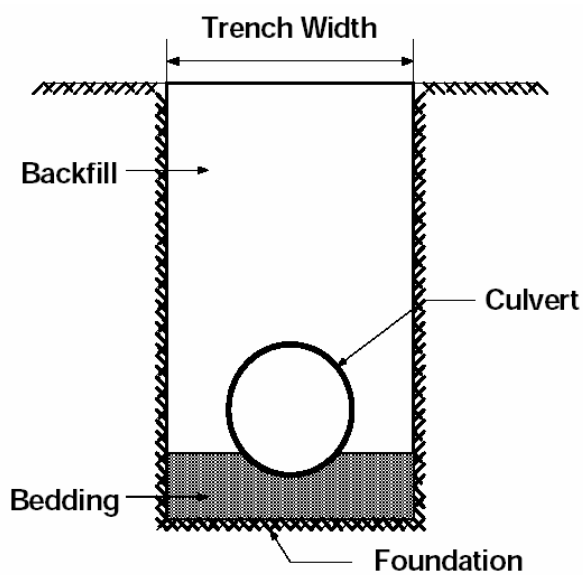


Figure P.3.5 Culvert Construction and Installation Requirements

3.4 Culvert Shapes

A wide variety of standard shapes and sizes are available for most culvert materials. Since equivalent openings can be provided by a number of standard shapes, the selection of shape may not be critical in terms of hydraulic performance. Shape selection is often governed by factors such as depth of cover or limited headwater elevation. In such cases a low profile shape may be needed. Other factors such as the potential for clogging by debris, the need for a natural stream bottom, or structural and hydraulic requirements may influence the selection of culvert shape. Each of the common culvert shapes are discussed in the following paragraphs.

Circular

The circular shape is the most common shape manufactured for pipe culverts (see Figure 3.6). It is hydraulically and structurally efficient under most conditions. Possible hydraulic drawbacks are that circular pipe generally causes some reduction in stream width during low flows. It may also be more prone to clogging than some other shapes due to the diminishing free surface as the pipe fills beyond the midpoint. With very large diameter corrugated metal pipes, the flexibility of the sidewalls dictates that special care be taken during backfill construction to maintain uniform curvature.

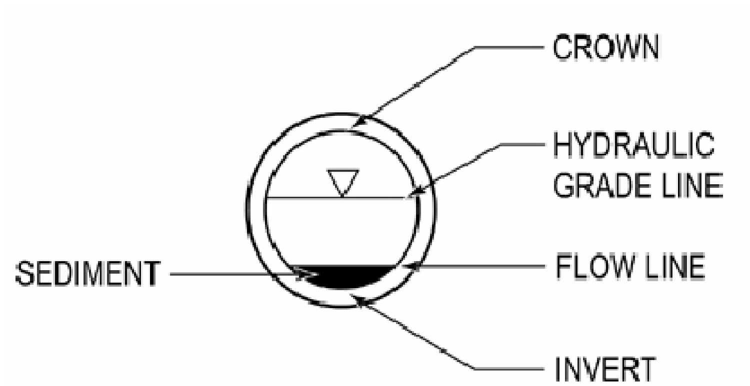


Figure 3.6 Circular Culvert Structure

Arches

Arch culverts offer less of an obstruction to the waterway than pipe arches and can be used to provide a natural stream bottom where the stream bottom is naturally erosion resistant (see Figure 3.7). Foundation conditions must be adequate to support the footings. Riprap is frequently used for scour protection.

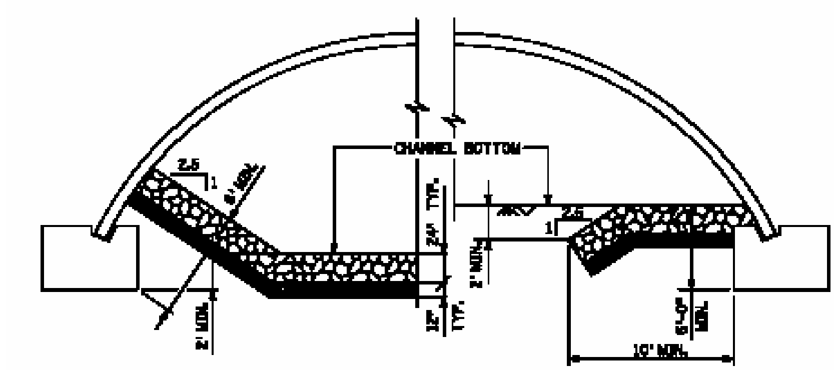


Figure 3.7 Arch Culvert

Box Sections

Rectangular cross-section culverts are easily adaptable to a wide range of site conditions including sites that require low profile structures. Due to the flat sides and top, rectangular shapes are not as structurally efficient as other culvert shapes (see Figure 3.8). In addition, box sections have an integral floor.

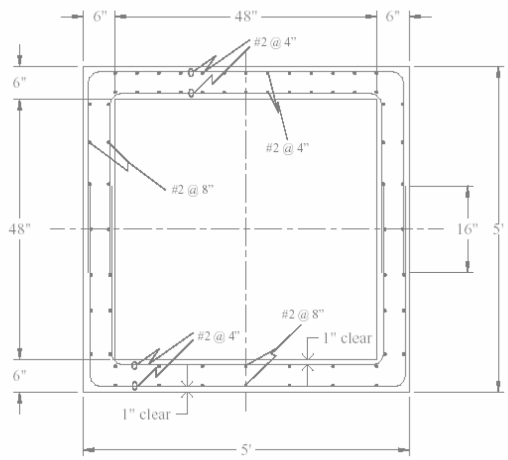


Figure 3.8 Concrete Box Culvert

Multiple Barrels Multiple barrels are used to obtain adequate hydraulic capacity under low embankments or for wide waterways (see Figure 3.9). In some locations they may be prone to clogging as the area between the barrels tends to catch debris and sediment. When a channel is artificially widened, multiple barrels placed beyond the dominant channel are subject to excessive sedimentation. The span or opening length of multiple barrel culverts includes the distance between barrels as long as that distance is less than half the opening length of the adjacent barrels.

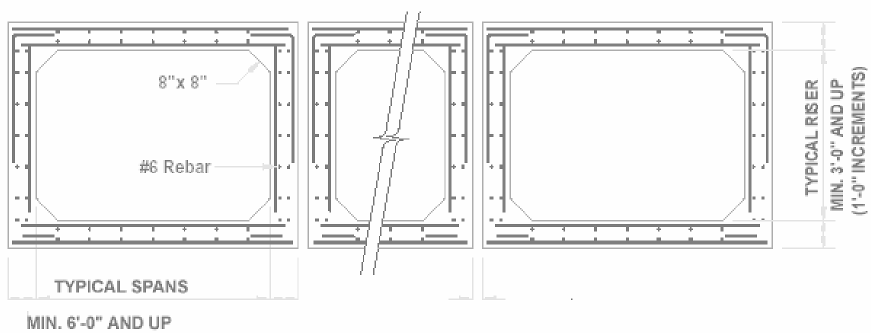


Figure 3.9 Multiple Cell Concrete Culvert

Frame Culverts

Frame culverts are constructed of cast-in-place or precast reinforced concrete. This type of culvert is similar to a Multiple Cell Culvert however frame culverts have no floor (concrete bottom) and fill material is placed over the structure.

3.5 Culvert Materials

Precast Concrete

Precast concrete culverts are manufactured in six standard shapes:

- Circular
- Pipe arch
- Horizontal elliptical
- Vertical elliptical

- Rectangular
- Arch

With the exception of box culverts, concrete culvert pipe is manufactured in up to five standard strength classifications. The higher the classification number, the higher the strength. Box culverts are designed for various depths of cover and live loads. All of the standard shapes are manufactured in a wide range of sizes. Circular and elliptical pipes are available with standard sizes as large as 144 inches in diameter, with larger sizes available as special designs. Standard box sections are also available with spans as large as 144 inches. Precast concrete arches on cast-in-place footings are available with spans up to 41 feet.

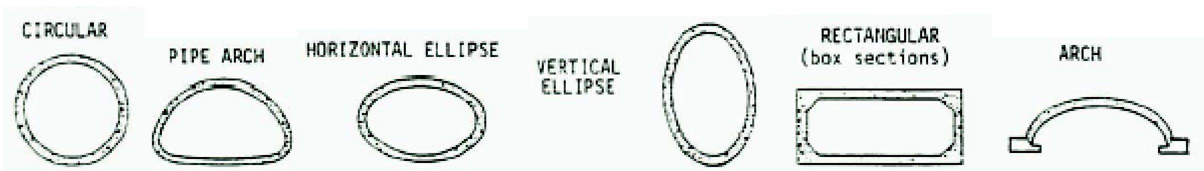


Figure 3.10 Standard Concrete Pipe Shapes

Cast-in-Place Concrete

Culverts that are reinforced cast-in-place concrete are typically either rectangular or arch-shaped. The rectangular shape is more common and is usually constructed with multiple cells (barrels) to accommodate longer spans. One advantage of castin-place construction is that the culvert can be designed to meet the specific requirements of a site. Due to the long construction time of cast-in-place culverts, precast concrete or corrugated metal culverts are sometimes selected. However, in many areas, cast-in-place culverts are more practical and represent a significant number of installations.

Metal Culverts

Flexible culverts are typically either steel or aluminum and are constructed from factory-made corrugated metal pipe or field assembled from structural plates. Structural plate products are available as plate pipes, box culverts, or long span structures. Several factors such as span length, vertical and horizontal clearance, peak stream flow and terrain determine which flexible culvert shape is used.

Masonry

Stone and brick are durable, low maintenance materials. Prior to the 1920's, both stone and brick were used frequently in railroad and road construction projects because they were readily available from rock cuts or local brickyards. Currently stone and brick are seldom used for constructing culvert barrels. Stone is used occasionally for this purpose in locations which have very acidic runoff, but the most common use of stone is for headwalls where a rustic or scenic appearance is desired.

Timber

There are a limited amount of timber culverts throughout the nation. Timber culverts are generally box culverts and are constructed from individual timbers similar to railroad ties. Timber culverts are also analagous to a short span timber bridge on timber abutments.

Existing timber culverts may have the following defects:

- Defects from Checks, Splits, and Shakes
- Decay by Fungi
- Damage by Parasites

- Damage from chemical attack
- Damage from fire
- Damage from Impact/Collisions
- Damage from Abrasion/Wear
- Damage from Overstress
- Damage from Weathering/Warping

3.6 Culvert End Treatments

Aluminum, steel, concrete, and stone masonry are the most commonly found materials for existing culverts. Other materials may have been used for culvert construction, including cast iron, stainless steel, terra cotta, asbestos cement, and plastic. These materials are not commonly found because they are either relatively new (plastic), labor intensive (terra cotta), or used for specialized situations (stainless steel and cast iron).

Culverts may have end treatments or end structures. End structures are used to control scour, support backfill, retain the embankment, improve hydraulic efficiency, protect the culvert barrel, and provide additional stability to the culvert ends.

The most common types of end treatments are:

- Projecting - The barrel simply extends beyond the embankment. No additional support is used.
- Mitered - The end of the culvert is cut to match the slope of the embankment. This type of treatment is also referred to as beveling and is commonly used when the embankment has some sort of slope paving (see Figure 3.11).
- Skewed - Culverts, which are not perpendicular to the roadway, may have their ends cut parallel to the roadway.
- Pipe end section - A section of pipe is added to the ends of the culvert barrel. These are typically used on relatively smaller culverts.
- Headwalls - Used along with wingwalls to retain the fill, resist scour, and improve the hydraulic capacity of the culvert. Headwalls are usually reinforced concrete (see Figure 3.12), but can be constructed of timber or masonry. Metal headwalls are usually found on metal box culverts.

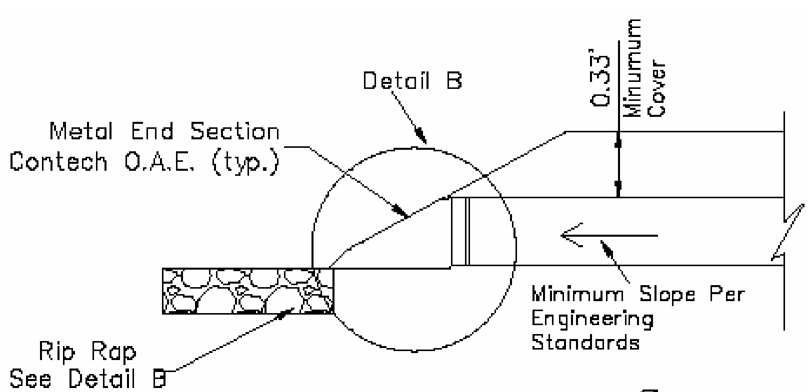


Figure 3.11 Culvert Mitered End

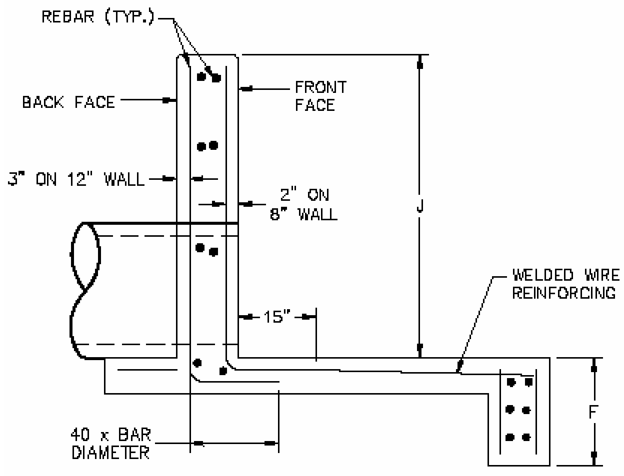


Figure 3.12 Culvert Headwall

Miscellaneous Appurtenance Structures may also be used with end treatments to improve hydraulic efficiency and reduce scour. Typical appurtenances are:

- Aprons - Used to reduce streambed scour at the inlets and outlets of culverts. Aprons are typically concrete slabs, but they may also be riprap. Most aprons include an upstream cutoff wall to protect against undermining.
- Energy Dissipators - Used when outlet velocities are likely to cause streambed scour downstream from the culvert. Stilling basins, riprap or other devices that reduce flow velocity can be considered energy dissipators (see Figure 3.13).

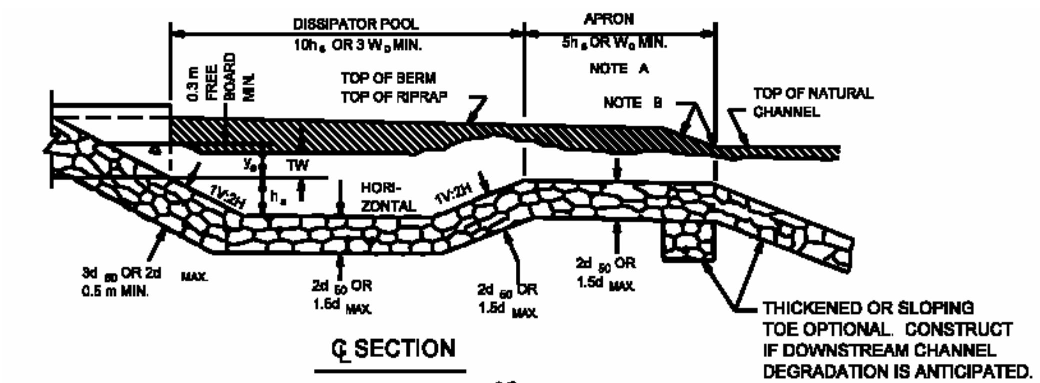


Figure 3.13 Riprap Type Energy Dissipator

3.7 Hydraulics of Culverts

Culverts are primarily constructed to convey water under a highway, railroad, or other embankment. A culvert which does not perform this function properly may jeopardize the throughway, cause excessive property damage, or even loss of life. The hydraulic requirements of a culvert usually determine the size, shape, slope, and inlet and outlet treatments. Culvert hydraulics can be divided into two general design elements:

- Hydrologic Analysis
- Hydraulic Analysis

A hydrologic analysis is the evaluation of the watershed area for a stream and is used to determine the design discharge or the amount of runoff the culvert should be designed to convey.

A hydraulic analysis is used to select a culvert, or evaluate whether an existing culvert is capable of adequately conveying the design discharge. To recognize whether a culvert will perform adequately the engineer should understand the factors that influence the amount of runoff to be handled by the culvert as well as the factors which influence the culvert's hydraulic capacity.

Hydrologic Analysis

Most culverts are designed to carry the surface runoff from a specific drainage area. The selection and use of appropriate methods of estimating runoff requires a person experienced in hydrologic analysis, it is necessary to understand how changes in the topography of the drainage area can cause major changes in runoff. Climatic and topographic factors are briefly discussed in the following sections.

Climatic Factors

Climatic factors that may influence the amount of runoff include:

- Rainfall intensity
- Storm duration
- Rainfall distribution within the drainage area
- Soil moisture
- Snow melt
- Rain-on-snow
- Rain-hail
- Other factors

Topographic Factors

Topographic factors that may influence runoff include:

- The land use within the drainage area
- The size, shape, and slope of the drainage area
- Other factors such as the type of soil, elevation, and orientation of the area

Land use is the most likely characteristic to change significantly during the service life of a culvert. Changes in land use may have a considerable effect on the amount and type of runoff. Some surface types will permit more infiltration than other surface types. Practically all of the rain falling on paved surfaces will drain off while much less runoff will result from undeveloped land. If changes in land use were not planned during the design of a culvert, increased runoff may exceed the capacity of an existing culvert when the land use does change.

The size, shape, and slope of a culvert's drainage area influence the amount of runoff that may be collected and the speed with which it will reach the culvert. The amount of time required for water to flow to the culvert from the most remote part of a drainage area is referred to as the time of concentration. Changes within the drainage area may influence the time of concentration.

Straightening or enclosing streams and eliminating temporary storage by replacing undersized upstream pipes are examples of changes which may decrease time of concentration. Land use changes may also decrease time of concentration since water will flow more quickly over paved surfaces. Since higher rainfall intensities occur for shorter storm durations, changes in time of concentration can have a significant impact on runoff. Drainage areas are sometimes altered and flow diverted from one watershed to another.

Hydraulic Capacity

The factors affecting capacity may include headwater depth, tailwater depth, inlet geometry, the slope of the culvert barrel, and the roughness of the culvert barrel. The various combinations of the factors affecting flow can be grouped into two types of conditions in culverts:

- Inlet control
- Outlet control

Inlet Control

Under inlet control the discharge from the culvert is controlled at the entrance of the culvert by headwater depth and inlet geometry (see Figure 3.14). Inlet geometry includes the cross-sectional area, shape, and type of inlet edge. Inlet control governs the discharge as long as water can flow out of the culvert faster than it can enter the culvert.

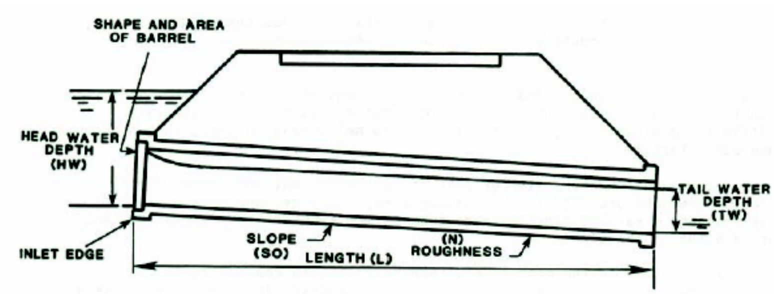


Figure 3.14 Factors Affecting Culvert Discharge

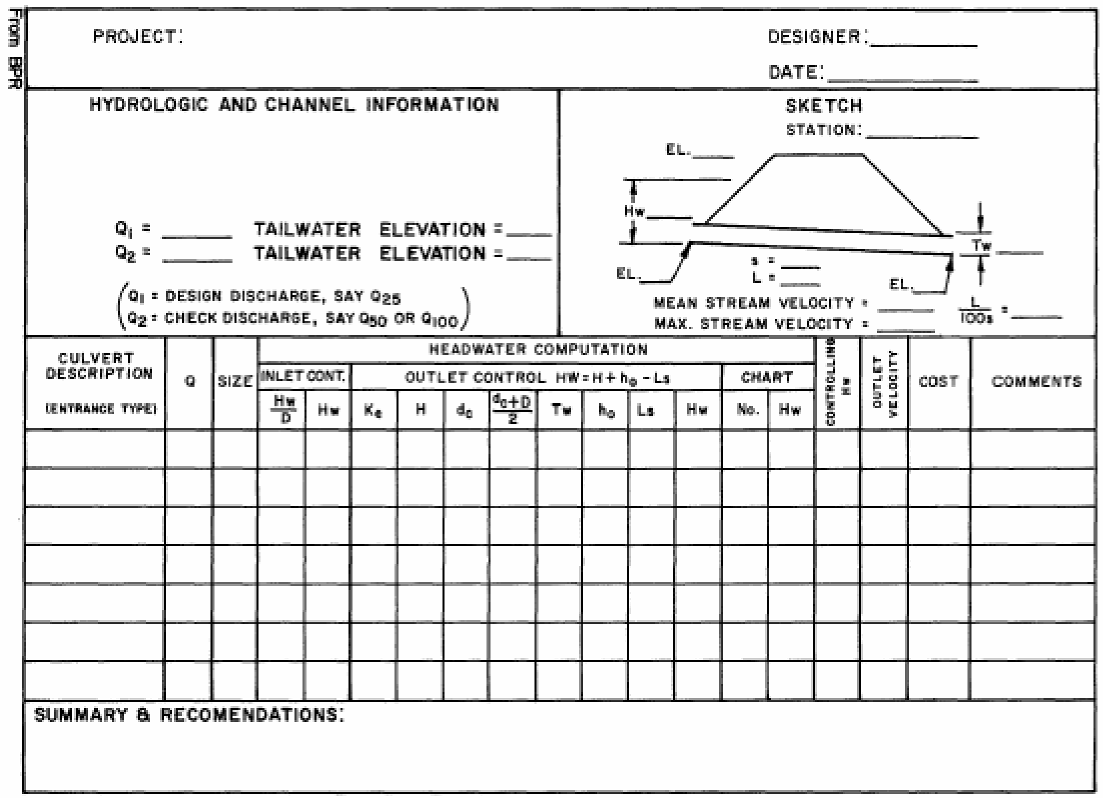
Most culverts, except those in flat terrain, are designed to operate under inlet control during peak flows. Since the entrance characteristics govern, minor modifications at the culvert inlet can significantly effect hydraulic capacity. For example, change in the approach alignment of the stream may reduce capacity, while the improvement of the inlet edge condition, or addition of properly designed headwalls and wingwalls, may increase the capacity.

Outlet Control

Under outlet control water can enter the culvert faster than water can flow through the culvert. The discharge is influenced by the same factors as inlet control plus the tailwater depth and barrel characteristics (slope, length, and roughness). Culverts operating with outlet control usually lie on flat slopes or have high tailwater.

When culverts are operating with outlet control, changes in barrel characteristics or tailwater depth may effect capacity. For example, increased tailwater depth or debris in the culvert barrel may reduce the capacity.

Design computation sheets (see figure 3.15) and nomographs (see figures 3.16 and 3.17) are used to assist engineers in the design and sizing of culverts.



From BPR

PROJECT:

DESIGNER: ________

DATE: ________

HYDROLOGIC AND CHANNEL INFORMATION

Q_1 = ______ TAILWATER ELEVATION = ____

Q_2 = ______ TAILWATER ELEVATION = ____

(Q_1 = DESIGN DISCHARGE, SAY Q_{25}
Q_2 = CHECK DISCHARGE, SAY Q_{50} OR Q_{100})

SKETCH

STATION: ________

MEAN STREAM VELOCITY = _____

MAX. STREAM VELOCITY = _____

$\frac{L}{100s}$ = _____

CULVERT DESCRIPTION (ENTRANCE TYPE)	Q	SIZE	HEADWATER COMPUTATION												CONTROLLING Hw	OUTLET VELOCITY	COST	COMMENTS
			INLET CONT.		OUTLET CONTROL $HW = H + h_o - Ls$								CHART					
			$\frac{Hw}{D}$	Hw	K_e	H	d_c	$\frac{d_c+D}{2}$	Tw	h_o	Ls	Hw	No.	Hw				

SUMMARY & RECOMENDATIONS:

Figure 3.15 Design computation sheet

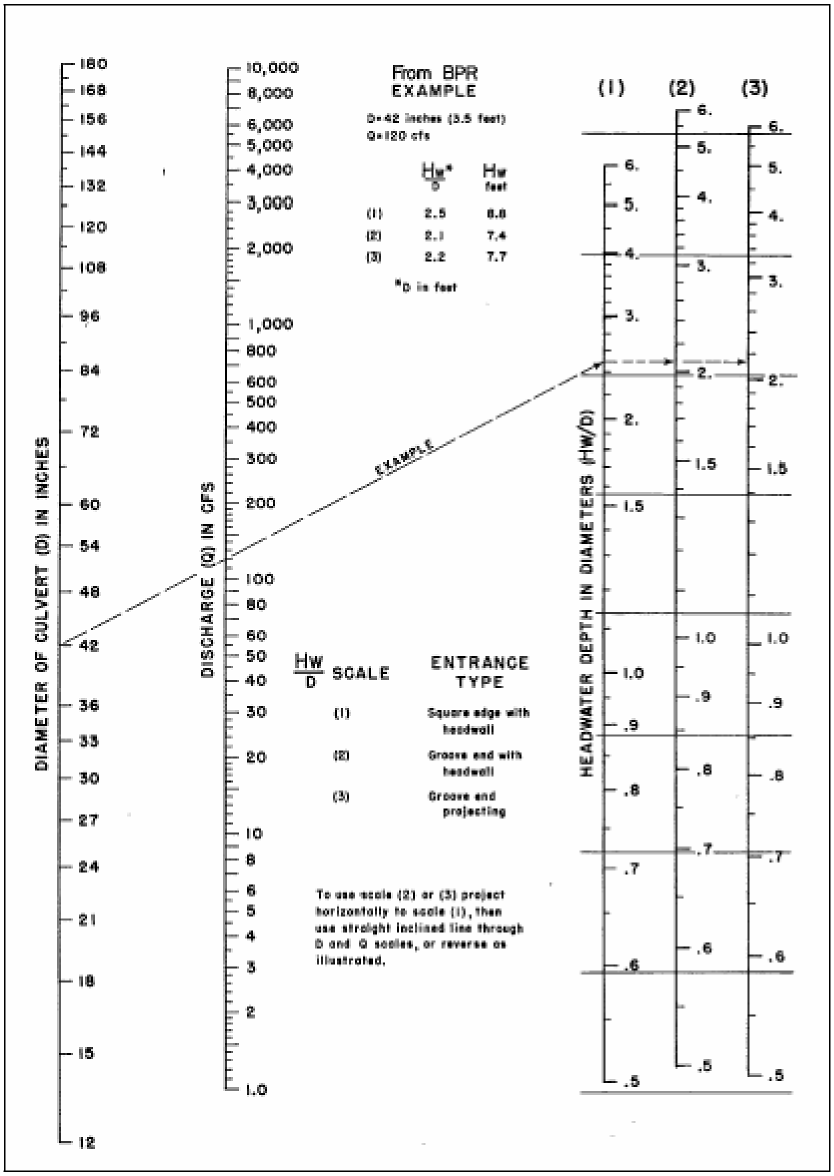


Figure 3.16 Inlet control nomograph

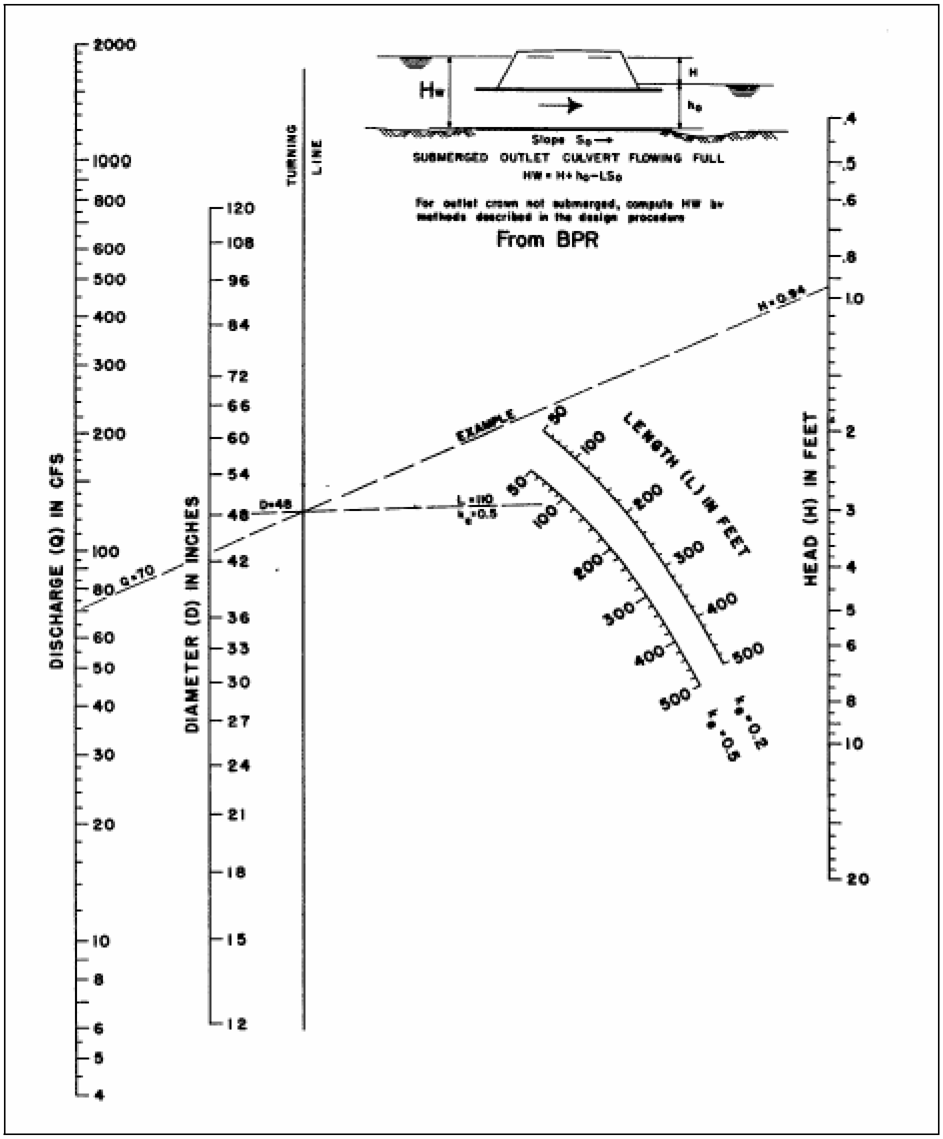


Figure 3.17 Outlet control nomograph

The use of the nomographs shown is limited to cases where tailwater depth is higher than the critical depth in the culvert. The advantage of the capacity charts over the nomographs is that the capacity charts are direct where the nomographs are trial and error. The capacity charts can be used only when the flow passes through critical depth at the outlet. When the critical depth at the outlet is less than the tailwater depth, the nomographs must be used; however, both give the same results where either of the two methods may be used. The procedure for design requires the use of both nomographs and is as follows:

1. List design data: Q (cfs), L (ft), invert elevations in and out (ft), allowable Hw (ft), mean and maximum flood velocities in natural stream (ft/sec), culvert type and entrance type for first selection.

2. Determine a trial size by assuming a maximum average velocity based on channel considerations to compute the area, $A = Q/V$.

3. Find *Hw* for trial size culvert for inlet control and outlet control. For inlet control connect a straight line through *D* and *Q* to scale (1) of the *Hw/D* scales and project horizontally to the proper scale, compute *Hw* and, if too large or too small, try another size before computing *Hw* for outlet control.

4. Next, compute the *Hw* for outlet control. Enter the graph with the length, the entrance coefficient for the entrance type, and the trial size. Connect the length scale and the culvert size scale with a straight line, pivot on the turning line, and draw a straight line from the design discharge on the discharge scale through the turning point to the head scale (head loss, *H).* Compute *Hw* from the equation:

$$Hw = H + h_o - Ls$$

where:

Hw = headwater depth (ft)
H = head loss (ft)
ho = tailwater depth or elevation at the outlet of a depth equivalent to the location of the hydraulic grade line (ft)
L = length of culvert (ft) s =
slope of culvert (ft/ft)

For *Tw* greater than or equal to the top of the culvert, *ho* = *Tw,* and for *Tw* less than the top of the culvert:

where:

dc = critical depth (ft) Tw = tailwater depth (ft)

If *Tw* is less than *dc,* the nomographs cannot be used, see *Hydraulic Design of Highway Culverts* (FHWA 1985) for critical depth charts.

5. Compare the computed headwaters and use the higher *Hw* to determine if the culvert is under inlet or outlet control. If outlet control governs and the *Hw* is unacceptable, select a larger trial size and find another *Hw* with the outlet control nomographs. Since the smaller size of culvert had been selected for allowable *Hw* by the inlet control nomographs, the inlet control for the larger pipe need not be checked.

Special Hydraulic Considerations

Inlet and Outlet Protection

The inlets and outlets of culverts may require protection to withstand the hydraulic forces exerted during peak flows. Inlet ends of flexible pipe culverts, which are not adequately protected or anchored, may be subject to entrance failures due to buoyant forces. The outlet may require energy dissipators to control erosion and scour and to protect downstream properties. High outlet velocities may cause scour which undermines the endwall, wingwalls, and culvert barrel. This erosion can cause end-section drop-off in rigid sectional pipe culverts.

Protection Against Piping

Seepage along the outside of the culvert barrel may remove supporting material. This process is referred to as "piping", since a hollow cavity similar to a pipe is often formed. Piping can also occur through open joints. Piping is controlled by reducing the amount and velocity of water seeping along the outside of the culvert barrel. This may require watertight joints and in some cases anti-seep collars. Good backfill material and adequate compaction of that material are also important.

Types and Locations of Culvert Distress

Types of Distress

Some of the common factors that can affect the performance of a culvert include the following:

- Construction Techniques - Specifically, how well the foundation was prepared, the bedding placed, and the backfill compacted.
- The characteristics of the stream flow - water depth, velocity, turbulence.
- Structural Integrity - how well the structure can withstand the loads to which it is subjected, especially after experiencing substantial deterioration and section loss.
- Suitability of the Foundation - Can the foundation material provide adequate support?
- Stability of the embankment in relationship to other structures on the upstream or downstream side.
- Hydraulic capacity - if the culvert cross section is insufficient for flow, upstream ponding could result and damage the embankment.
- The presence of vegetation - can greatly affect the means and efficiency of the flow through the culvert.
- The possibility of abrasion and corrosion caused by substances in the water, the surrounding soil or atmosphere.

3.9 Factors Affecting Culvert Performance

The combination of high earth loads, long pipe-like structures and running water tends to produce the following types of distress:

- Shear or bending failure - High embankments may impose very high loads on all sides of a culvert and can cause shear or bending failure.
- Foundation failure - Either a smooth sag or differential vertical displacement at construction or expansion joints (settlement). Tipping of wingwalls. Lateral movement of precast or cast-in-place box sections.
- Hydraulic failure - Full flow design conditions result in accelerated scour and undermining at culvert ends as well as at any irregularities within the culvert due to foundation problems.
- Debris accumulation - Branches, sediment and trash can often be trapped at the culvert entrance restricting the channel flow and causing scour.

3.10 Durability

Although the structural condition is a very important element in the performance of culverts, durability problems are probably the most frequent cause of replacement. Culverts are more likely to "wear away" than fail structurally. Durability is affected by two mechanisms: corrosion and abrasion.

Corrosion

Corrosion affects all metals and alloys, although the rates can vary widely depending both upon the chemical and physical properties of the metal and upon the environmental condition to which it is exposed. When a metal corrodes a very low voltage electrical current is established between two parts of a metal surface that have different voltage potential. The difference in voltage potential may be caused by slight variations in the material, changes in surface condition, or the presence of foreign materials. The current removes metallic ions from one location and deposits them at another location, causing corrosion. The chemicals present in the water greatly influence its effectiveness as an electrolyte.

Corrosion is the deterioration of culvert materials by chemical or electrochemical reaction to the environment. Culvert corrosion may occur in many different soils and waters. These soils and waters may contain acids, alkalis, dissolved salts, organics, industrial wastes or other chemicals, mine drainage, sanitary effluents, and dissolved or free gases. However, culvert corrosion is generally related to water and the chemicals that have reacted to, become dissolved in, or been transported by the water.

Corrosion can attack the inside or outside of the culvert barrel. The chemicals in drainage water can attack the material on the interior of the culvert. Culverts subject to continuous flows or standing water with aggressive chemicals are more likely to be damaged than those with intermittent flows. The exterior of culverts can be attacked by chemicals in the ground water which can originate in the soil, be introduced through contaminates in the backfill soil, or be transported by subsurface flow.

Although less common than with metal pipe, corrosion can occur in concrete culverts. Metallic corrosion can take place in the reinforcing steel when it is exposed by cracking or spalling, when the concrete cover is inadequate or when the concrete is porous enough to allow water to contact the reinforcing steel.
If the steel corrodes, the corrosion products expand and may cause spalling of the concrete. Corrosion can also take place in the concrete itself. It is not, however, the same type of electrochemical reaction that occurs in metal. Other reactions between the concrete materials and the chemicals present in the stream flow or ground water are involved and can result in deterioration of the concrete.

Abrasion

Abrasion is the process of wearing down or grinding away surface material as water laden with sand, gravel, or stones flows through a culvert. Abrasive forces increase as the velocity of the water flowing through a culvert increases; for example, doubling the velocity of a stream flow can cause the abrasive power to become approximately four-fold.

Often corrosion and abrasion operate together to produce far greater deterioration than would result from either alone. Abrasion can accelerate corrosion by removing protective coatings and allowing water-borne chemicals to come into contact with corrodible culvert materials.

3.11 Soil and Water Conditions that Affect Culverts

Certain soil and water conditions have been found to have a strong relationship to accelerated culvert deterioration. These conditions are referred to as "aggressive" or "hostile." The most significant conditions of this type are:

pH Extremes

pH is a measure of the relative acidity or alkalinity of water. A pH of 7.0 is neutral; values of less than 7.0 are acid, and values of more than 7.0 are alkaline. For culvert purposes, soils or water having a pH of 5.5 or less are strongly acid and those of 8.5 or more are strongly alkaline.

Acid water stems from two sources, mineral and organic. Mineral acidity comes from sulfurous wells and springs, and drainage from coal mines. These sources contain dissolved sulfur and iron sulfide which may form sulfurous and sulfuric acids. Mineral acidity as strong as pH 2.3 has been encountered. Organic acidity usually found in swampy land and barnyards rarely produces a pH of less than 4.0. Alkalinity in water is caused by strong alkali-forming minerals and from limed and fertilized fields. Acid water (low pH) is more common to wet climates and alkaline water (high pH) is more common to dry climates. As the pH of water in contact with culvert materials, either internally or externally, deviates from neutral, 7.0, it generally becomes more hostile.

Electrical Resistivity

This measurement depends largely on the nature and amount of dissolved salts in the soil. The greater the resistance the less the flow of electrical current associated with corrosion. High moisture content and temperature lower the resistivity and increase the potential for corrosion. Soil resistivity generally decreases as the depth increases. The use of granular backfill around the entire pipe will increase electrical resistivity and will reduce the potential for galvanic corrosion.

Several states rely on soil and water resistivity measurements as an important index of corrosion potential. Some states and the FHWA have published guidelines that use a combination of the pH and electrical resistivity of soil and water to indicate the corrosion potential at proposed culvert sites. The collection of pH and electrical resistivity data during culvert inspections can provide valuable information for developing local guidelines.

Soil Characteristics

The chemical and physical characteristics of the soil, which will come into contact with a culvert, can be analyzed to determine the potential for corrosion. The presence of base-farming and acid-forming chemicals is important. Chlorides and other dissolved salts increase electrical conductivity and promote the flow of corrosion currents. Sulfate soils and water can be erosive to metals and harmful to concrete. The permeability of soil to water and to oxygen is another variable in the corrosion process.

3.12 Culvert Protective Systems

There are several protective measures that can be taken to increase the durability of culverts. The more commonly used measures are:

Extra Thickness

For some aggressive environments, it may be economical to provide extra thickness of concrete or metal.

Bituminous Coating

This is the most common protective measure used on corrugated steel pipe. This procedure can increase the resistance of metal pipe to acidic conditions if the coating is properly applied and remains in place. Careful handling during transportation, storage, and placement is required to avoid damage to the coating. Bituminous coatings can also be damaged by abrasion. Field repairs should be made when bare metal has been exposed. Fiber binding is sometimes used to improve the adherence of bituminous material to the metallic-coated pipe.

Bituminous Paved Inverts

Paving the inverts of corrugated metal culverts to provide a smooth flow and to protect the metal has sometimes been an effective protection from particularly abrasive and corrosive environments. Bituminous paving is usually at least 3 mm (1/8-inch) thick over the inner crest of the corrugations. Generally only the lower quadrant of the pipe interior is paved. Fiber binding is sometimes used to improve the adherence of bituminous material to the metallic-coated pipe.

Other Coatings

There are several other coating materials that are being used to some degree throughout the country. Polymeric, epoxy, fiberglass, clay, and concrete field paving, have all been used as protection against corrosion. Galvanizing is the most common of the metallic coatings used for steel. It involves the application of a thin layer of zinc on the metal culvert. Other metallic coatings used to protect steel culverts are aluminum and aluminum-zinc.