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A Look at Bridges: A Study of Types, Histories, and the Marriage of Engineering and Architecture

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CODY CHASE

SENIOR INTEGRATIVE PROJECT:
INDEPENDENT STUDY

ARCHITECTURAL STUDIES
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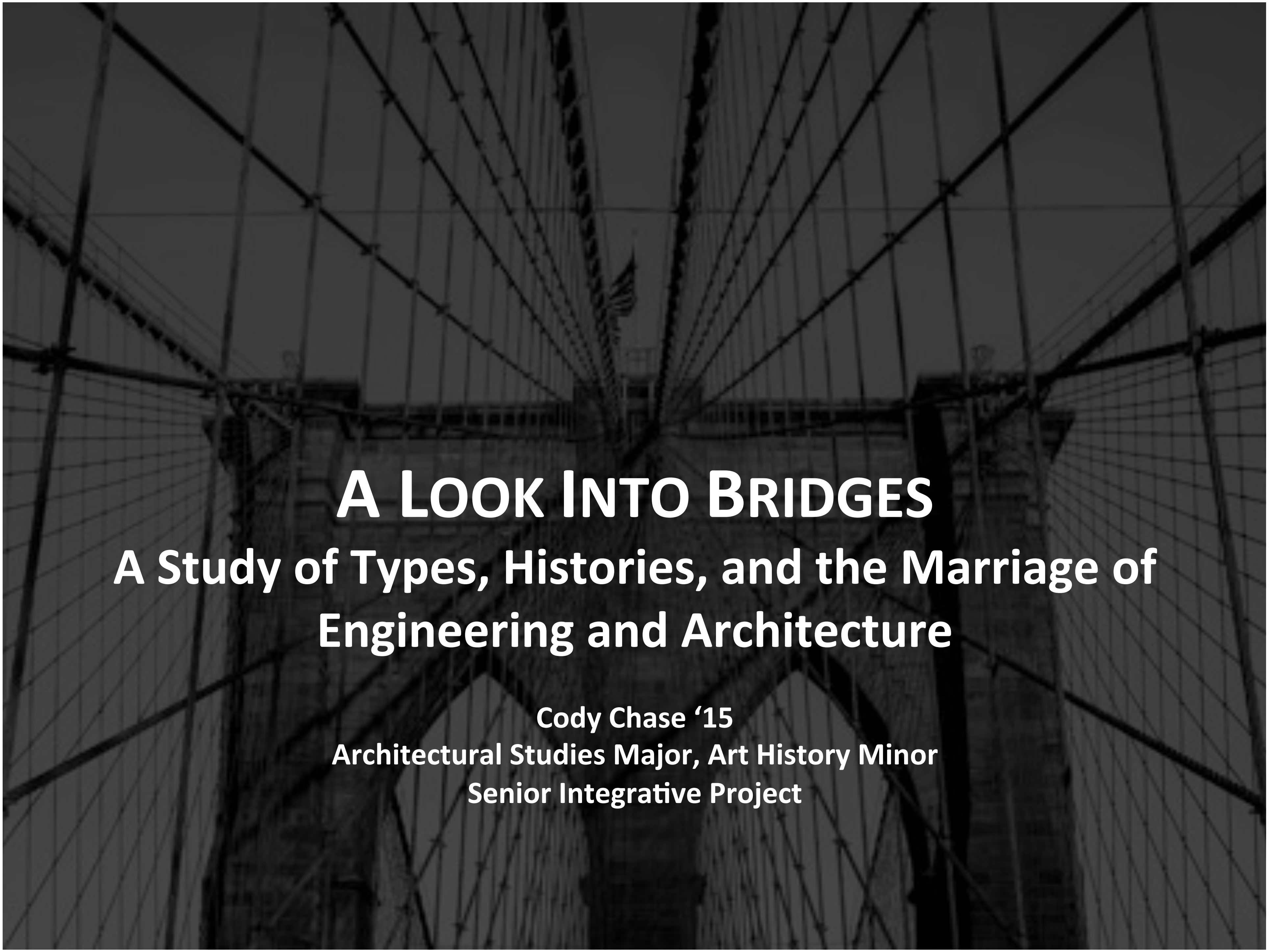


A Look Into Bridges

A Study of Types, Histories, and the Marriage of Engineering and Architecture

Cody Chase '15
Architectural Studies Major, Art History Minor
Senior Integrative Project

Why Bridges?

Where to begin?

TYPES

- Arch
- Beam/Girder/Stringer
- Truss
- Suspension
- Cable-Stayed
- Moveable Span

OTHER

- Glossary
- Materials
- History of Failures
- Models

What makes a bridge stand up?

FORCES

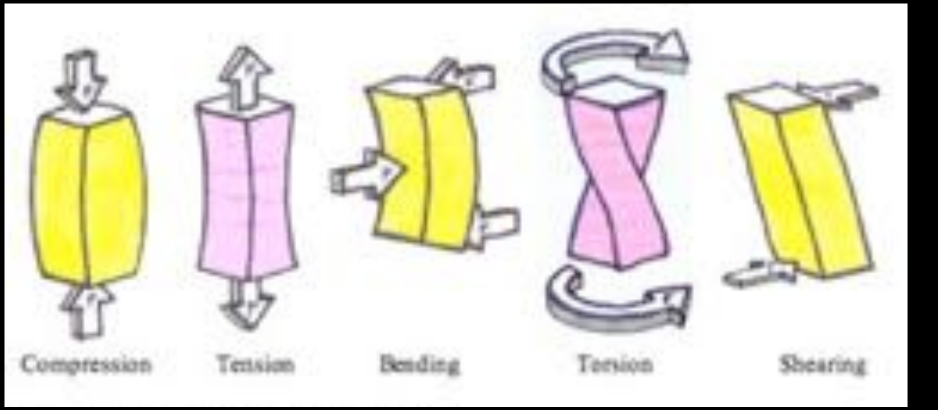
***Compression: the stress on a member where it is compressed by either live or dead loads; this can lead to cracking or crumbling

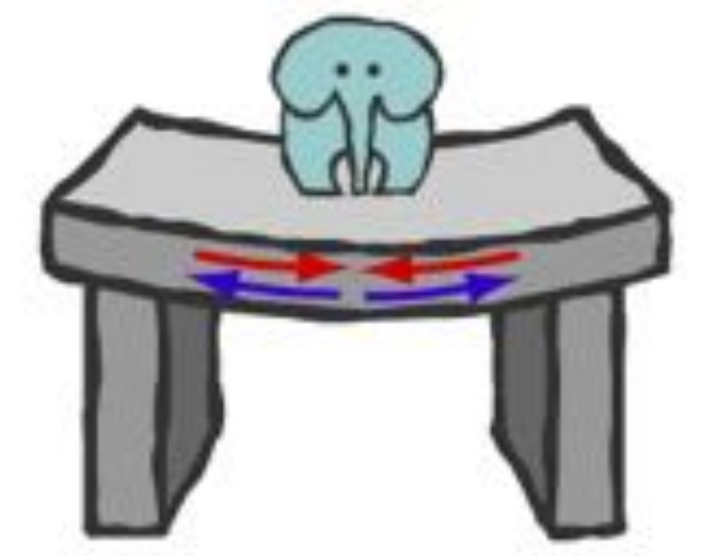
***Tension: the stress on a member where it is stretched by either live or dead loads; this can cause deformation fracture

Bending (Flexure): the force on an object that causes it to bend

Torsion: the force that causes twisting in a bridge

Shear: the force that causes stress on materials laterally





Materials: Stone

PROS

- Great in compression
- Abundant
- Extremely durable
- Low maintenance
- Aesthetics

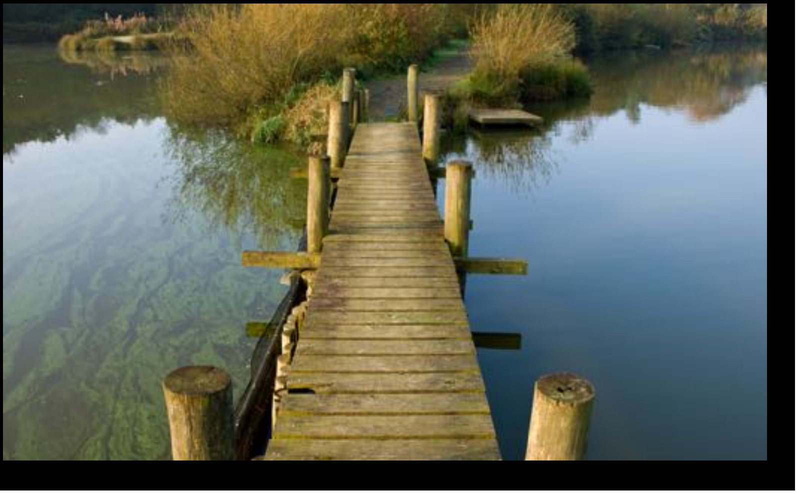
CONS

- Weak in tensile strength

Aqueduct of Segovia, Spain, 1st c. CE

Materials: Wood

Bogoda Wooden Bridge, Sri Lanka, 16th c.



PROS

- Good in tension and compression
- Economical
- Abundant
- Easy to manage
- Aesthetics/Good for rural settings

CONS

- Not very strong
- Ephemeral

Materials: Iron

Cast vs. Wrought

PROS
- Not many
- Initially popular due to the novelty of the mass produced material

CONS
- Not very strong in tension of compression

The Iron Bridge, Coalbrookdale, England, 1781

The Brittania Bridge, North Wales, 1850

Materials: Steel

PROS
- Great in tension
- Strong
- Pliable
  - Structural, cabling, reinforcing

CONS
- Not great in compression
- Rusts — Can be high maintenance

The St. Louis Bridge, Mississippi, 1874

The Forth Bridge, Edinburgh, Scotland, 1882

The Golden Gate Bridge, San Francisco, CA, 1937

Materials:(Reinforced) Concrete

PROS
- Great in compression, like stone
- Pliable
- Low maintenance
- Easily combinable with other materials

CONS
- Not great in tension
  - Except when reinforced

Pre-stressing

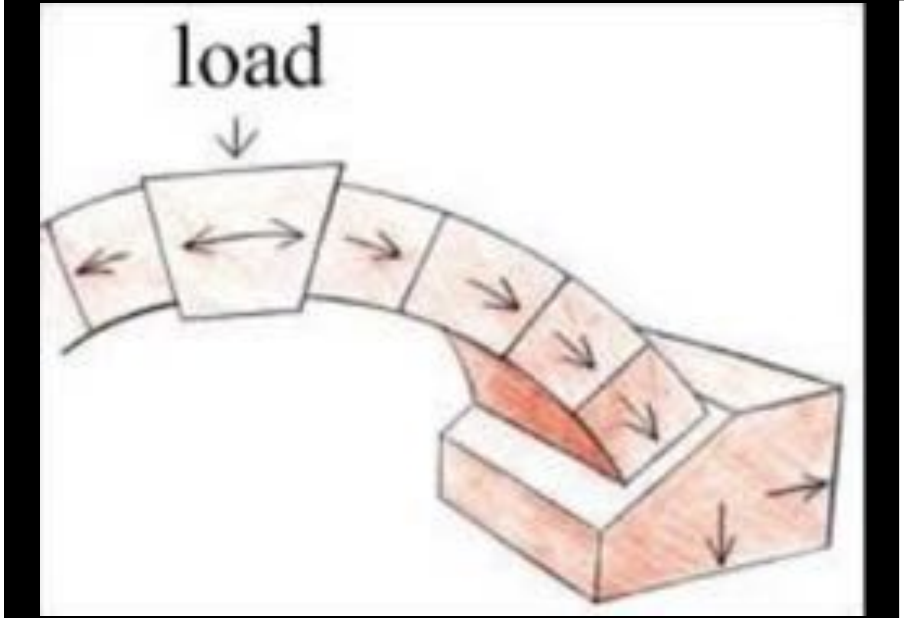
Post-tensioning

Types: Arch

True/Round

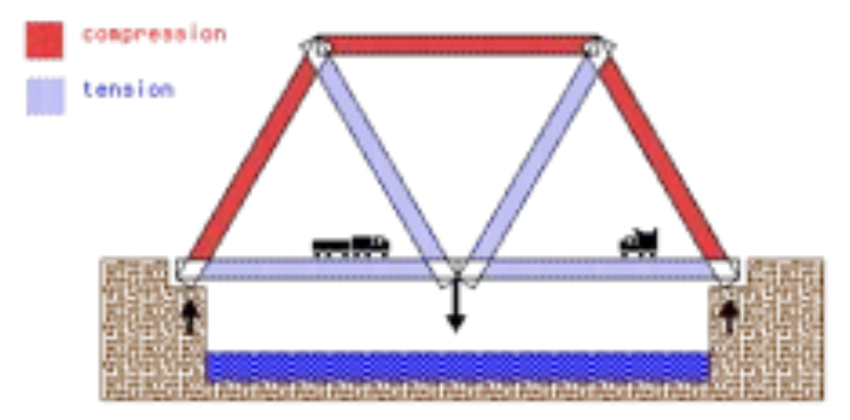
Corbelled

Segmental

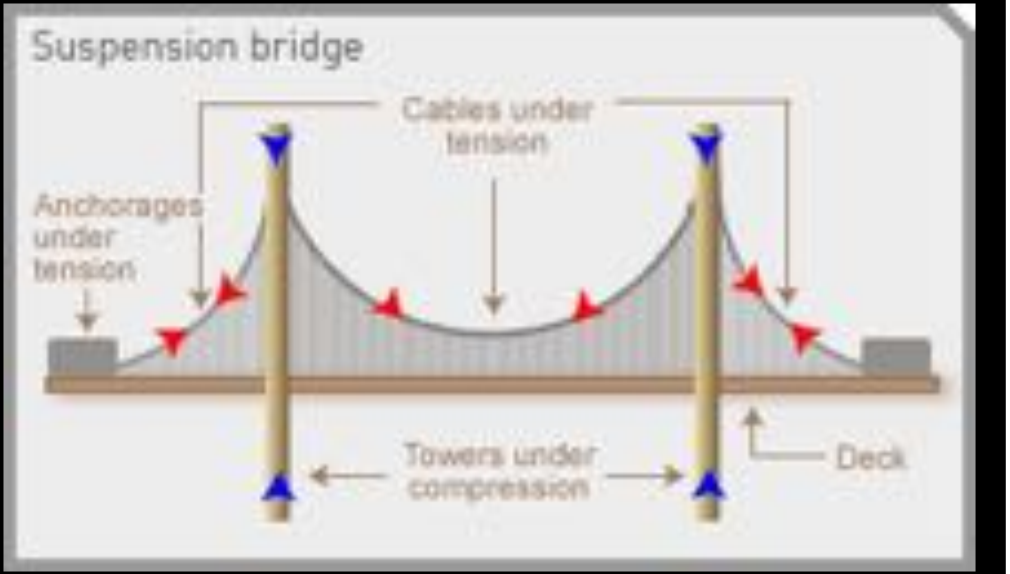


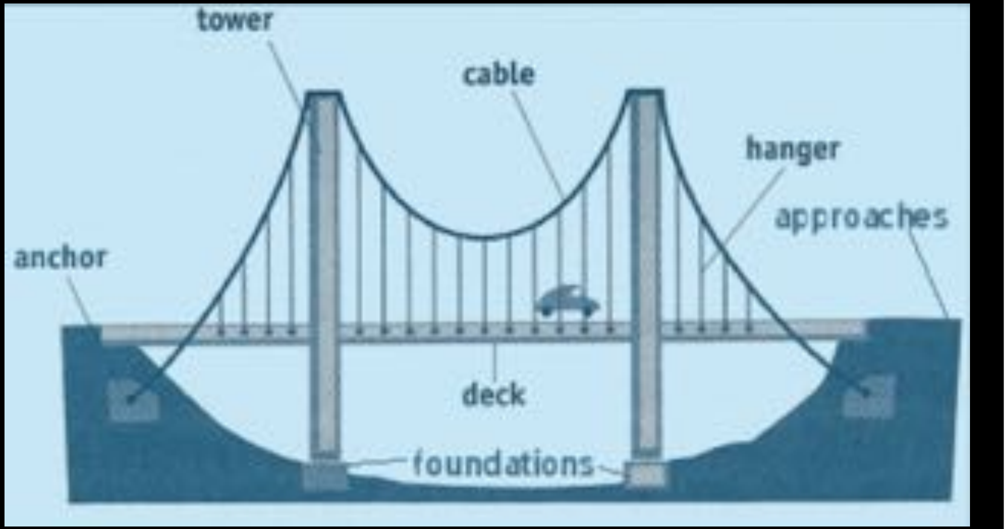
Types: Beam/Girder/Stringer

Types: Truss



Types: Suspension

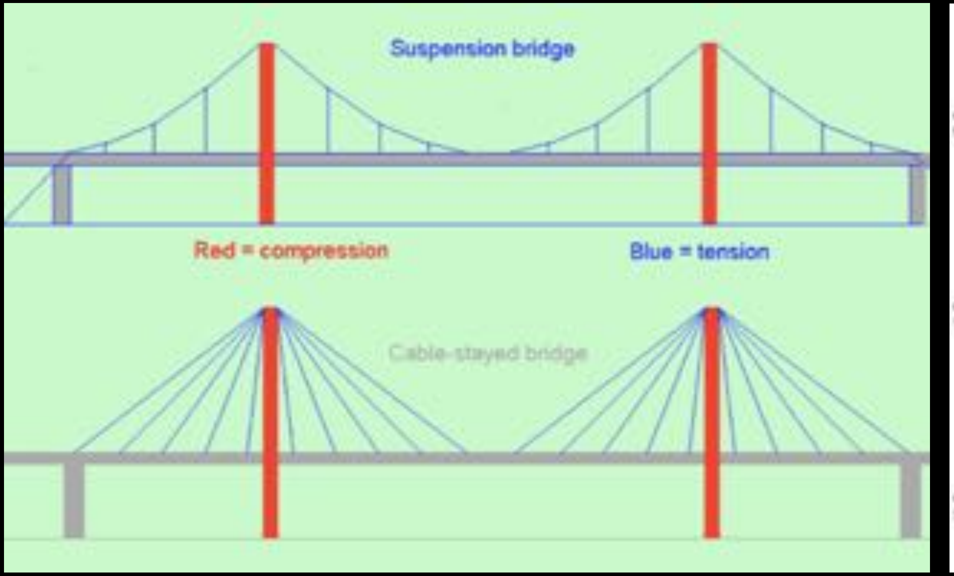


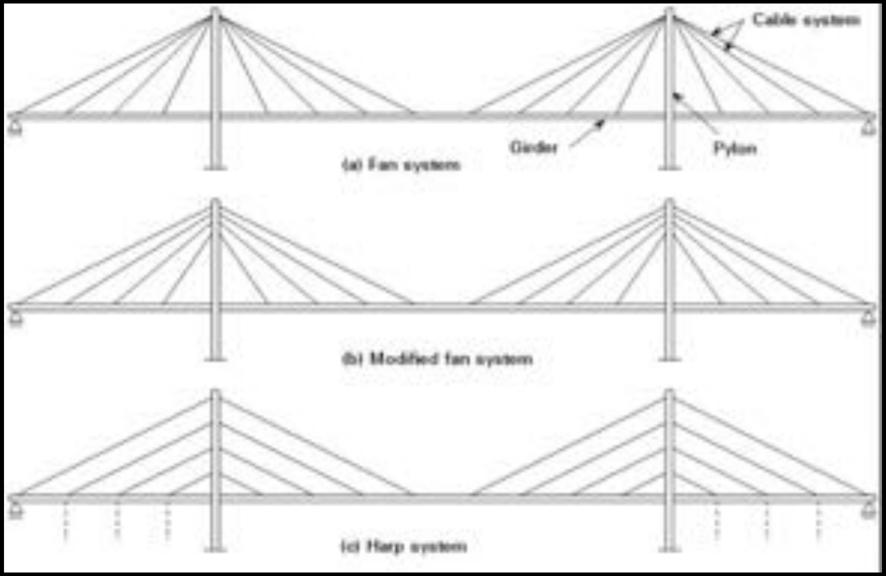



Brooklyn Bridge, New York, 1883; main span: 1,595 feet


Akashi Kaikyo Bridge, Japan, 1998; main span: 6,532 feet

Types: Cable-Stayed





Types: Moveable Span


Swing


Lift


Bascule


Tilt


Submersible


Retractable


Folding


Rolling

Failures

Most Common Reasons:

- Misuse of Materials
- Poor Construction Methods
- Impossible Design
- Post-Construction Mishaps

Tacoma Narrow Bridge collapse, Puget Sound, Washington, 1940

Bridge Issues Today

607,000
Bridges in the US and Puerto Rico

84,748
"Functionally obsolete"

66,749
"Structurally deficient"

= 25%
in need of immediate repair

Federal Highway Administration, 2013

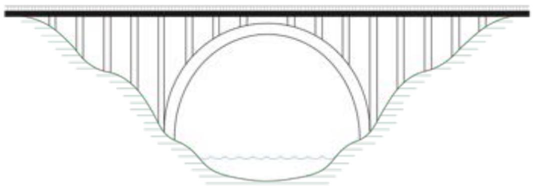
"We know there are plenty of **cheap**, **badly built bridges**, which engineers are watching with anxious fears, and which, to all appearances, **only stand by the grace of God**!"

-*Iron Age* Magazine,1876

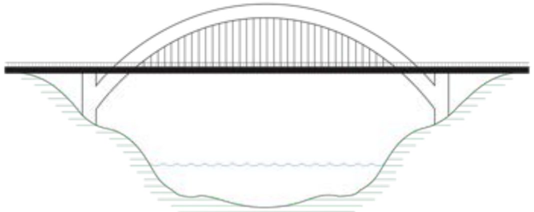
Conclusions: Architecture

Conclusions: Personal Study

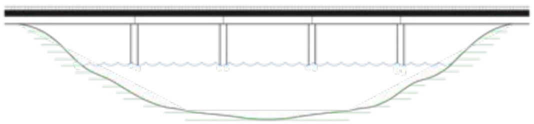
TYPE: ARCH
Subtype: True/Round
Other Classifications: Deck Bridge, Open Spandrels



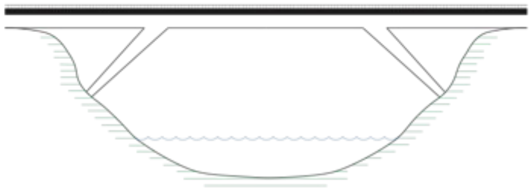
TYPE: ARCH
Subtype: Segmental
Other Classifications: Through Bridge



TYPE: Beam/Stringer/Girder
Subtype: Reinforced Concrete Girder
Other Classifications: N/A

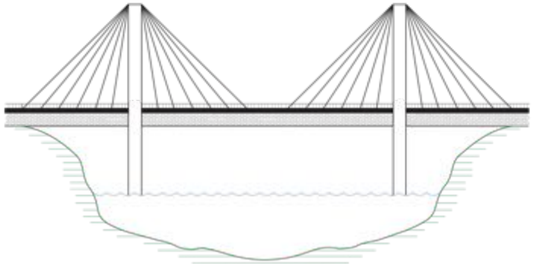


TYPE: Beam/Stringer/Girder
Subtype: Reinforced Concrete Rigid Frame
Other Classifications: N/A

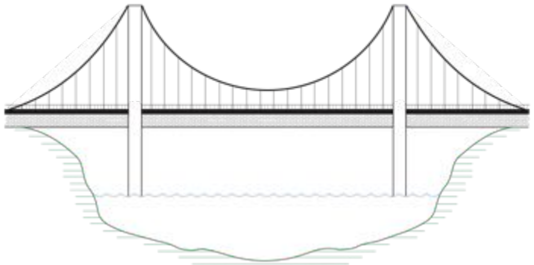


QUESTIONS?

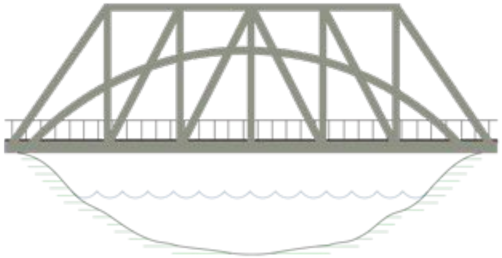
TYPE: Cable-Stayed
Subtype: Fan Style Cables
Other Classifications: Truss-Stiffened Deck



TYPE: Suspension
Subtype: N/A
Other Classifications: Truss-Stiffened Deck



TYPE: Truss
Subtype: Burr
Other Classifications: Through Bridge



TYPE: Truss
Subtype: Bowstring
Other Classifications: Through Bridge

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ARCHITECTURAL STUDIES SENIOR INTEGRATIVE PROJECT

by Cody Chase

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III. MATERIALS

IV. TYPES

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* Sources are organized by section at the end of the study.

I. INTRODUCTION

The bridge has been a necessary tool in every civilization throughout history. Depending on the needs, materials and knowledge of its creator, each bridge has been a product unique to the culture that developed it. Due to the fact that a bridge is built as an essential and permanent solution to the struggles of crossing difficult terrain, many bridges have survived long past their creators, making them icons of a civilization. Today, bridge creators take many considerations into account before deciding on the design of a bridge, this includes location, purpose, required length and width, desired height and clearance, budget, time frame for construction, desired appearance, and much more. Through the combination of lessons from the past, modern science, and technology the bridges of today are the most advanced designs in history. Stemming from this growth was a higher level of security in structural design and therefore many more options regarding aesthetic qualities.

Six main bridge types are currently in practice: arch, beam/girder, truss, suspension, cable-stayed and moveable spans. Variation and crossover exist on a case-by-case basis but the basic principles for each type help decide how, why and where a specific bridge is constructed. This study is thus organized to highlight the variations between each type, with a focus on the differentiation of forces and the strengths and weaknesses. The additional sections on materials, failures and the glossary are included for better comprehension of structure and history.

Bridges are a universal language because they deal with a universal issue: overcoming earthly obstacles to enhance civilization. Knowing their history is vital to understanding how they are made and why they are still so necessary in life today. People use them every day often without even realizing it, which is reflected in the large number of unattractive and horribly neglected bridges. This study hopes to inspire interest in the world of architecture for the sake of future ground-breaking designs, creative possibilities, and reinvigorated pride in these iconic structures.

II. GLOSSARY

BRIDGE ELEMENTS

Abutment (Wing Wall): the support that exists on either end of the bridge to connect the bridge to the landmass; in the case where the earth needs to be built up to a berm to support a high spanned bridge the abutment acts as a retaining wall for the earth

Arch Ring: the round space beneath the bridge created by an arch

Diaphragms: secondary or tertiary design elements that support the space in between the stringers latitudinally, often seen as an “X” shape, parallel to pile bents

Pile Bents (Piers): the intermediate supports for a bridge between the abutments at either end; pile bents can either remain below the deck as substructure, or rise above the deck, often as a tower

Ribs: the longitudinal curved beams, girders or trusses that make up the arch shape and carry the primary loads

Shoe (Bearing): a member that supports a truss or a beam by connecting it to an abutment or pile bent

Slab: the decking of a bridge, often concrete or reinforced concrete, that lies upon the substructure of a bridge

Spandrel: the space between the top of the arch ring and deck in a bridge, can be opened or closed depending on the design

Stringer (Girder): a longitudinal support that resides under the deck of a bridge, it can be as long as the entire length of a short span bridge or as long as the spans between piers

Suspender: a member in tension between the deck and a structural element above the deck; in a suspension bridge the suspenders connect the deck to the main longitudinal cables, in a suspended deck arch bridge the suspenders connect the deck to the arch above the deck; in both suspension bridges and suspended deck arch bridges the deck hangs from the main structural element

CONNECTORS

Bolted: a metal pin that is inserted through pieces to make a connection, often met with a nut on the other side

Hinged: a connection that purposefully allows pieces to move independently, mainly for temperature change

Mortise and Tenon Joints: a connection where a hole in one piece is matched with a peg in the other

Pinned: a connection similar to bolted but sometimes constructed to allow intentional and independent movement in the pieces

Riveted: a connection where a metal pin is inserted through pieces to make a connection and then hammered on the other side to make two heads, sometime done with hot metal for better molding capabilities

Treenail (Trunnel): a connection where a wooden peg is used like a nail to connect two pieces of wood; common in covered wooden bridges

Welded: a connection where metal is fused together

DECK LOCATION

Deck: the deck rests above the primary structural element; this includes most arch bridges, many beam/girder bridges and some truss bridges

Through: the deck is placed so that is passes below the primary structural element; often seen in truss bridges or steel arches

Pony: typically seen in a truss bridge, this design places the deck midway between the top and bottom chords of a truss; the sides of the truss do not meet along the top to form a box

FORCES

Bending (Flexure): the force on an object that causes it to bend, with compression on one side and tension on the other

Compression: the stress on a member where it is compressed by either live or dead loads; this can lead to cracking or crumbling

Shear: the force that causes stress on materials laterally, possibly causing fracture and sliding in opposite directions

Tension: the stress on a member where it is stretched by either live or dead loads; this can cause deformation fracture

Torsion: the force that causes twisting in a bridge, this can cause cracks and fractures

MISCELLANEOUS

Arcade: a series of arches end to end, a system that is commonly used in viaducts and aqueducts

ASCE: "The American Society of Civil Engineers represents more than 145,000 members of the civil engineering profession in 174 countries. Founded in 1852, ASCE is the nation's oldest engineering society. ASCE stands at the forefront of a profession that plans, designs, constructs, and operates society's economic and social engine – the built environment – while protecting and restoring the natural environment."

Cathedral Arch: a structural system where the deck is supported only by the connection to the crown of the arch, with no additional supports in the spandrel spaces

Falsework (Centring): a frame, typically wooden, that acts as a support for a bridge while it is under construction. In the case of an arch bridge, the voussoirs are set in place atop the centring; once the keystone finalizes the arch, then the falsework can be removed for the arch will support itself

Trestle: a type of bridge with a rigid frame of supports for the entire length of the bridge

III. MATERIALS

This short examination of materials shows how the history of bridge design has been structured by the advancement of technology. More examples of these materials in bridges will be discussed later in the sections on types.

TYPES:

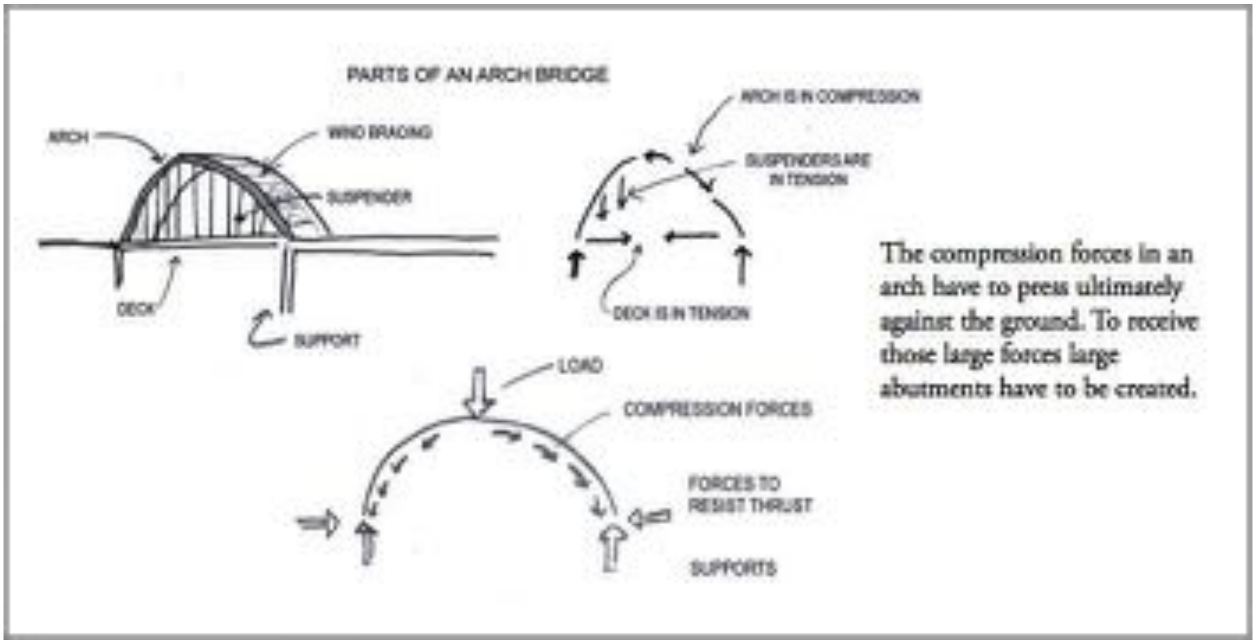
- Stone
- Timber
- Iron
- Steel
- Concrete

STONE

Stone is one of the two oldest building materials, given that is has been so readily available to all cultures around the world. A stone bridge is a natural occurrence in nature; as a stone becomes an obstacle rising above the stream it makes a perfect footing for the person or animal hoping to cross. And furthermore, if a crack develops in the rock beneath the water, the flow of the stream could eventually carve away an opening, leading to a natural arch.

These occurrences gradually led to the development of human-made stone bridges, evolving with civilization into more grandiose structures over time. There is evidence of seventh century BCE stone aqueducts under the rule of Sennacherib and much more rudimentary structures before that, dating back to the hunter-gatherer tribes 10,000 years ago. Stone has been present throughout the course of bridge history and remains a staple today. Despite more modern materials, the charm and historical reference in a simple stone arch bridge is still a popular choice in certain locations.

Stone is best used in compression, its tensile strength is much weaker when compared to other materials. This is the reason that stone is almost always used in an arch, so much so that the ancient Romans found if they had the perfect stones they did not need mortar to hold them together once the keystone was placed. Today there are examples of many types of arch bridges, from the early voussoir and corbeled arches to the more modern segmental and elliptical.

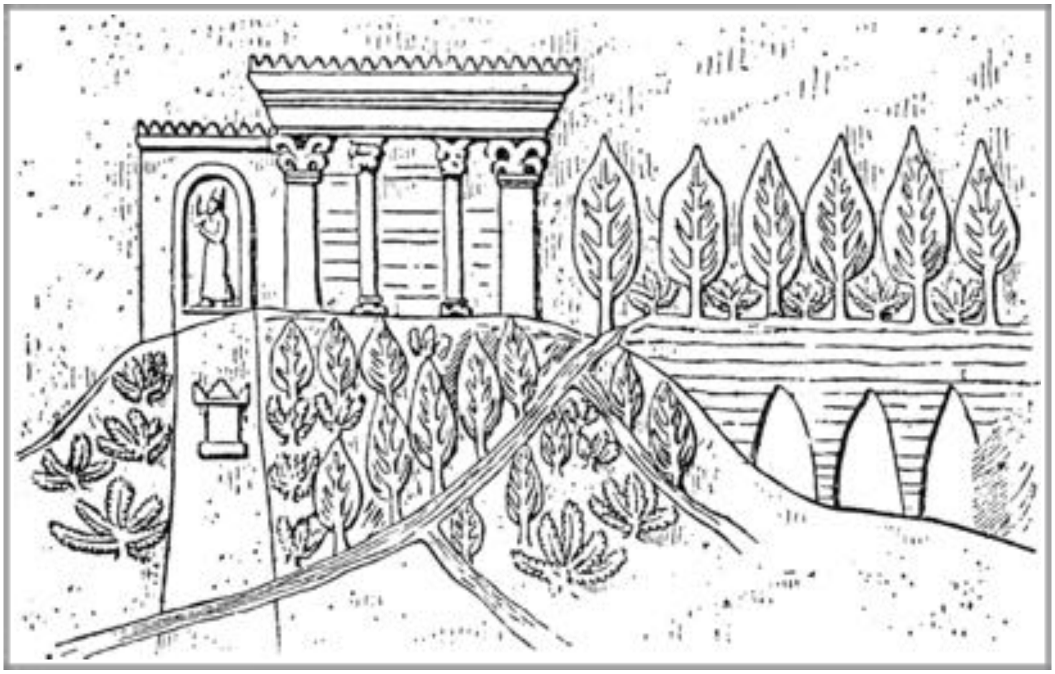


The compression forces in an arch have to press ultimately against the ground. To receive those large forces large abutments have to be created.

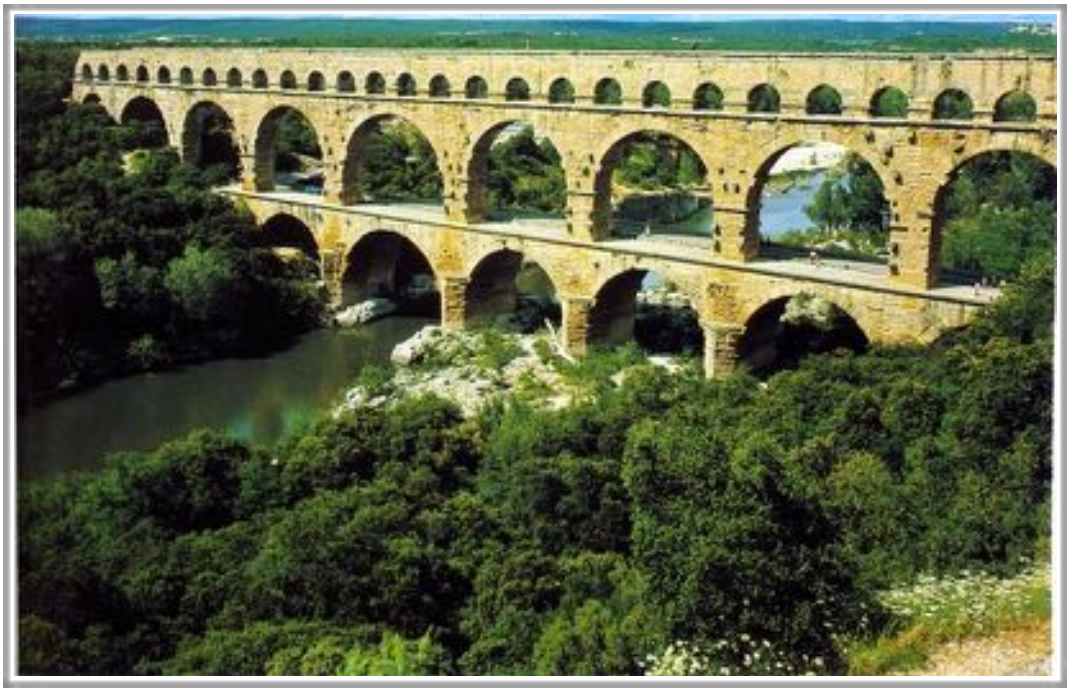
Figure 1.1: Diagram of the forces on an arch.

Examples:

Figure 1.2: Stepping Stone Bridge, Dartmoor, England, 15th century



Figures 1.3, 1.4: Sennacherib's canal network around Ninevah including a stone aqueduct. Seventh century BCE, 920 feet tall, 66 feet wide, crossing the small river valley at Jerwan



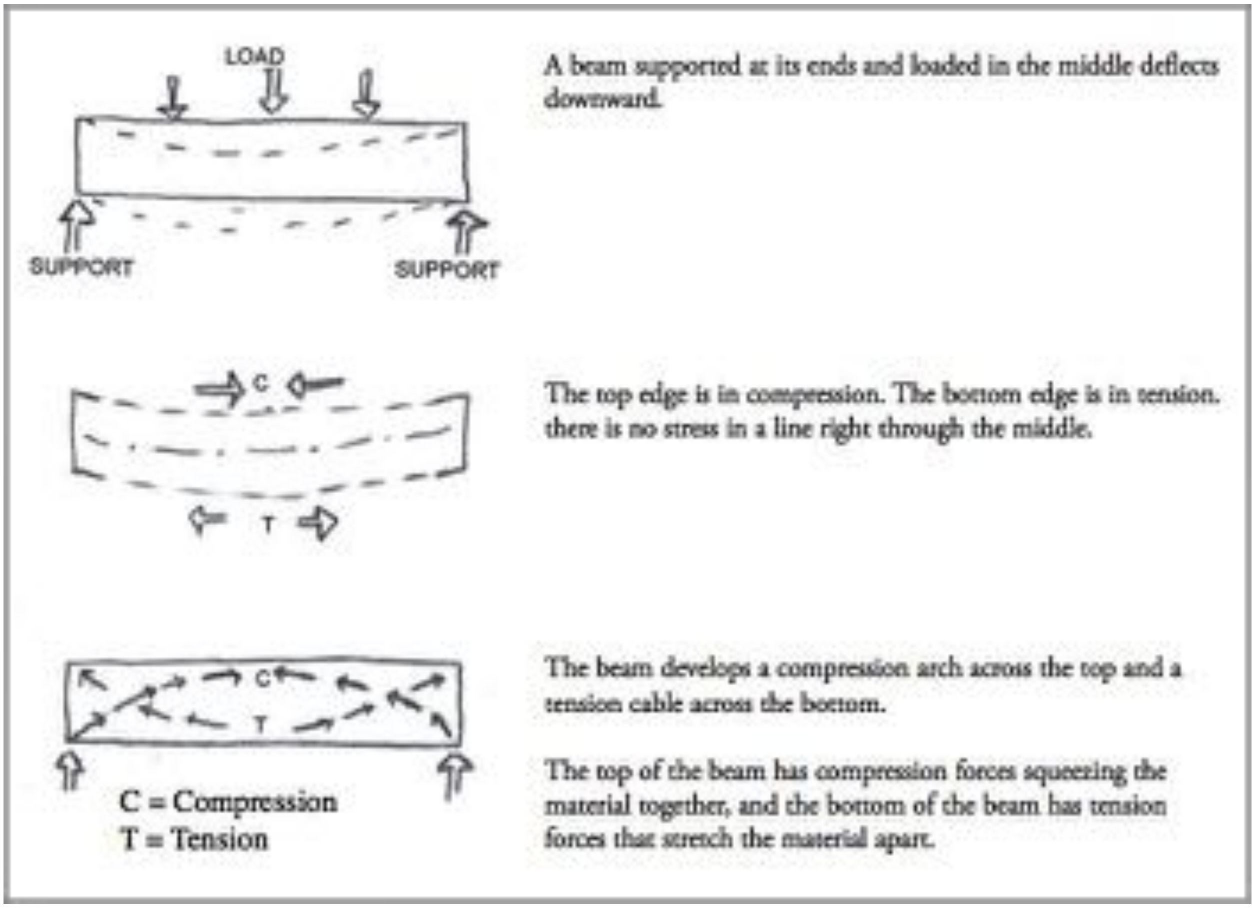
Figures 1.5, 1.6: Pont du Gard, 1st century CE; Aqueduct of Segovia, Spain, 1st century CE. These are two of the eleven aqueducts built in ancient Rome by 226 CE. Most of Rome's bridges were made of timber but have since disappeared, highlighting another characteristic of stone bridges: their longevity.

Figure 1.7: Ponte Vecchio, Florence, Italy, 1345; segmental arch bridge, which means it is only part of the circle that is in the arch. The bridge had two predecessors that were destroyed by floods. This is not the first use of buildings on a bridge, the old Tower Bridge in London also used to have buildings on it before it became too weighty for the old bridge.

Figure 1.8: Karlsbrucke Bridge, Prague, 1357

TIMBER

Timber is the second oldest material in used bridge design. Beginning with a log that fell across a stream, then building to a design with multiple logs and a deck, to today, where wood can be used in a multitude of ways. It works well in both compression and tension, but neither of those strengths matches up to the power that other materials have to offer. Wood is unreliable and typically reserved for smaller bridges and ones erected for short term purposes. Cedar and black locust are the best natural options for longer lasting bridges, or the more modern option of treated wood. For flexible designs it is best to use elm, or oak for a stronger material. The main reason for the lack of older timber bridges today is the short lifespan of wood as a structural material. It is desirable because of its cheap price, ready availability, and its easy manipulation.



A beam supported at its ends and loaded in the middle deflects downward.

The top edge is in compression. The bottom edge is in tension. there is no stress in a line right through the middle.

The beam develops a compression arch across the top and a tension cable across the bottom.

The top of the beam has compression forces squeezing the material together, and the bottom of the beam has tension forces that stretch the material apart.

C = Compression
T = Tension

Figure 2.1: Diagram of the forces on a beam.

Examples:

Figure 2.2: The Bogoda Wooden Bridge near Badulla, Sri Lanka, 16th century. It is one of the oldest continually standing timber bridges in the world. All of its components were constructed from wood including the substructure, decking, roof, roof tiles, balustrade and nails.

Figure 2.3: This painting from Canaletto of *Old Walton Bridge* shows the type of timber bridge that was aesthetically pleasing and desired in the 17th century. A form that seemed mathematical and sturdy in the countryside was idealistic, explaining its presence here.

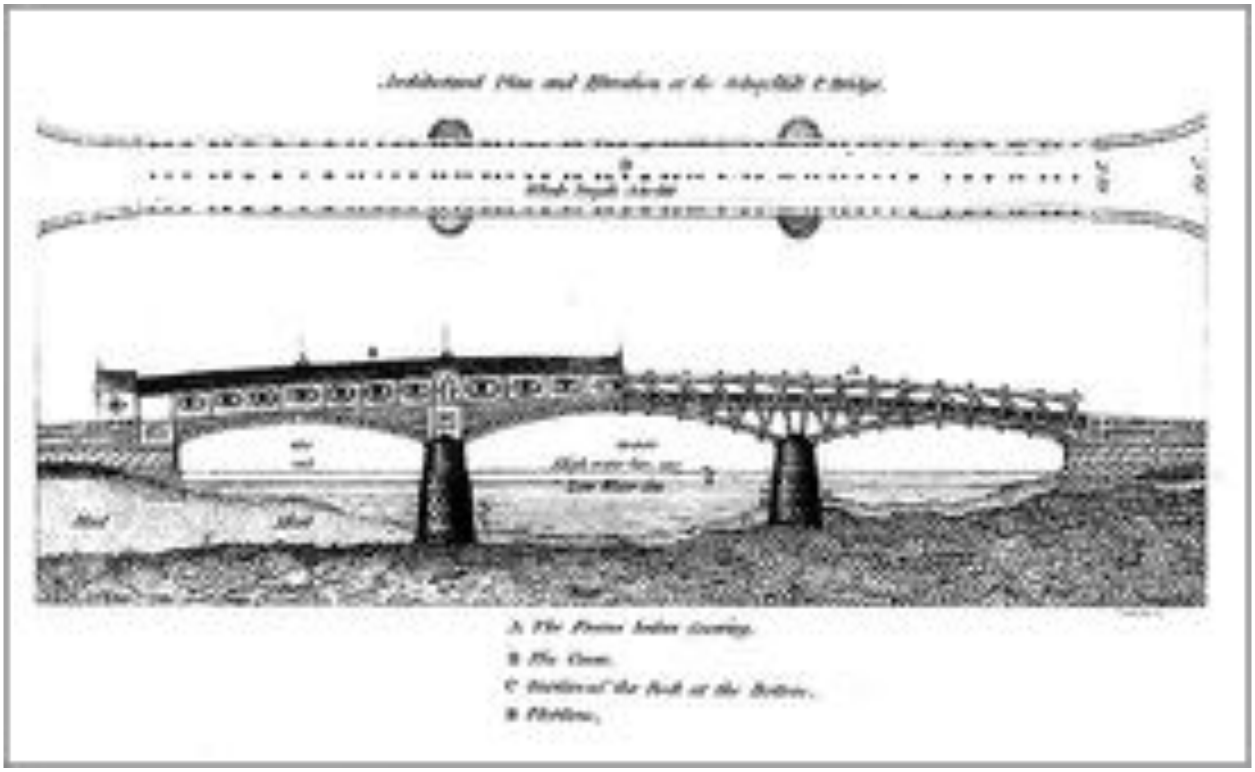


Figure 2.4: Timothy Palmer, first American covered bridge, triple-span arch over Schuylkill River in Philadelphia, 1805. The president of the Schuylkill Bridge Company wanted to protect the bridge and insisted upon the roofing, this led to the very popular design in timber bridges.

Figures 2.5, 2.6: British Isambard Kingdom Brunel, two examples of his sixty-four wooden railroad viaducts, built between 1849-1864. Due to the rising railway industry there was a new need for bridges that had to be met quickly. Brunel worked strictly in wood to create 64 viaducts for the South Devon, West Cornwall and Cornwall Railways.

IRON

The two main types of iron are cast and wrought. Cast iron has more carbon in it (around 2-4% of its makeup), making it strong in compressive forces. Wrought iron is worked to remove the carbon, making it more malleable and less brittle and thus suitable to carry tensile forces, although it is weaker in compression than cast iron. Iron had a short lifespan as a material for bridge design. It was not as efficient as stone for compression and its tensile strength was not strong enough for long spans. Steel quickly surpassed the abilities of iron when it became available in industrial quantities. The Iron Bridge by Thomas Pritchard at Coalbrookdale in Shropshire, England in 1781 is perhaps the most famous example, and it is still in use to this day. It was the first cast-iron arch span, semi-circular design with five main ribs that were cast in half, each weighing about six tons. The design was modern at the time, characterized by its redundant members and jointing techniques taken from timber bridges. In 1788 philosopher Thomas Paine took out a patent for the segmental arch iron bridge, an idea that was enacted by Thomas Wilson in the bridge over the River Wear in Sunderland, England in 1793-96. The bridge was twice as long as the Coalbrookdale bridge at 236 feet. Thomas Telford soon built a bridge in Buildwas, England that was thirty feet longer than Coolbrookdale and yet it only used 173 tons of iron, compared the former's 378 tons.

In 1800, John Rennie completed the first bridge made of wrought iron, as this material only became available in large quantities in the 1780s. The bridge weighed just over 3 tons, a design that would have required 208 tons in cast iron. Rennie went on to build three iron toll bridges over the River Thames in the course of ten years, most notably the one in Southwark.

A new design in iron bridges was developed in the 1840s when Robert Stevenson was tasked with finding a way to cross the Menai Strait. The project called for two spans of 460 feet, a length that would have required girders so deep that they would not meet the clearance requirement. Stevenson resolved to use wrought iron tubes (much like today's reinforced concrete box girders), which were prefabricated and brought to the site via huge pontoon boats.

There were also many failures in the iron bridge era. Bridges had the reputation of being unsafe, and without any sort moderated inspection system failures were commonplace. Thomas Wilson, a popular designer at the time, built a cast iron bridge over the Thames in 1803 that needed to be removed within its first year due to fracturing. Another bridge near Coalbrookdale by William Jessop lasted less than a year. Perhaps the most devastating was the Tay Bridge train disaster of 1878. The wrought iron rail bridge was the longest in the world when the main span fell into the water during a snowstorm, killing all seventy-five passengers aboard the train. It was not until the introduction of steel that metal bridges were deemed safe again.

Examples:

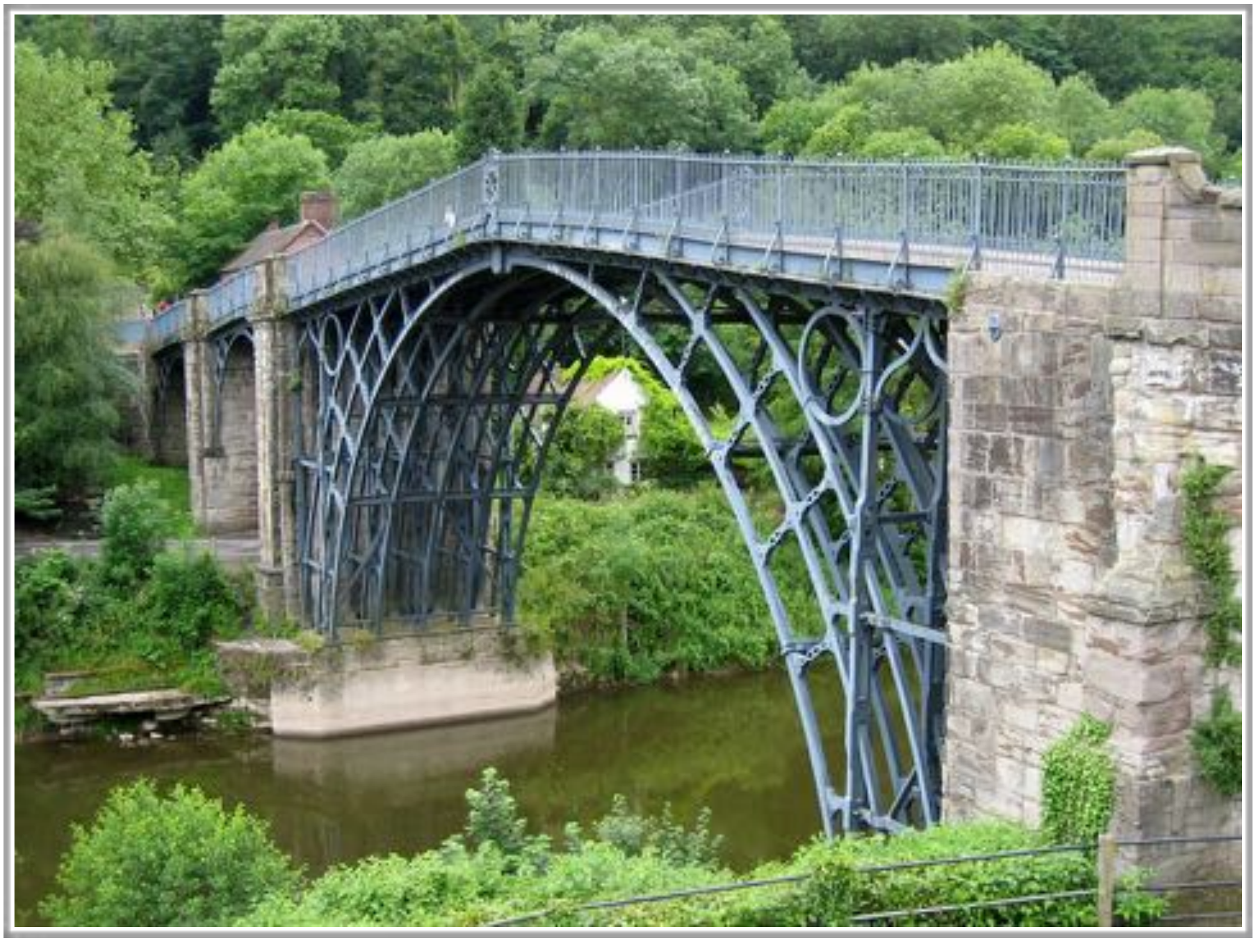
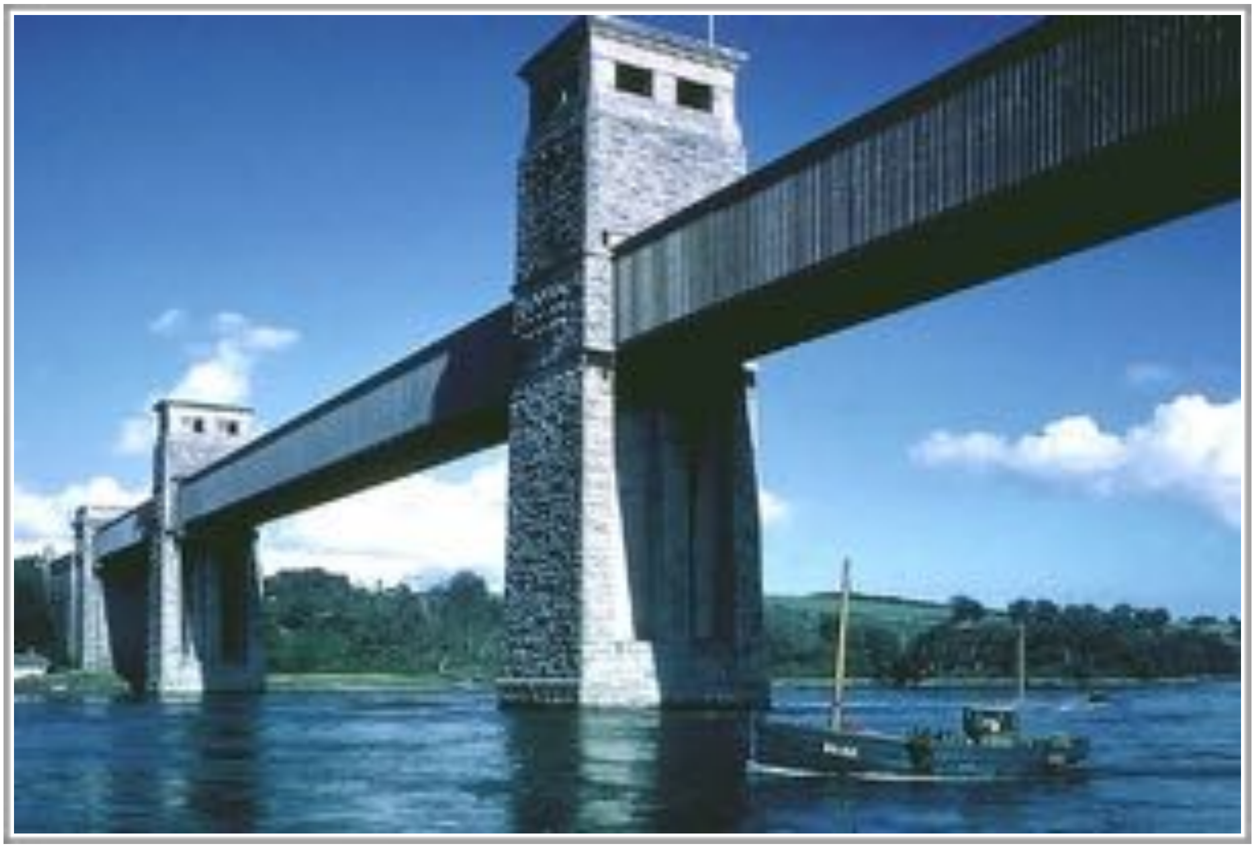


Figure 3.1 The Iron Bridge in Coalbrookdale, Shropshire, England. Although it was “over-designed” the cast iron structure has a beloved delicate design. The stone abutments on either end are massive to counter the outward thrust of the heavy iron arch truss.

Figure 3.2: Thomas Wilson’s Sunderland Bridge in the North of England, built in 1793-96, took an evolutionary step in creating a segmental design with twice the span of any previous cast iron bridge. Again, the abutments on the banks are large to handle the weight of the iron span.

Figure 3.3: Thomas Wilson’s Old Iron Bridge in Spanish Town, Jamaica in 1801.



Figures 3.4, 3.5: Robert Stevenson's Britannia Bridge in Anglesey, North Wales from 1850 features wrought iron tubes to handle the long spans. The bridge was a success and remained operational until it was replaced due to a fire in 1970.

STEEL

Steel is much stronger than iron due to its methodical development. The level of carbon is controlled and supplemented by materials like chromium, nickel and manganese. Depending on the manufacturer steel can have different components and ratios, affecting the strength of the product. Although steel was available much earlier than the first steel bridge, it was not until industrial production begun that it was readily available for the whole of a bridge.

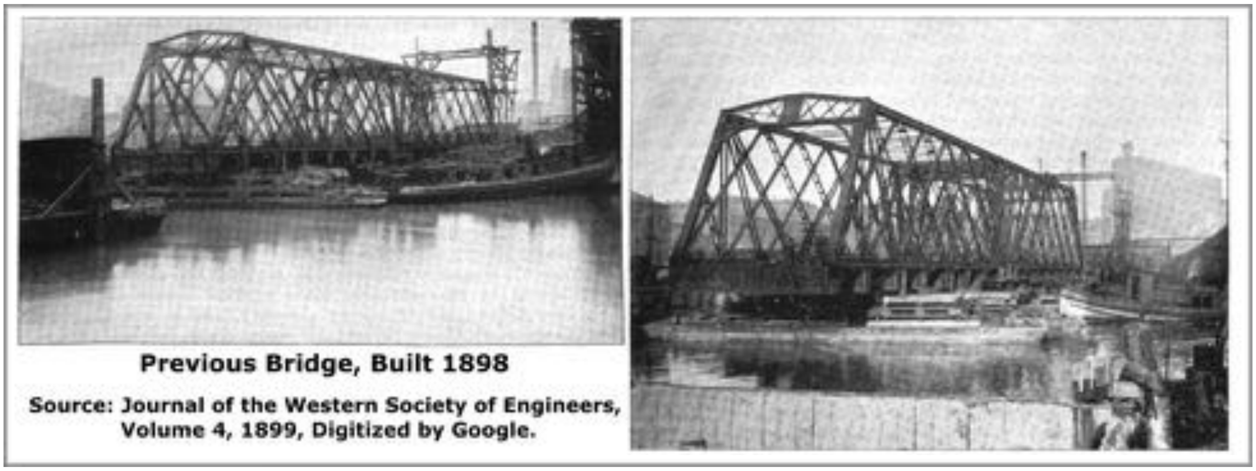
James B. Eads designed the first large steel bridge in the Unites States, the St. Louis Bridge over the Mississippi River in 1874, using chrome steel patented by Julius Barr. The bridge has three arches just over 500 feet and a double-decked design with a railroad level beneath the roadway deck. The construction process was a particular challenge due to the sandy riverbed, causing over 100 construction workers to become crippled by the bends.

Early steel bridges stuck to the iron bridge's incorporation of stone piers. The first all steel bridge was built in Glasglow, Missouri by General William Sooy Smith in 1879. The railroad crossing consisted of five 311-foot trusses for a railroad crossing. Another bridge to break records was the Firth of Forth Bridge west of Edinburgh, Scotland in 1882. The design included 58,000 tons of steel and the unique design of two spans of 680 feet with a suspended center truss of 350 feet. Soon followed was the Viaur Viaduct in France in 1898 with a central cantilever of 721 feet and the Queensboro Bridge, the first big cantilevered bridge in America in 1909. Today the Sydney Harbor Bridge is among the world's most famous bridges. Completed in 1932, it features a whopping 1,650-foot span with four rail lines and six lanes for highway. The high tensile silicon steel for the arch weighs 38,390 tons.

Steel became a reliable bridge material causing it to be used in multiple ways. From the beginning of steel in bridge design it has been utilized in high strength cable for suspension and cable-stay bridges. And in addition to the development of steel structures, reinforcing steel bars also became used as the tensile strength in reinforced concrete. Introduced at the end of the 19th century, reinforcing, pre-stressing and post-tensioning concrete with steel created the ultimate composite material for compression and tension. Today steel is one of the most highly prized building materials in the world.

Examples:

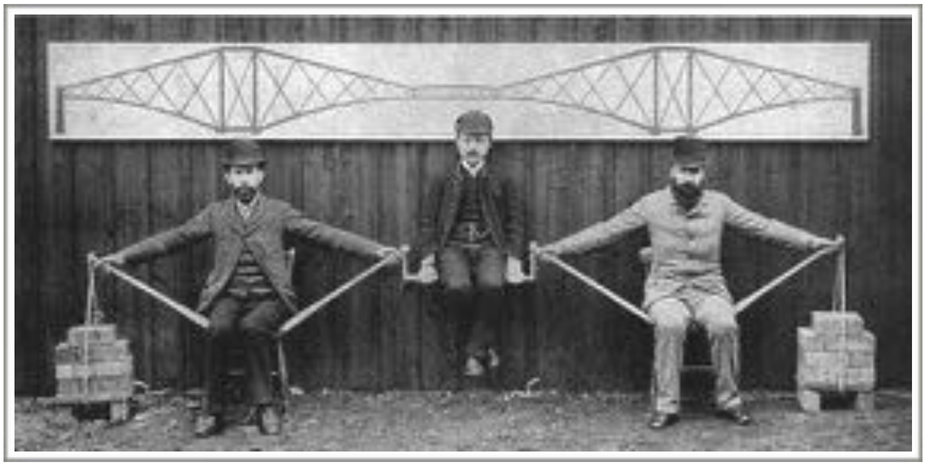
Figures 4.1, 4.2, 4.3: The St. Louis Bridge over the Mississippi River by James B. Eads in 1874.



Previous Bridge, Built 1898

Source: Journal of the Western Society of Engineers, Volume 4, 1899, Digitized by Google.

Figure 4.4: The General William Sooy Smith Bridge in Glasglow, Missouri from 1879.



Figures 4.5, 4.6: The Forth Bridge by Sirs John Fowler and Benjamin Baker in Edinburgh, Scotland in 1882. Figure 4.6 is a famous image of the stress test featuring the two designers and an assistant for the project. The test proves that the stress in the men's outstretched arms balance the compression in the lower members, allowing the structure to support a suspended span in the middle.

Figure 4.7: The 1898 Viaur Viaduct in France.

Figure 4.8: The more modern Golden Gate Bridge in San Francisco, CA, completed in 1937.

CONCRETE

Concrete dates back to ancient Rome, a civilization known for its multiple grand structures that have stood for two millennia. The recipe, however, died with the civilization. It was not until the late eighteenth century that John Smeaton started to develop new technology with waterproof pozzolanic cements. In the last decade of the nineteenth century James Parker patented Roman cement, which was later replaced by Joseph Aspdin's Portland cement in 1824. Portland cement is most often used today, combined with aggregate and water to create concrete.

Concrete, like stone, is good in compression but has weak tensile strength. The first major use of concrete was in 1898 in the Glenfinnan Viaduct in Invernessshire, Scotland, a 21-arch viaduct. The style echoes the ancient Roman viaducts with the arcade of semi-circular arches.

The desire for additional tensile strength soon became apparent, which could be achieved by combining concrete and metal. Experimentation began with Frenchman Joseph Monier in 1867 when he made cement cylinders with embedded iron mesh. The early stages of concrete bridges featured mainly arches due to their compressive strength, but reinforcement could mean longer and thinner arches. The first example was in France in 1869, a shallow arch footbridge in the castle park of Marquis Tillere de Chazelet. Bridge designer Eugene Freyssinet was the next great innovator in concrete technology, his accomplishments include planning around concrete creep (where the concrete settles and shrinks when it dries) and fathering the idea of pre-stressed concrete. Franz Dischinger built the first pre-stressed concrete bridge in Alsleben, Germany in 1927, a feat that was later met in the United States in 1950 in Philadelphia with the Walnut Street Bridge.

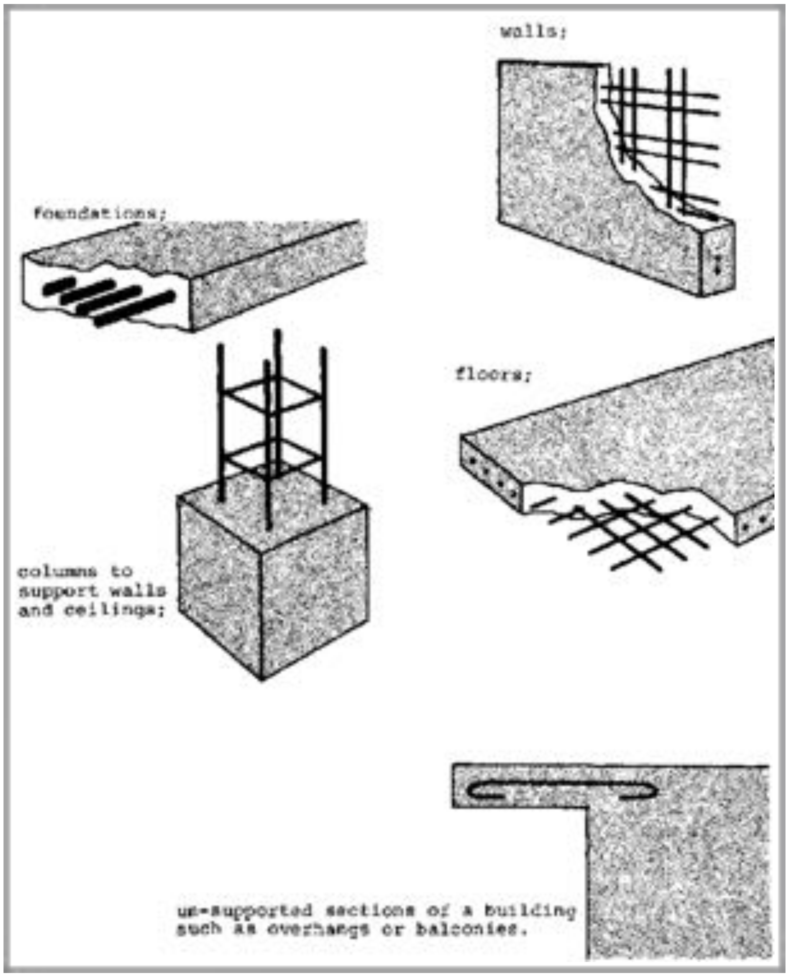
Originally the reinforcing material was iron, but today steel is predominantly used for maximum tensile strength. Carbon fiber and other synthetics, however, are entering the market as non-corrosive substitutions. The three main methods to introduce tension strength are conventional reinforcing bars, pre-stressing and post-tensioning. Sometimes all three methods are used together for maximum strength.

Conventional reinforcing is typically introduced by laying metal rods or mesh in the formwork before pouring the wet concrete, creating a tension frame within the concrete to eliminate fractures.

Pre-stressing includes stretching and holding the ends of high strength steel rods or cables in the formwork before placing the wet concrete. Once the concrete dries the ends of the prestressing steel are released, causing the concrete to contract under the stress of the detracting metal. After the beam is in place it will have increased capacity to resist additional forces imposed upon it. If it is a slab for a bridge deck, for example, a heavy truck may introduce flexing tension in the bottom of the slab, but the pre-compression of the concrete from the pre-stressing steel will prevent any harmful cracks from forming.

Post-tensioning is similar to pre-stressing in the effects it has on the concrete. This method involves placing the concrete with tubular holes, or voids in the beam or slab. Once the concrete has cured, high strength steel rods or cables are threaded through the holes, and stretched taught, and the tubular void areas are is filled with grout to hold the metal in tension. Sometimes pre-stressing and post-tensioning are used together to provide additional tensile strength, or address specific construction needs.

Today concrete is extremely useful and versatile, especially when it is combined with steel to create the ultimate compressive/tensile material. Due to its reliability, economy, low maintenance, ability to be formed in almost any shape, and clean appearance, reinforced concrete has become a staple in bridge design around the world.



Figures 5.1, 5.2, 5.3: Examples and sections of reinforced concrete.

Figures 5.4, 5.5: Examples of pre-stressed and post-tensioned concrete.

Examples:

Figure 5.6: The Glenfinnan Railroad Viaduct in Invernessshire, Scotland from 1869. A rare example of a large concrete structure with no reinforcing metal.

Figure 5.7: Eugene Freyssinet's Plougastel Bridge in Brest, France in 1930. Each of the three segmental arch spans is an impressive 592 feet long. Concrete-box girders form the arch; they are thirty-one feet wide, fourteen feet deep and rise ninety feet above the water level.

Figure 5.8 Robert Mailliart's Salginatobel Bridge in Schiers, Switzerland in 1930. The thin and simple 250-foot arch soars 1,000 feet above the valley below, making the bridge a landmark in concrete history. Bridge expert David Billington applauds Mailliart's design and vision stating he "was the first engineer to sense that the full expression in concrete structures could be efficient (safe performance with minimum materials), economical (accountable to the public welfare or private industry with competitive costs), and elegant all in the same construction."

IV. TYPES OF BRIDGES

A. ARCH

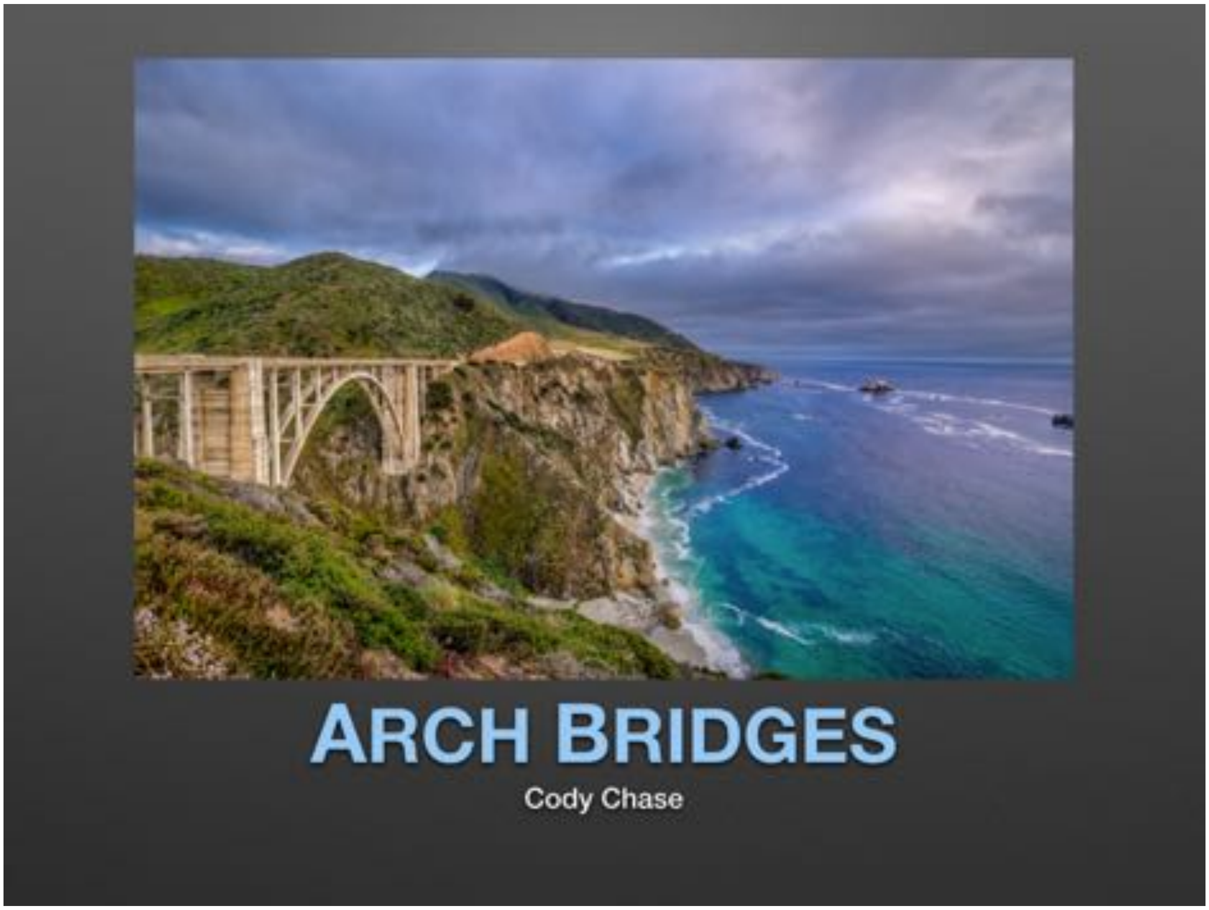
The arch bridge is one of the oldest types in the world. Many advancements have been made in materials and design to lengthen these bridges far past the examples of past civilizations. Today it is used in a variety of lengths and locations due to its stability and beauty.

ARCH TYPES:

- True/Round
- Corbeled
- Segmental

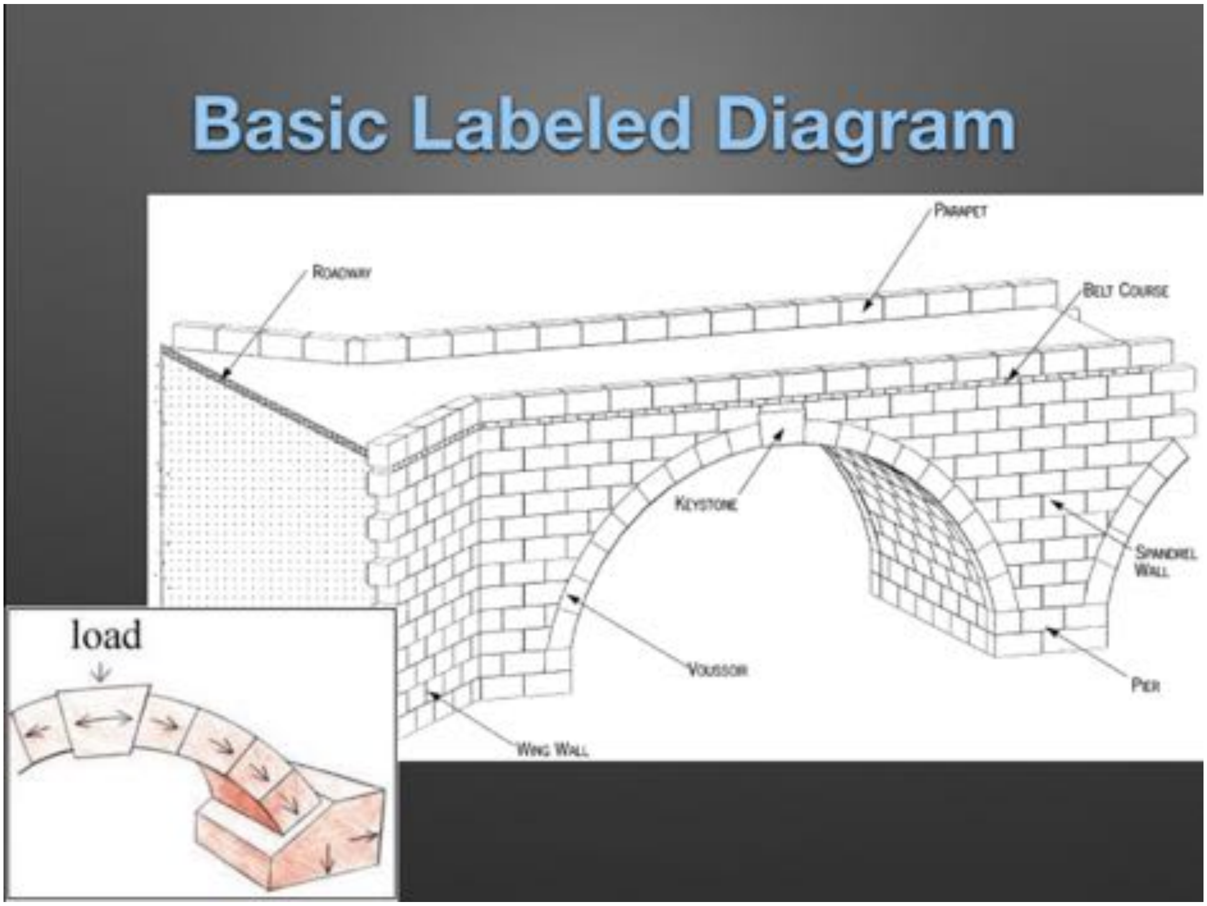
SUBTYPES:

- Deck
- Through
- Hinged
- Closed Spandrel
- Open Spandrel
- Skewed
- Fixed
- Tied/Bowstring
- Suspended Deck



ARCH BRIDGES

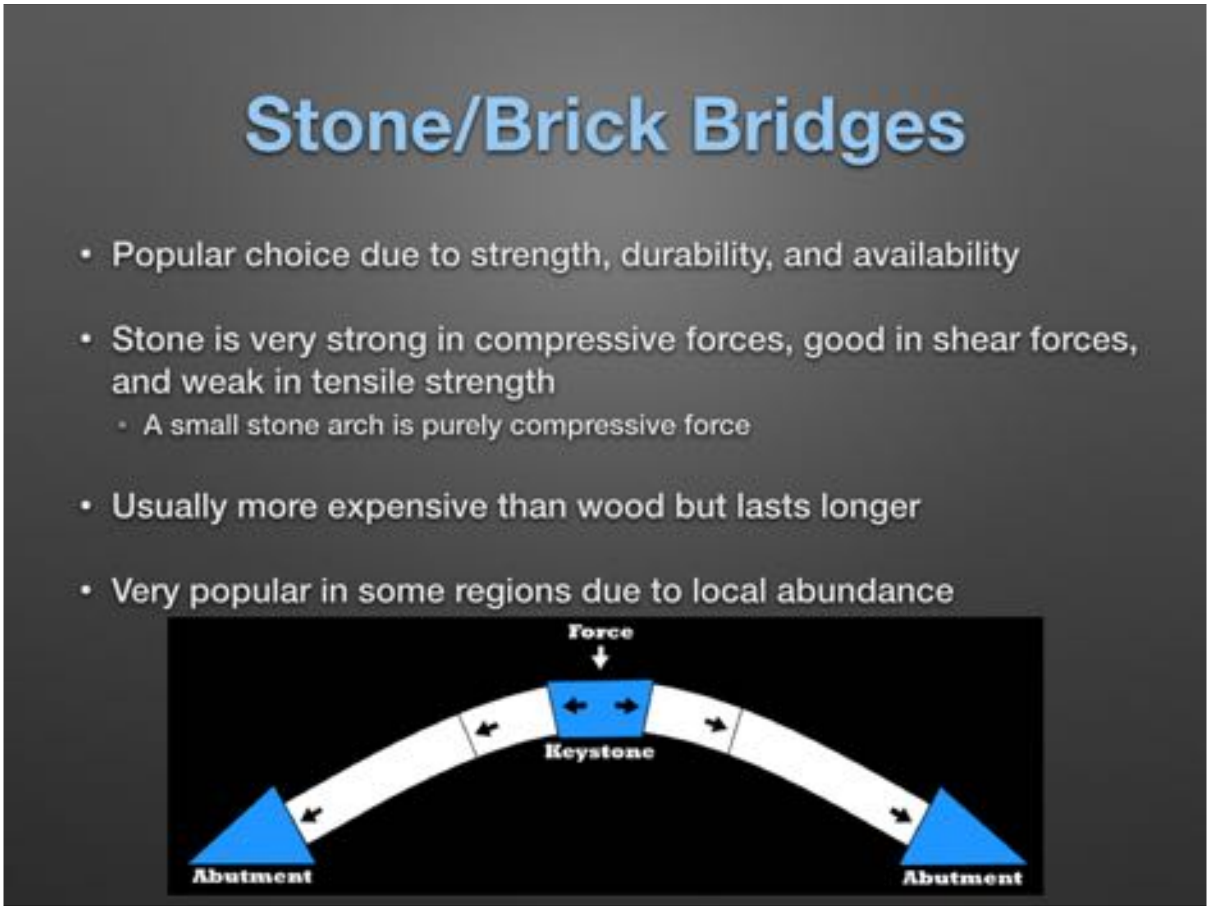
Cody Chase



Basic Labeled Diagram

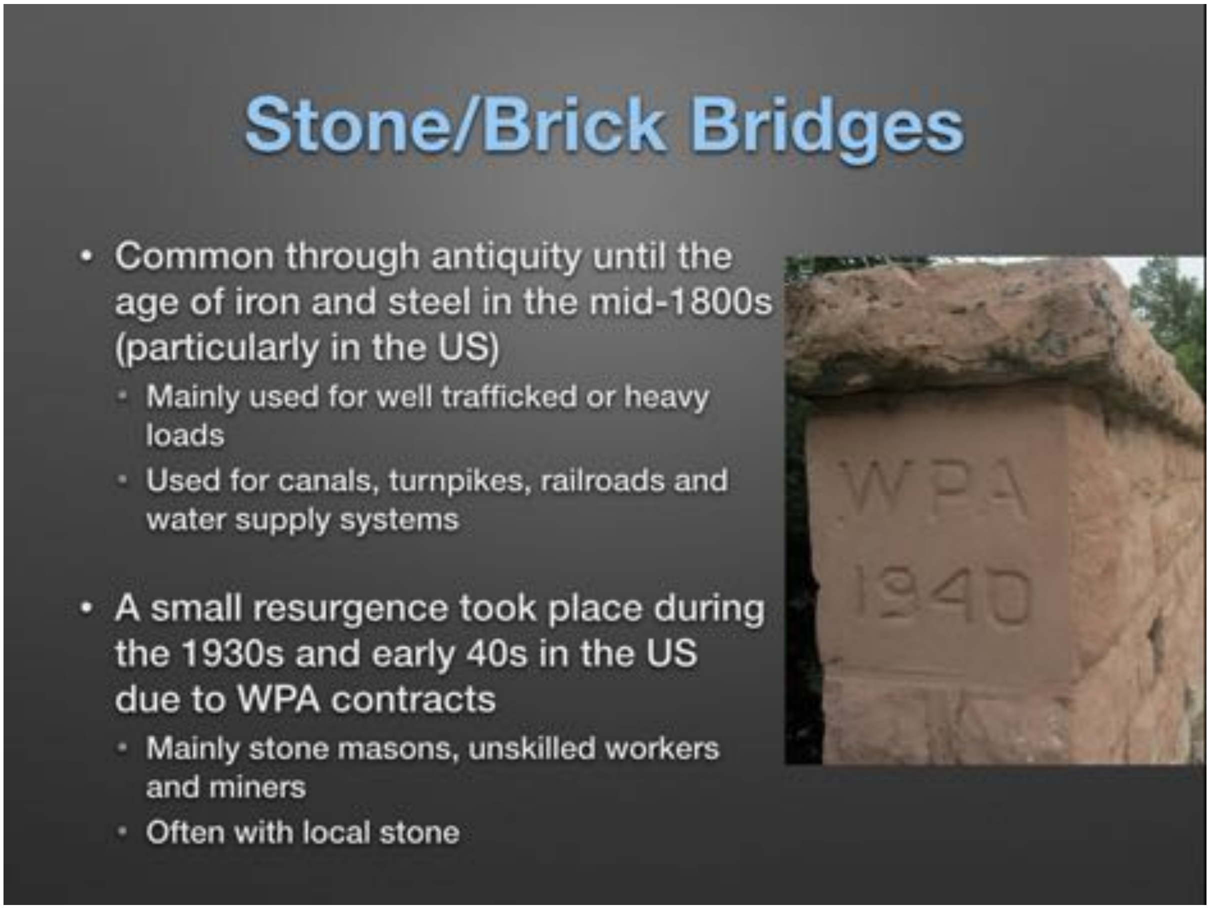
Materials

- Stone
- Concrete
- Steel
- Reinforced Concrete



Stone/Brick Bridges

- Popular choice due to strength, durability, and availability
- Stone is very strong in compressive forces, good in shear forces, and weak in tensile strength
  - A small stone arch is purely compressive force
- Usually more expensive than wood but lasts longer
- Very popular in some regions due to local abundance

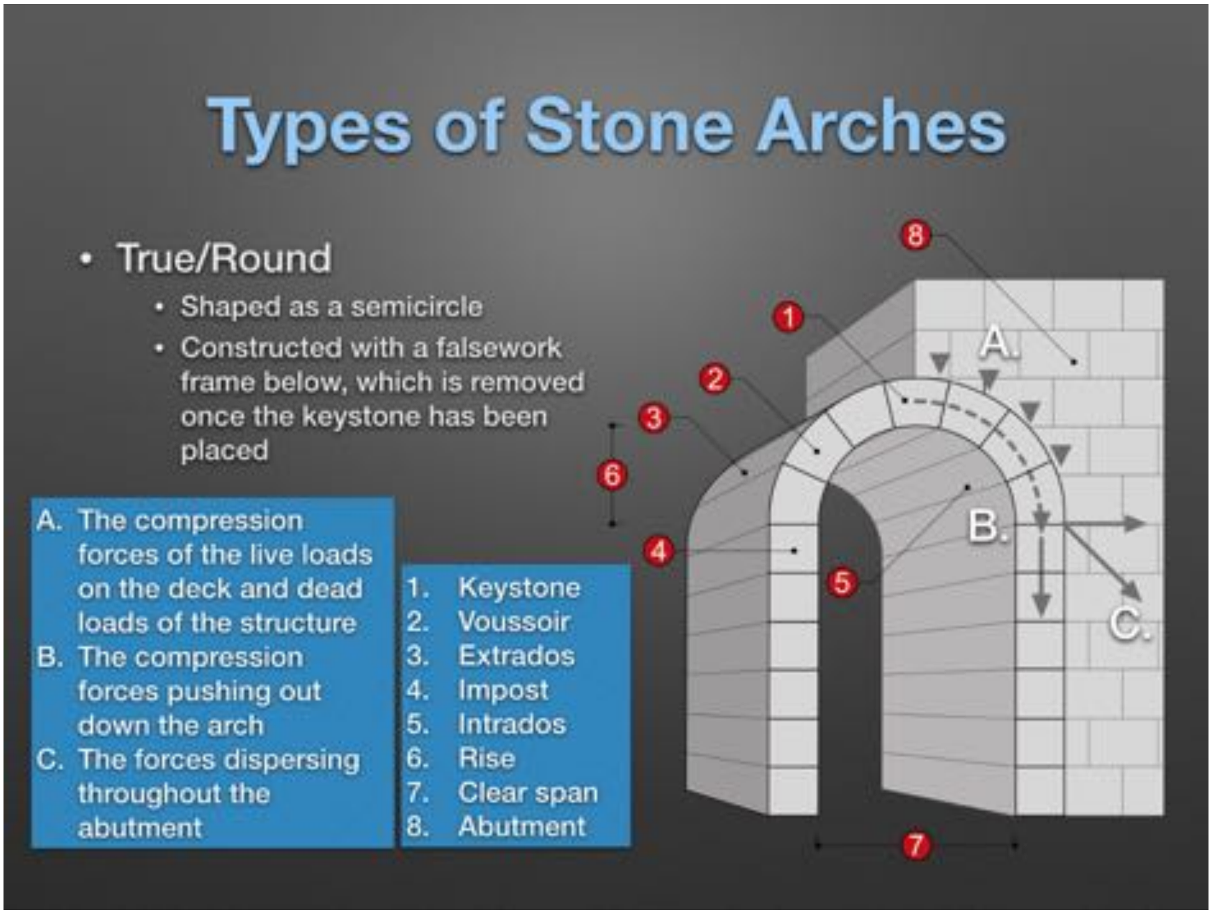


Stone/Brick Bridges

- Common through antiquity until the age of iron and steel in the mid-1800s (particularly in the US)
  - Mainly used for well trafficked or heavy loads
  - Used for canals, turnpikes, railroads and water supply systems
- A small resurgence took place during the 1930s and early 40s in the US due to WPA contracts
  - Mainly stone masons, unskilled workers and miners
  - Often with local stone

Types of Stone Arches

- Since antiquity there have been three main types
  - True/Round, Corbeled, Segmented
- All types have continued in use through to contemporary times

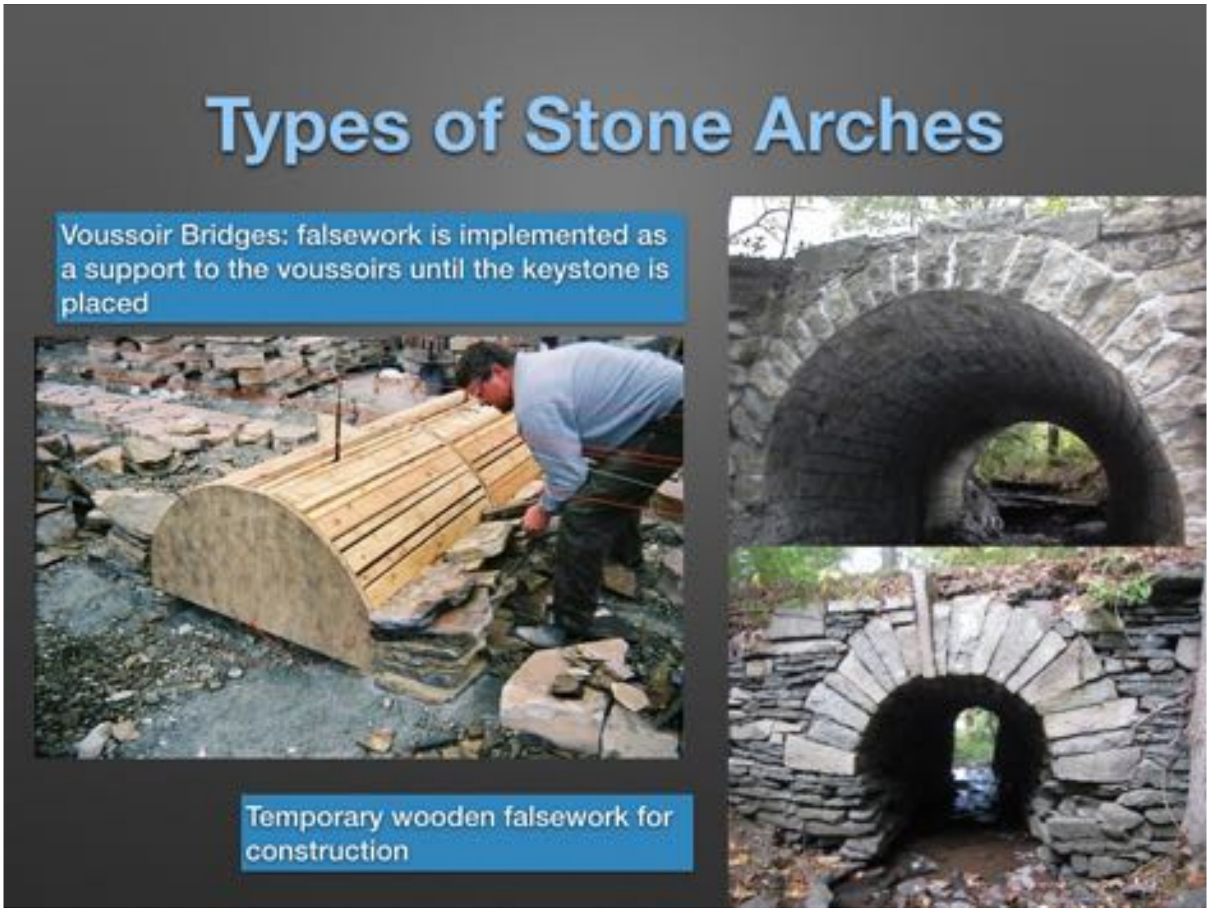


Types of Stone Arches

- True/Round
  - Shaped as a semicircle
  - Constructed with a falsework frame below, which is removed once the keystone has been placed

A. The compression forces of the live loads on the deck and dead loads of the structure
B. The compression forces pushing out down the arch
C. The forces dispersing throughout the abutment

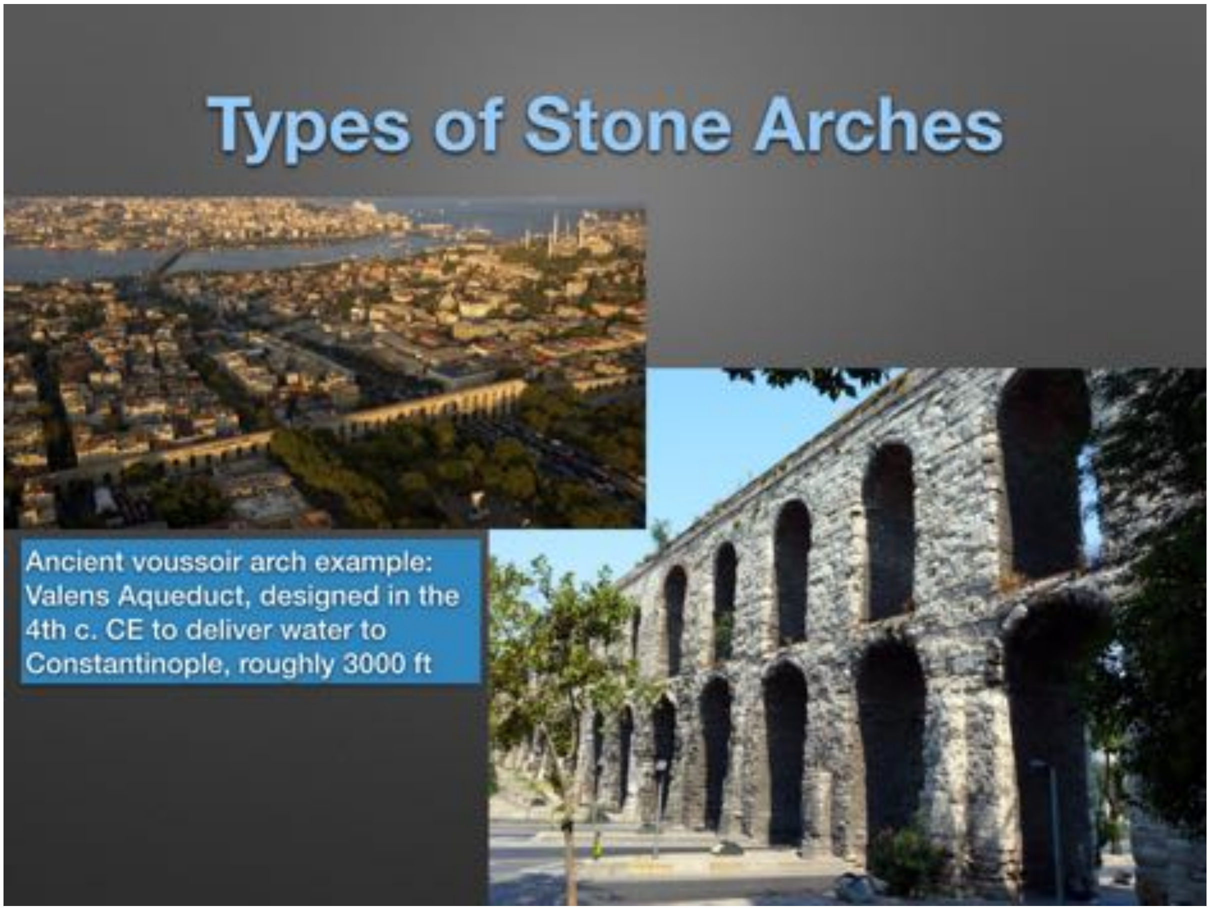
1. Keystone
2. Voussoir
3. Extrados
4. Impost
5. Intrados
6. Rise
7. Clear span
8. Abutment



Types of Stone Arches

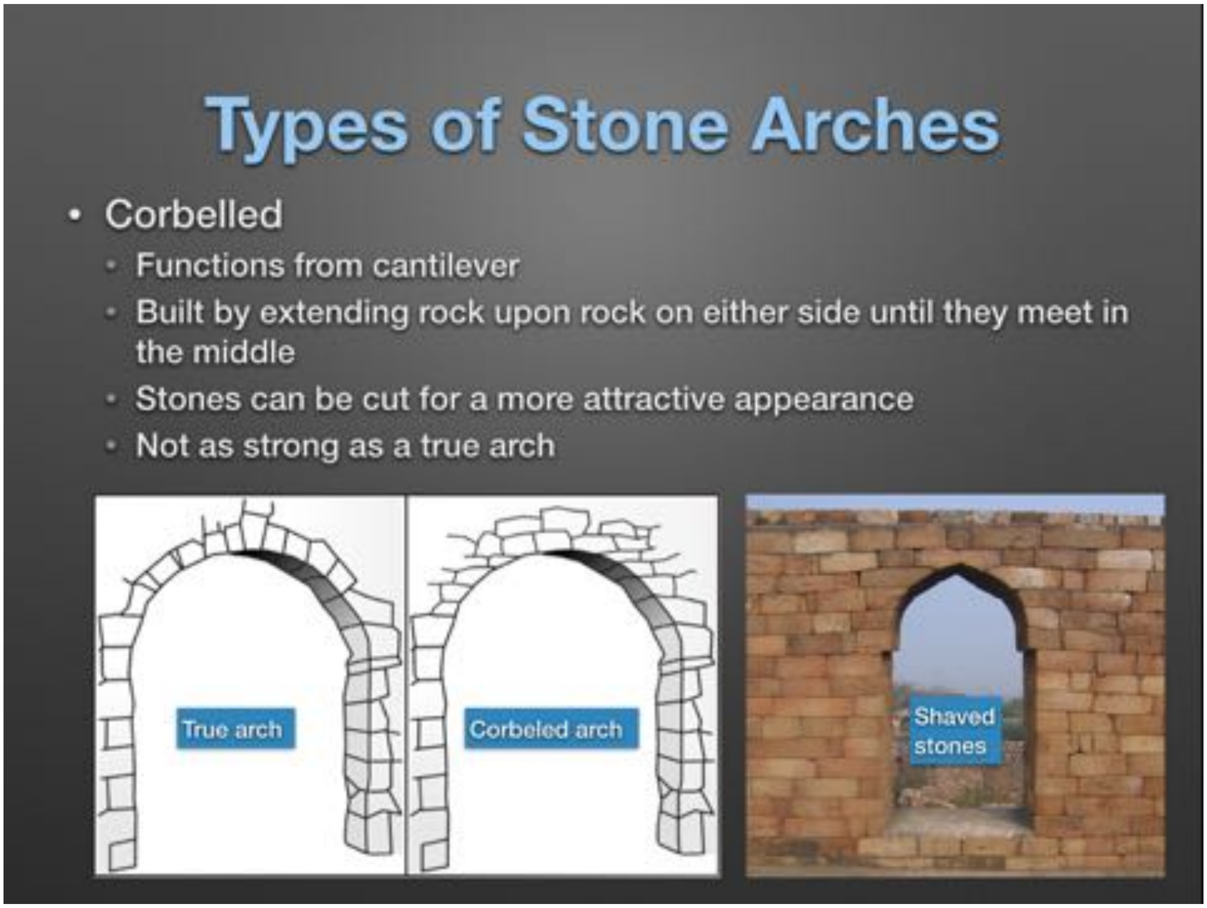
Voussoir Bridges: falsework is implemented as a support to the voussoirs until the keystone is placed

Temporary wooden falsework for construction



Types of Stone Arches

Ancient voussoir arch example: Valens Aqueduct, designed in the 4th c. CE to deliver water to Constantinople, roughly 3000 ft



Types of Stone Arches

- Corbelled
  - Functions from cantilever
  - Built by extending rock upon rock on either side until they meet in the middle
  - Stones can be cut for a more attractive appearance
  - Not as strong as a true arch

True arch

Corbeled arch

Shaved stones

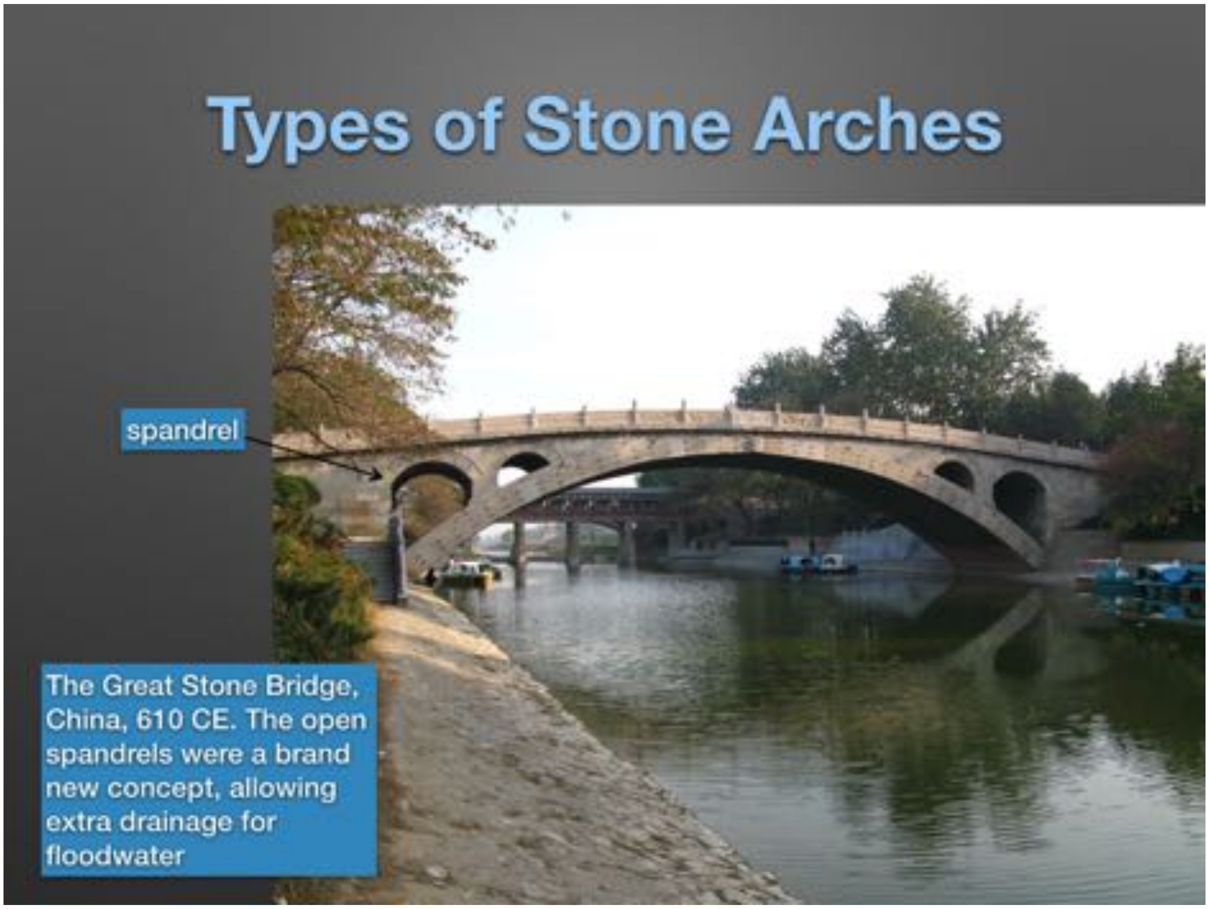
Types of Stone Arches

Arkadiko Bridge, Greece, 1300 BCE.
Early example of corbelled design in limestone.

Types of Stone Arches

- Segmented
  - Newer design formed from the voussoir arch concept
  - Altered the arch to allow a wider span, lower clearance, and more space underneath

Alconétar Bridge, Spain under Roman Empire, around 100 CE



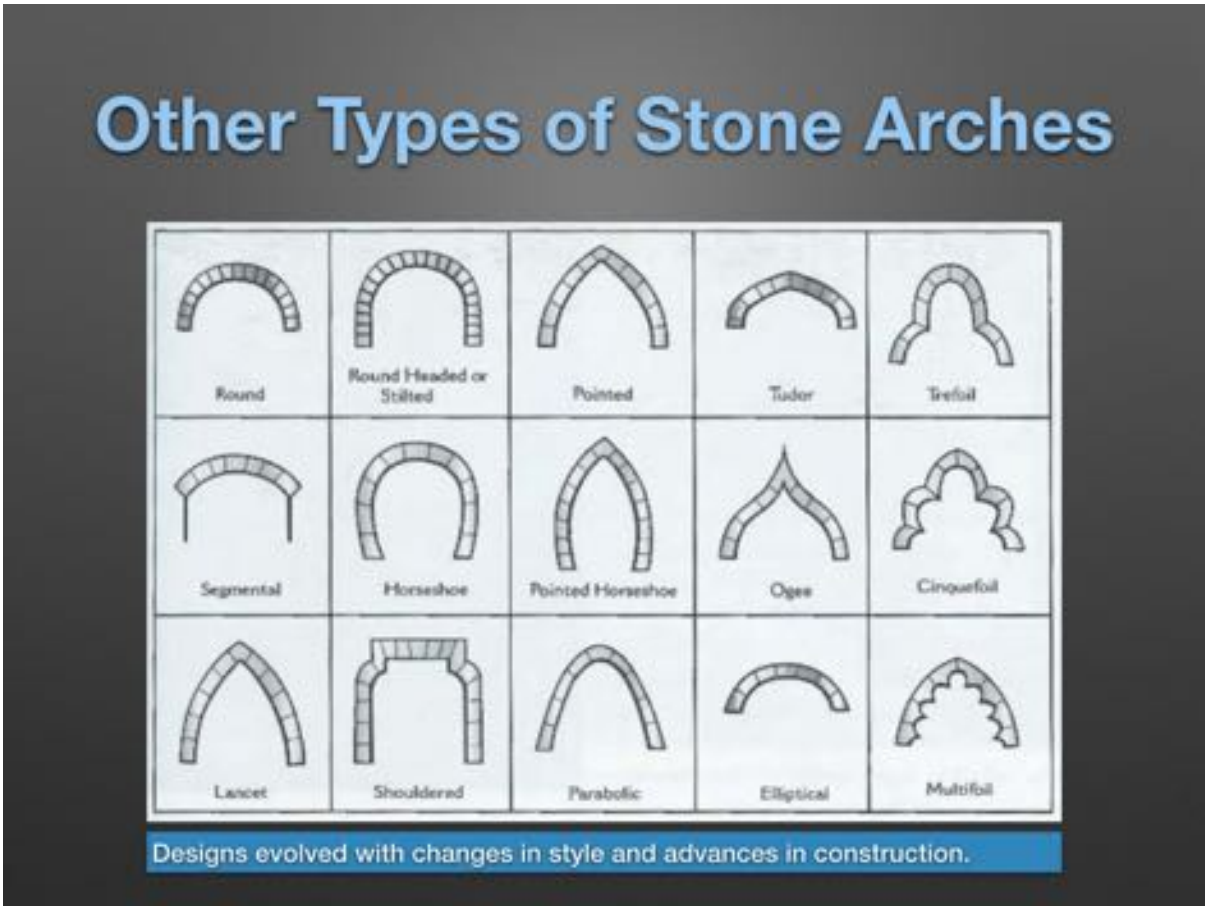
Types of Stone Arches

spandrel

The Great Stone Bridge, China, 610 CE. The open spandrels were a brand new concept, allowing extra drainage for floodwater

Types of Stone Arches

Ponte Vecchio, Florence, Italy, 1345
*Early Renaissance Segmental Stone Bridge



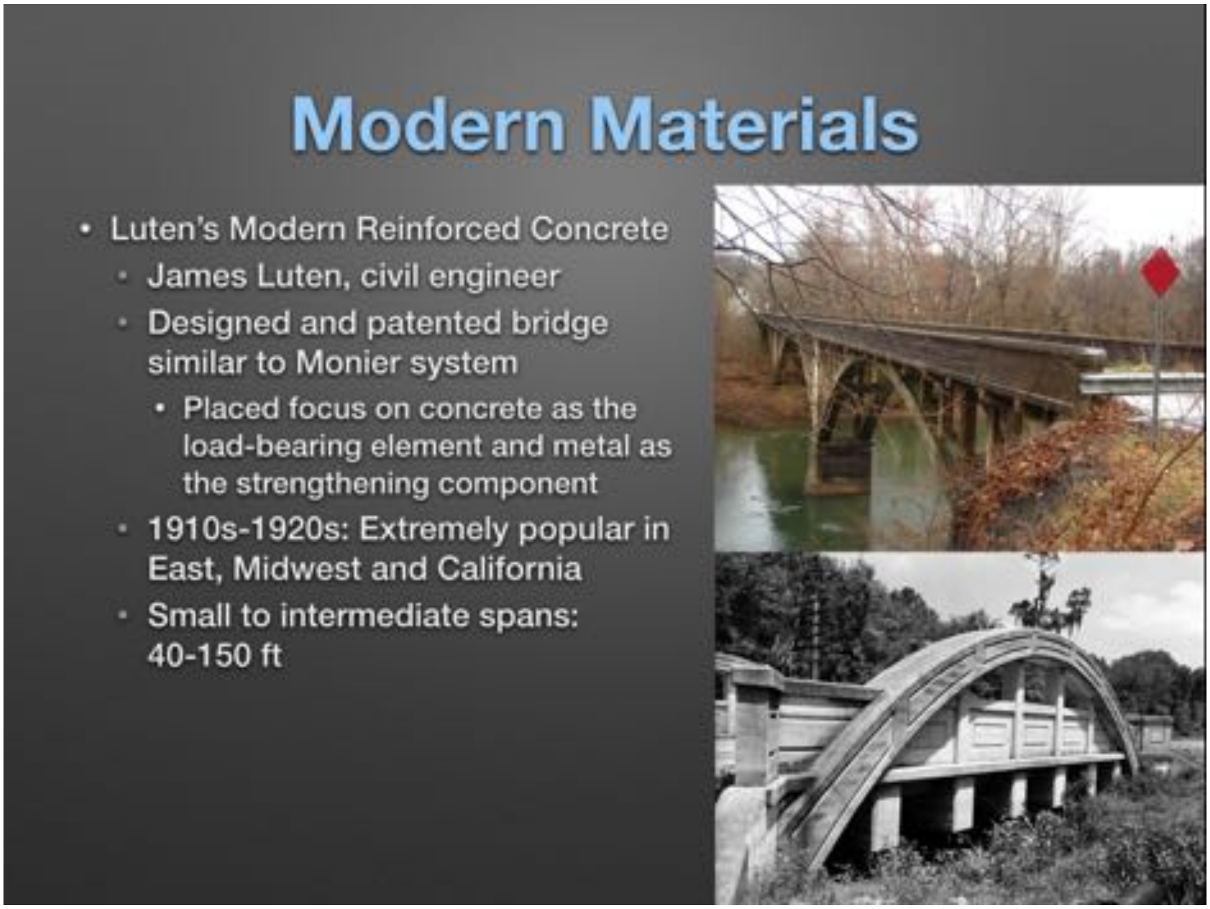
Other Types of Stone Arches

Designs evolved with changes in style and advances in construction.

Modern Materials

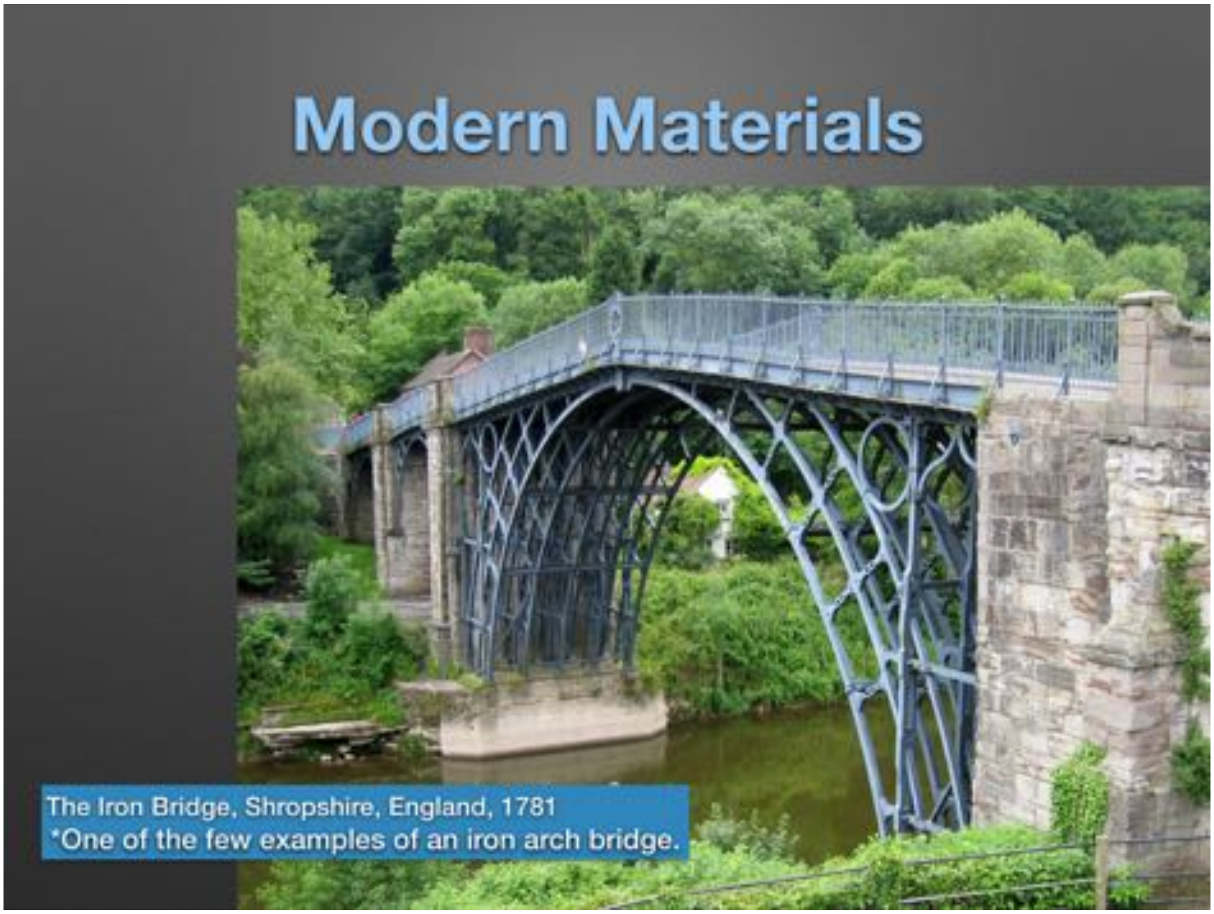
- Concrete
  - Strong in compressive strength but more complicated process than stone
  - Few unreinforced concrete bridges were made due to emerging experimentation with reinforcement

Cleft-Ridge Span, Prospect Park, NYC, 1871



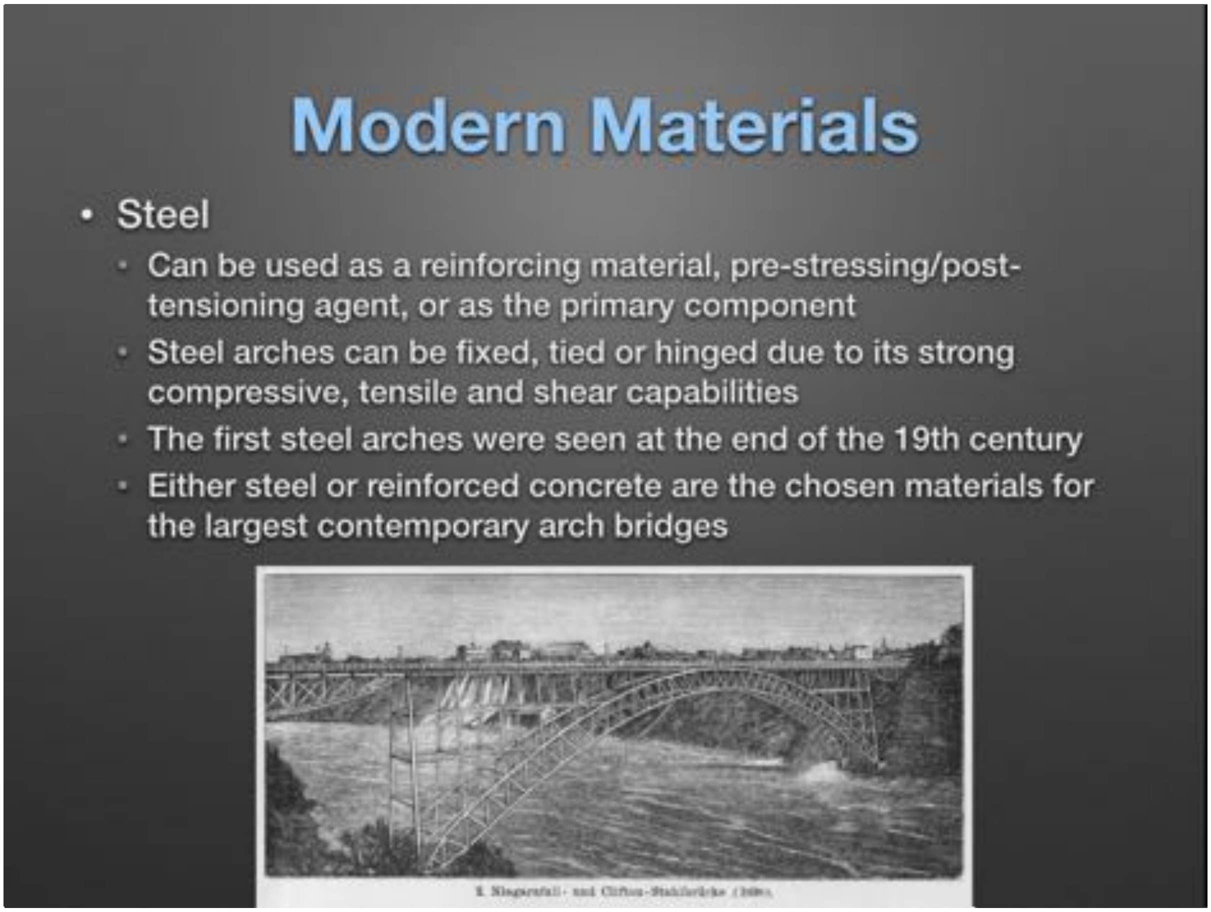
Modern Materials

- Luten's Modern Reinforced Concrete
  - James Luten, civil engineer
  - Designed and patented bridge similar to Monier system
    - Placed focus on concrete as the load-bearing element and metal as the strengthening component
  - 1910s-1920s: Extremely popular in East, Midwest and California
  - Small to intermediate spans: 40-150 ft



Modern Materials

The Iron Bridge, Shropshire, England, 1781
*One of the few examples of an iron arch bridge.

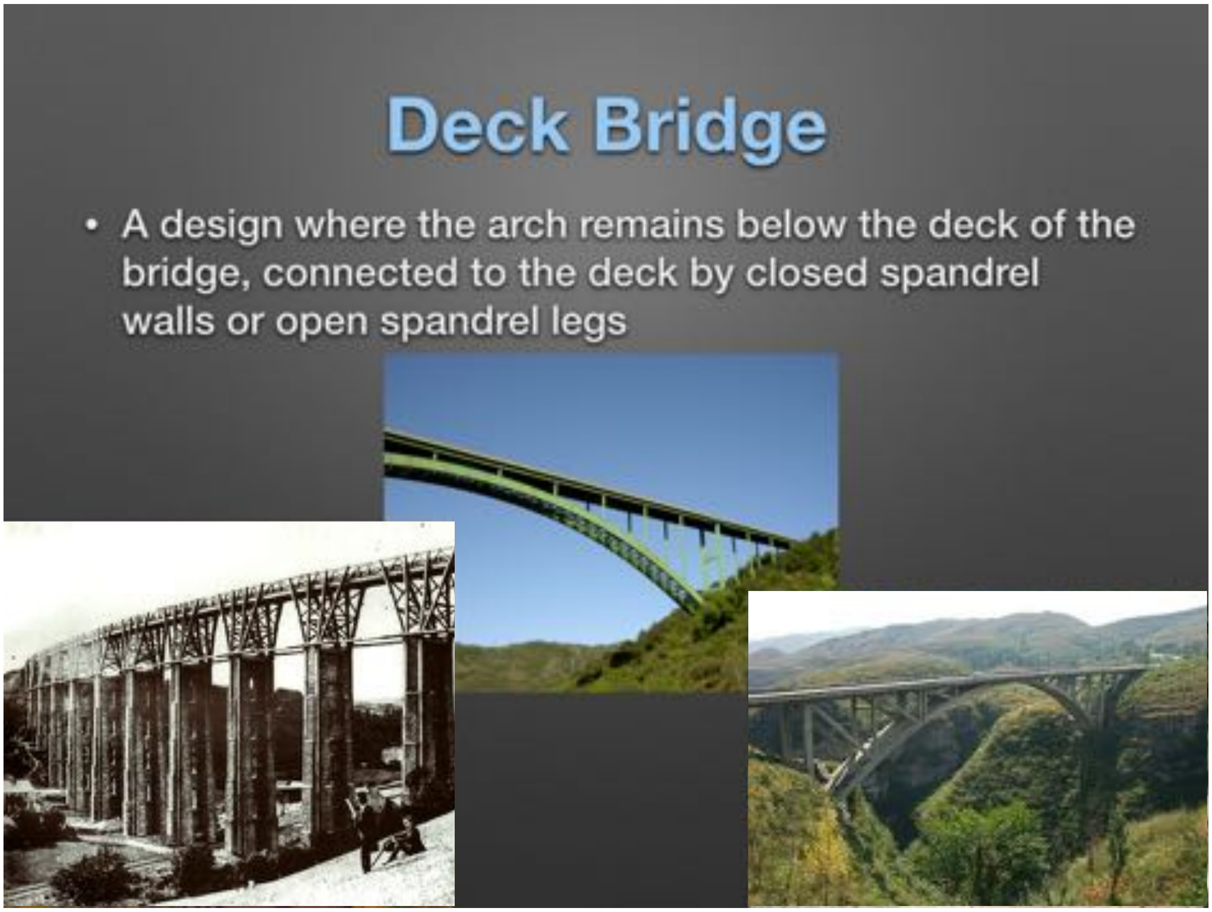


Modern Materials

- Steel
  - Can be used as a reinforcing material, pre-stressing/post-tensioning agent, or as the primary component
  - Steel arches can be fixed, tied or hinged due to its strong compressive, tensile and shear capabilities
  - The first steel arches were seen at the end of the 19th century
  - Either steel or reinforced concrete are the chosen materials for the largest contemporary arch bridges

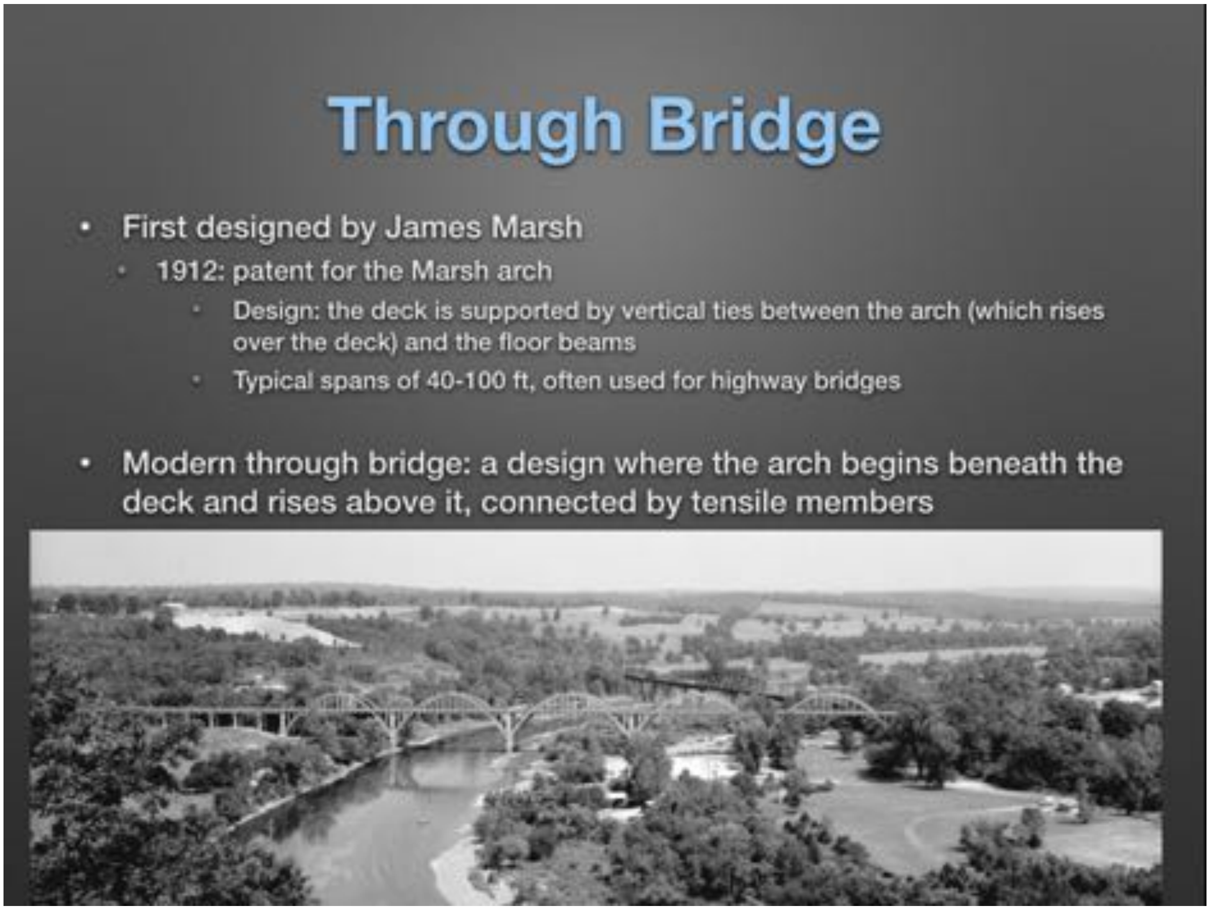
Design Variations

- Deck Bridge
- Through Bridge
- Hinged Bridge
- Closed Spandrel Bridge
- Open Spandrel Bridge
- Skewed Bridge
- Fixed Bridge
- Tied/Bowstring Bridge
- Suspended Deck Arch Bridge



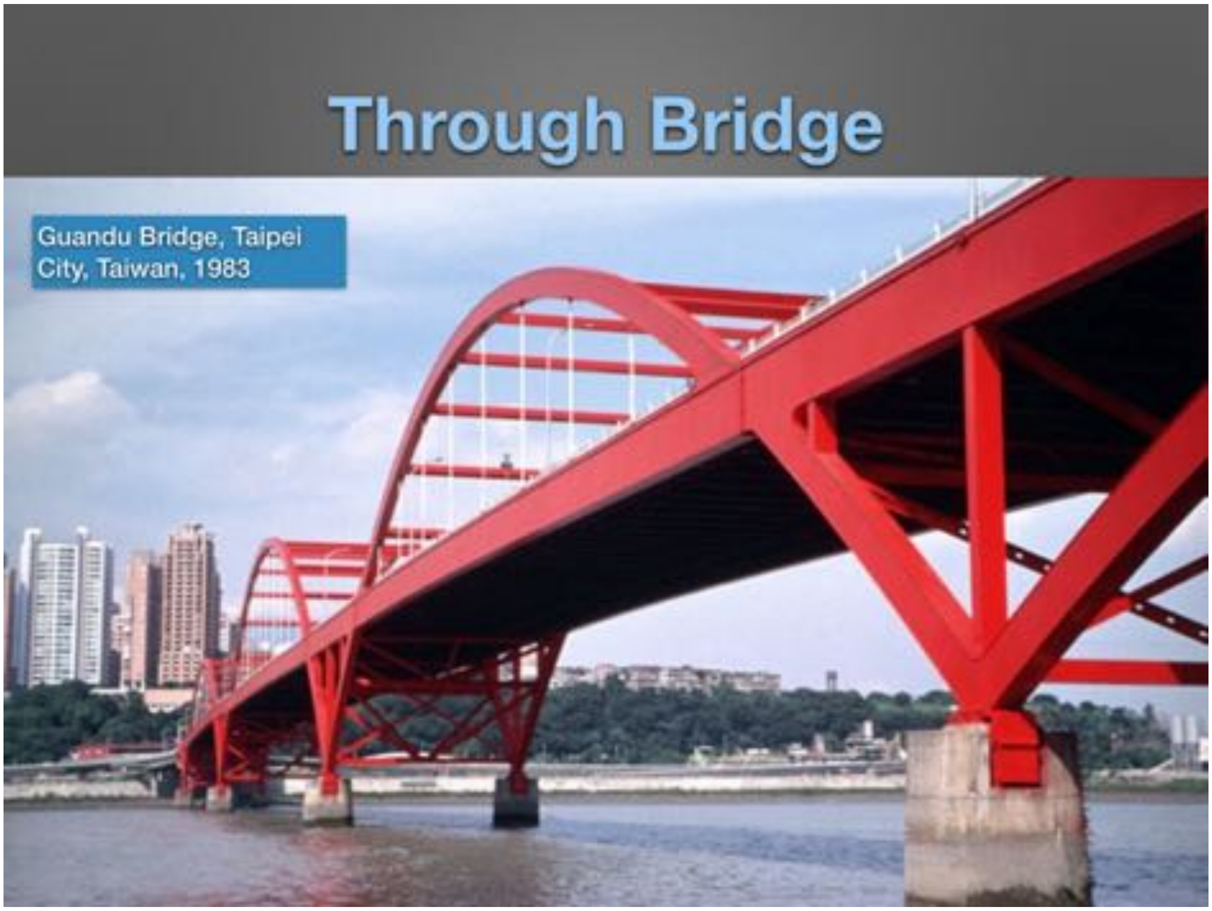
Deck Bridge

- A design where the arch remains below the deck of the bridge, connected to the deck by closed spandrel walls or open spandrel legs



Through Bridge

- First designed by James Marsh
  - 1912: patent for the Marsh arch
    - Design: the deck is supported by vertical ties between the arch (which rises over the deck) and the floor beams
    - Typical spans of 40-100 ft, often used for highway bridges
- Modern through bridge: a design where the arch begins beneath the deck and rises above it, connected by tensile members

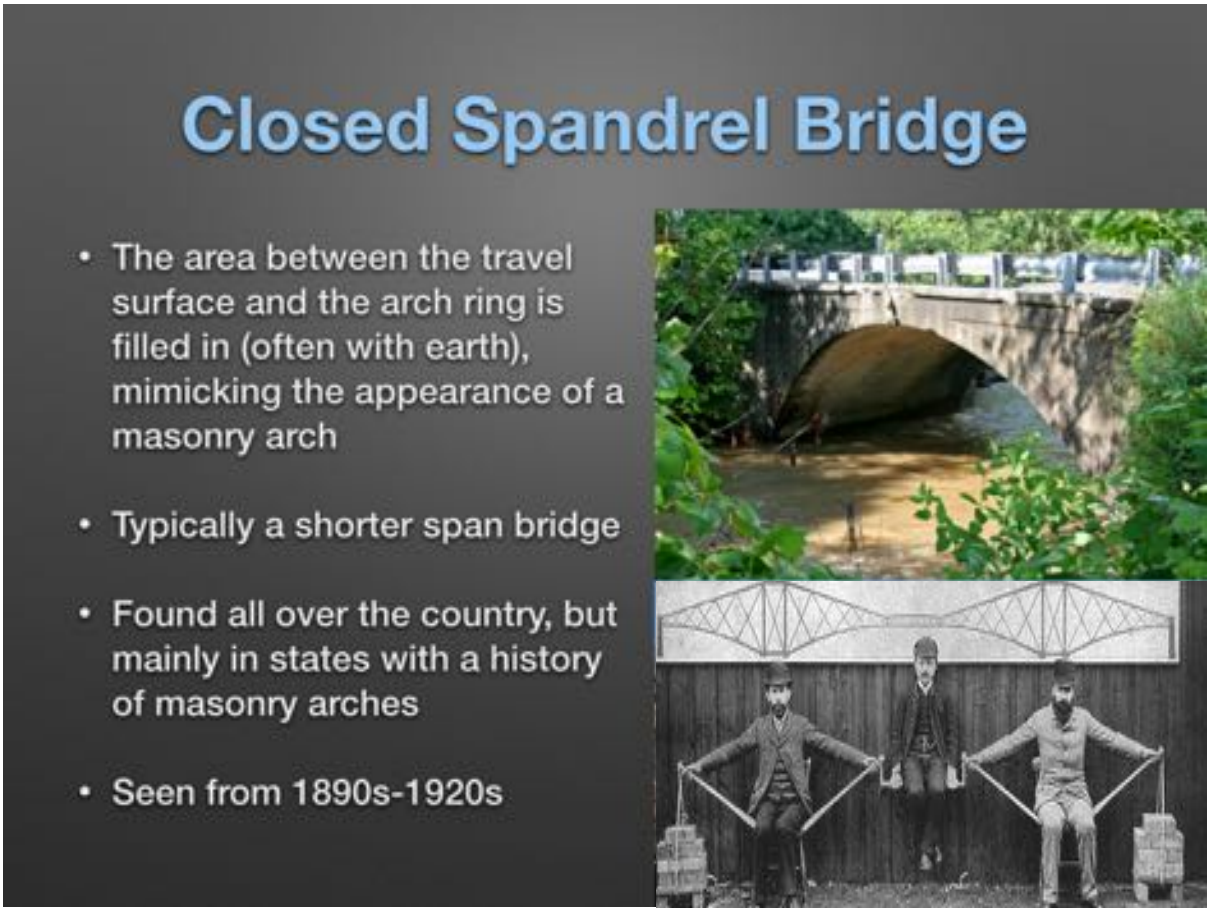


Through Bridge

Guandu Bridge, Taipei City, Taiwan, 1983

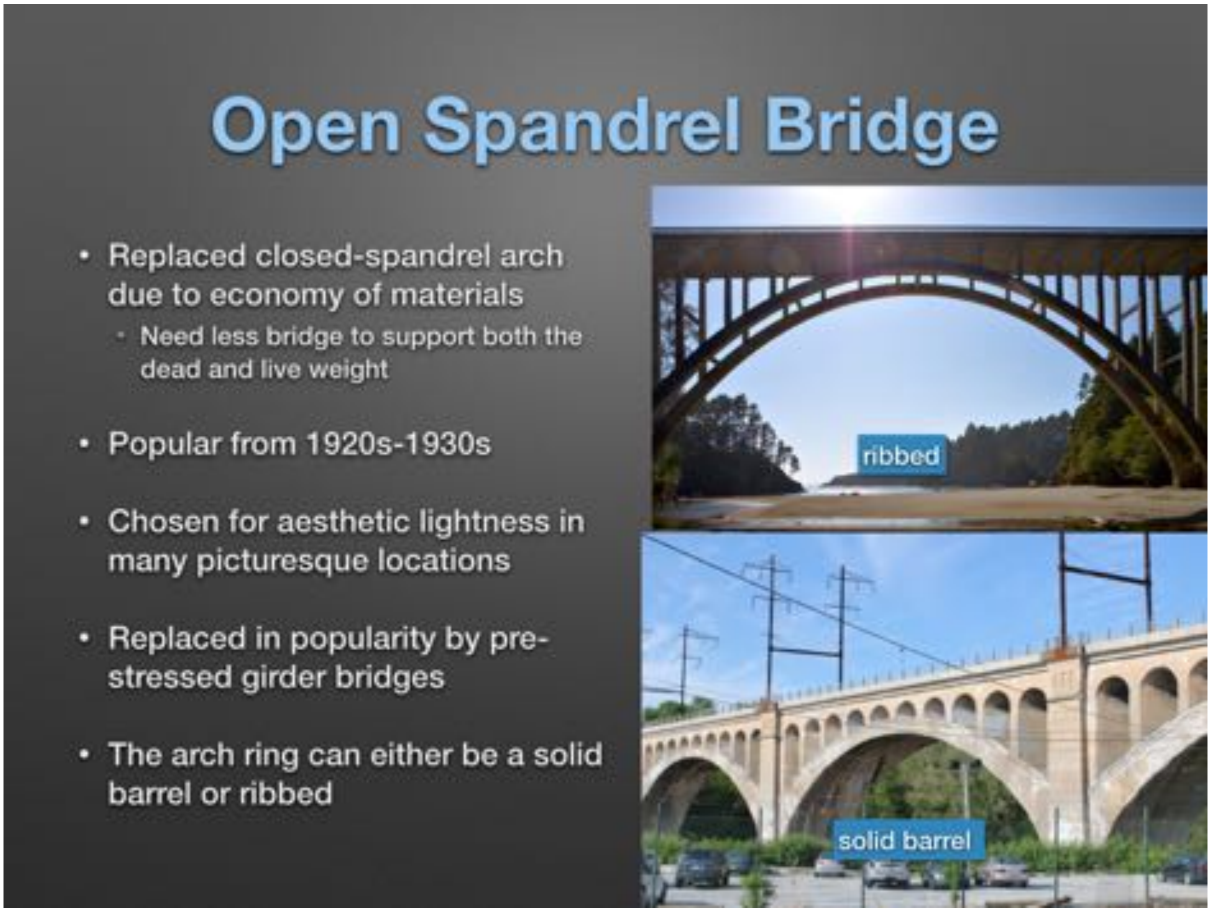
Hinged Bridge

- Started as early as pre-Civil War and through the 19th century; in the 1930s high strength alloy steels are introduced and continue to today
- Three types
  - One-hinge: one hinge at crown of arch, very uncommon
  - Two-hinge: most common, a hinge at each abutment allows the bridge to breathe with the weather, spans range from 500-1,675 ft
  - Three-hinge: a hinge at each abutment and at the crown of the arch, very breathable, mainly used for highway bridges
  - *Reinforced concrete hinged bridge: often three-hinge
- Famous examples
  - Hell Gate Bridge, NYC, 1916
  - Bayonne Bridge, New Jersey, 1931
  - Sydney Harbor Bridge, Australia, 1932



Closed Spandrel Bridge

- The area between the travel surface and the arch ring is filled in (often with earth), mimicking the appearance of a masonry arch
- Typically a shorter span bridge
- Found all over the country, but mainly in states with a history of masonry arches
- Seen from 1890s-1920s



Open Spandrel Bridge

- Replaced closed-spandrel arch due to economy of materials
  - Need less bridge to support both the dead and live weight
- Popular from 1920s-1930s
- Chosen for aesthetic lightness in many picturesque locations
- Replaced in popularity by pre-stressed girder bridges
- The arch ring can either be a solid barrel or ribbed

Skewed Bridge

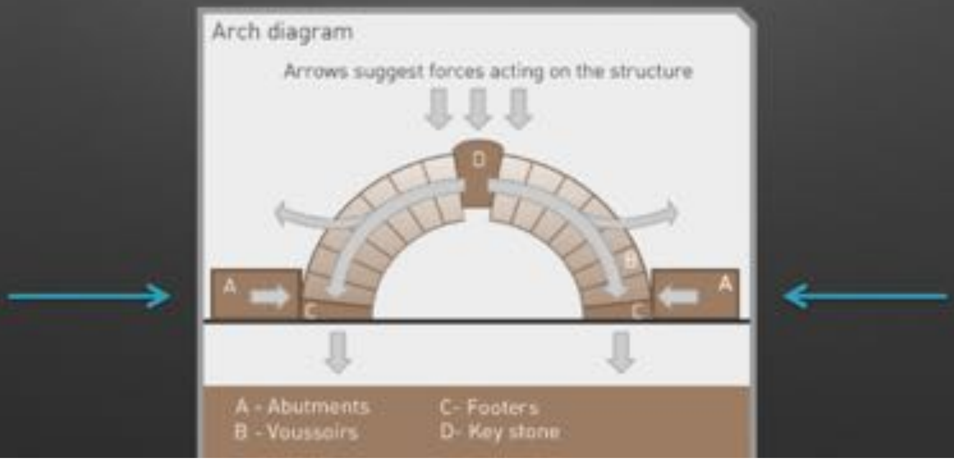
- A specific design necessary when the crossing is not at a right angle to the obstacle being crossed
- Stones and brick need to be cut with more exactness to ensure proper support
- Helicoidal: a design for skewed angles greater than 15°, designed by a mathematician
- An issue of great complication until the mid-1800s

Skewed Bridge

Bridge #704, Fairmount Park, Philadelphia, late 1800s

Fixed Bridges

- A fixed bridge is one where the structure of the span needs the counterweight from the abutment to balance the forces
- The abutment pushes against the horizontal force in the arch



Tied/Bowstring Bridge

- Not a fixed bridge
- A unique arch bridge where the compression is contained within the structure
  - The horizontal thrust of the arch is met with a member in tension, a "bowstring" or horizontal tie that links the ends of the arch together
  - This tie can be beams, girders or trusses, and they often play a role in the decking
- The abutment is only necessary as a solid foundation upon which to sit the bridge
  - Abutments could be much smaller in size due to the lack of horizontal counterweight necessary of other arch bridges
  - Useful design due to the smaller existing abutments from failed bridges in the past
- 1920s-1950s: common in the US

Tied/Bowstring Bridge

Page Avenue Tied Arch Bridge, St. Charles, MI, 2003

*Great design for movable bridges

Suspended Deck Arch Bridge

- A design where the arch is in compression and independently structurally stable; cables in tension connect the deck to the arch, effectively suspending it

Hulme Arch Bridge, Manchester, England, 1997

Types of Stone Arches

- Segmented
  - Newer design formed from the voussoir arch concept
  - Altered the arch to allow a wider span, lower clearance, and more space underneath

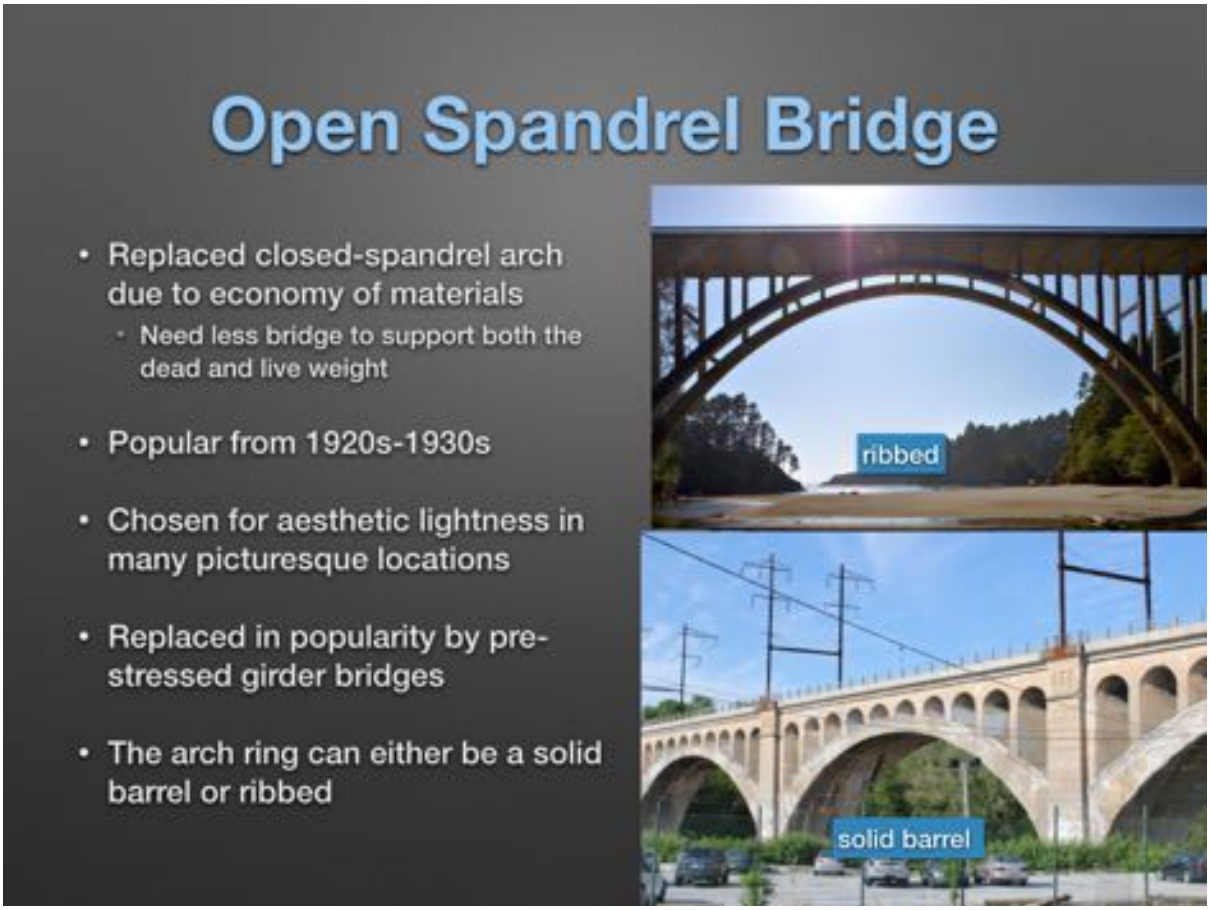
Alconétar Bridge, Spain under Roman Empire, around 100 CE

Gateshead Millennium Bridge, UK, 2001

*Also a moveable bridge

Main Street Bridge, Columbus, OH, 2010

*Example of asymmetrical arch, often used for iconic impact

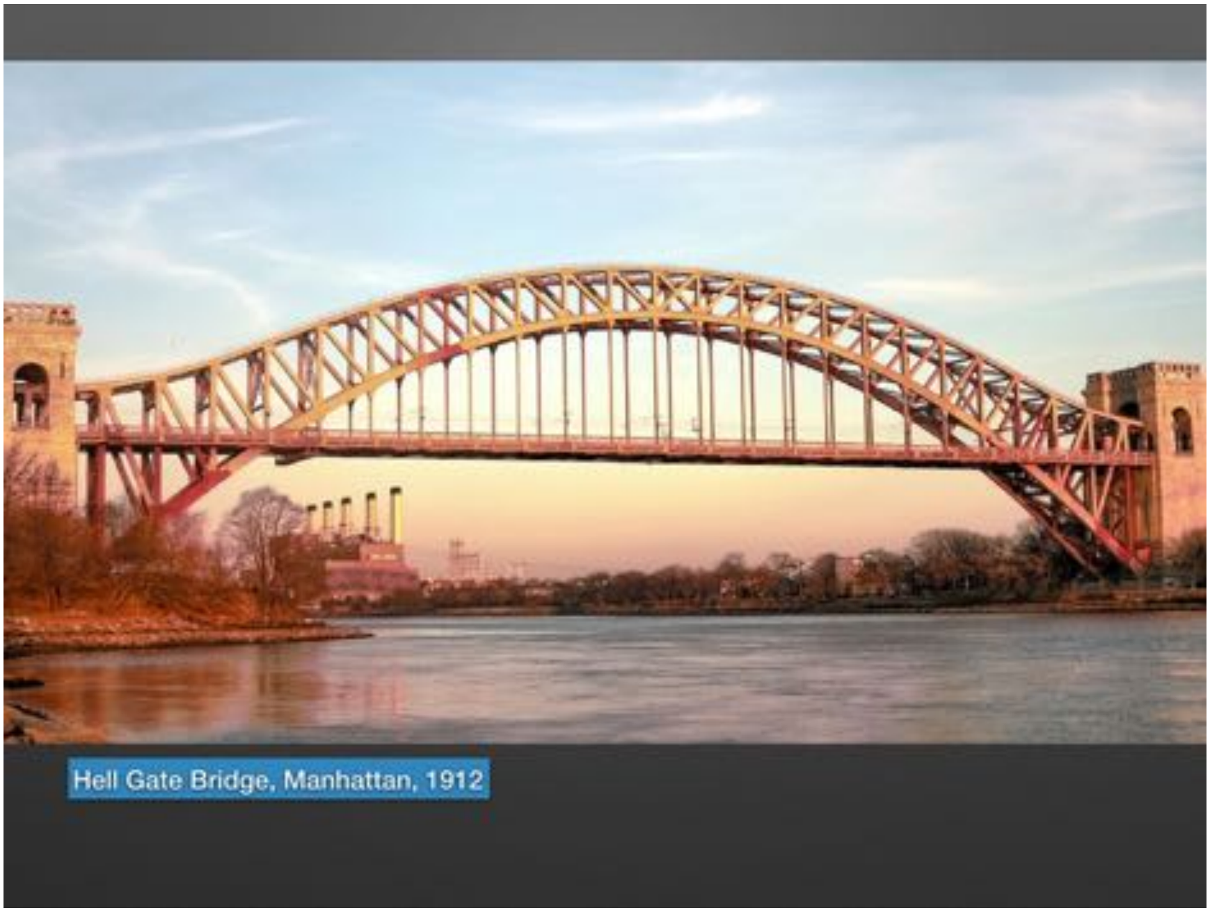


Open Spandrel Bridge

- Replaced closed-spandrel arch due to economy of materials
  - Need less bridge to support both the dead and live weight
- Popular from 1920s-1930s
- Chosen for aesthetic lightness in many picturesque locations
- Replaced in popularity by pre-stressed girder bridges
- The arch ring can either be a solid barrel or ribbed

Bixby Creek Bridge, Monterey, CA, 1931


Juscelino Kubitschek Bridge, Brasilia, Brazil, 2002


Hell Gate Bridge, Manhattan, 1912

Kintaikyo Bridge, Iwakuni, Japan, 1673

Solkan Bridge, Nova Gorica, Slovenia, 1927

Eads Bridge, St. Louis, MI, 1874

IV. TYPES OF BRIDGES

B. BEAM/GIRDER

As materials have improved, beam and girder bridges have been able to achieve new lengths and widths in design. As a relatively simple construction, this type is not often chosen for its aesthetic qualities in locations of picturesque significance. This type is most commonly seen as a small- to mid-length highway bridge.

SUBTYPES:

- Timber Stringer
- Reinforced Concrete Cast-in-Place Slabs
- Reinforced Concrete T-Beams
- Reinforced Concrete Channel Beams
- Reinforced Concrete Girders
- Reinforced Concrete Rigid Frames
- Reinforced Concrete Precast Slabs
- Prestressed Concrete I-Beams
- Prestressed Concrete Box Beams
- Metal Rolled Multi-Beams
- Metal Built-Up Girders (Plate-Girder)
- Steel Rigid Frame

TIMBER STRINGER

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Early 20th century	Around 1915-20s	Still used today in particular locations with low stress	10-30 ft often	Wood (older), rot-resistant timber laminated stringer

LOCATION	PRIMARY SUPPORT	SECONDARY SUPPORT	DEFINING CHARACTERISTICS
Low-trafficked rural back country roads, private roads, national forests or parks	Heavy square or rectangular wood beams	Wood plank deck	Associated with Depression era federal work programs and/or parks. Features: longitudinal beams/ stringers and abutments, possible railings and abutments.

REASONS FOR SELECTION	FIRST EXAMPLE	EXAMPLES	NOTES
Cheap, readily available materials, simple design. Today: quaint	-	Ancus Martius' Roman Pons Sublicius (3-4 c. BCE). Maitland Arroyo Bridge (1940). Grist Mill Bridge (early 1950s). Fishing Bridge, Yellowstone (1937). Lithodendron Was Bridge (193). Warrens Bridge, AR (1930).	Differs from wood trestle bridge: ends of stringers in timber stringer rest on single vertical support; trestle rests on framework of vertical members joined by horizontal/diagonal framework

Figure 1.1: Example of a timber stringer bridge

REINFORCED CONCRETE CAST-IN-PLACE SLABS

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Around 1900	1910s-40s	WWII	15-30 ft spans, popularity rose in multi-span slab bridges, increase in length equals increase in thickness and therefore weight	Reinforced concrete

LOCATION	PRIMARY SUPPORT	SECONDARY SUPPORT	DEFINING CHARACTERISTICS
Short highway	Horizontal slab of square or rectangular shape	Piers or abutments	One way flexure. The need for more piers as spans lengthened jacked up the price, making compete with popular T-beam bridge. Features: slab, parapet or railing, abutments, wingwalls, posible piers

REASONS FOR SELECTION	FIRST EXAMPLE	EXAMPLES	NOTES
Economical and easy to erect	-	Dry Creek Bridge, WA (1929), Chester Country Bridge, PA (1940), Coop Creek Bridge, AR (1940), Hartford Rd Bridge, AR (1943), Jacks Canyon Bridge, AR (1913), Ramsey Park Swayback Bridge, MN (1938)	C.A.P. Turner: 1905-1909 wrote to prove how two-way flexure is better to create longer spans. Introduce diagonal members as sheer reinforcement and therefore no expansion joints that let in water and road salt.

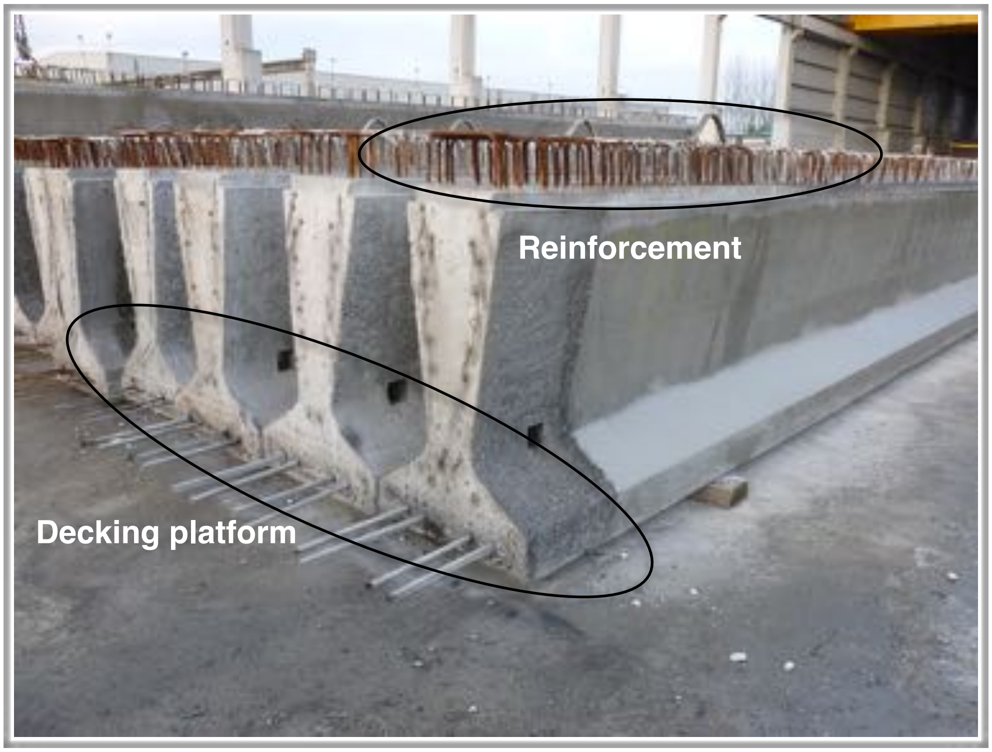
Figure 2.1: Example of a reinforced concrete cast-in-place slab under construction

REINFORCED CONCRETE T-BEAMS

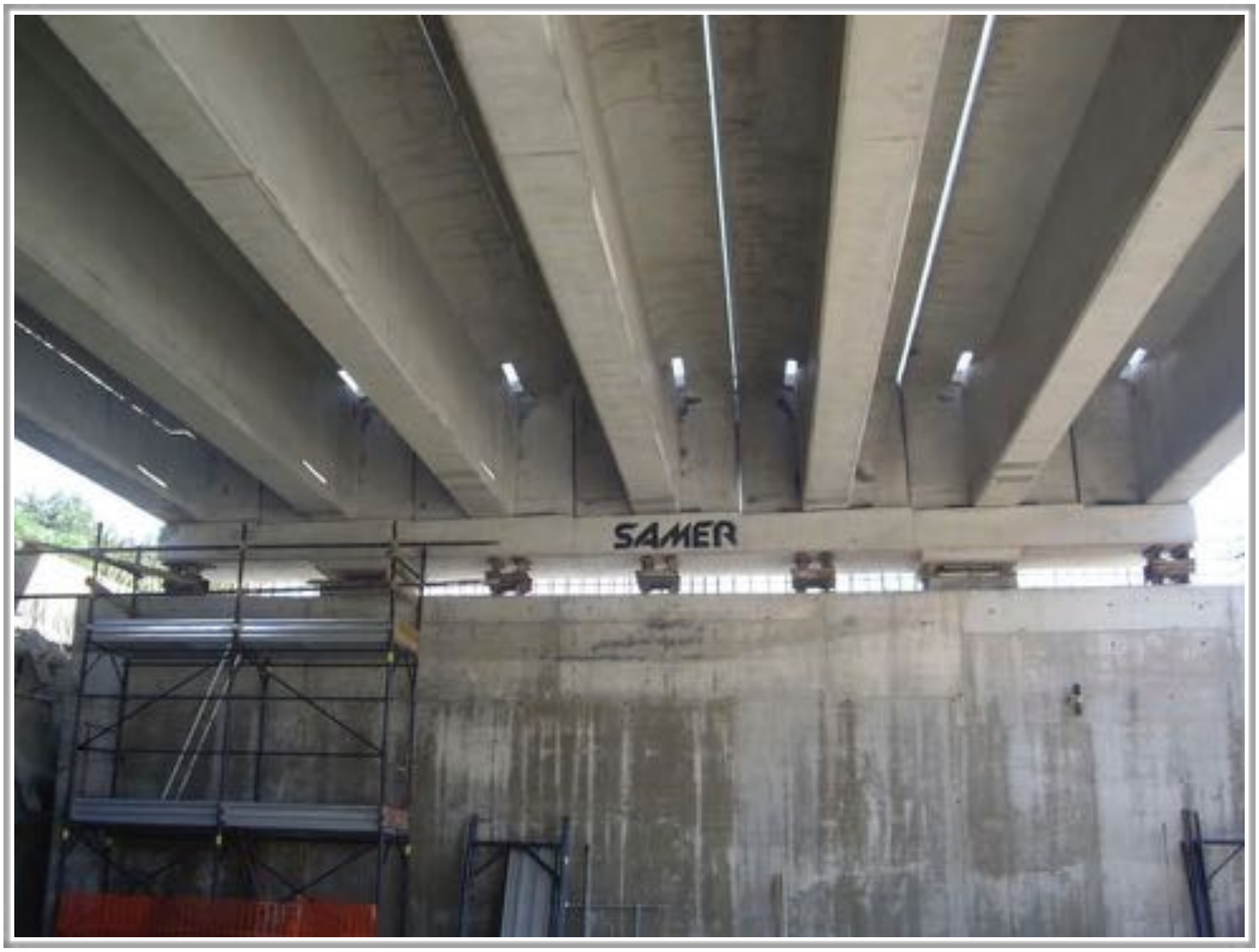
BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Early 20th century	1920s-30s	Early 1960s	Less than 50 ft	Reinforced concrete

LOCATION	PRIMARY SUPPORT	SECONDARY SUPPORT	DEFINING CHARACTERISTICS
Most common type in Montana 1912-56; one of the first types of standardized highway bridge types	To address tension: steel rods placed at the bottom of stems and placed transverse to the stem in the slab. Both kinds of rods are tied together with U-shaped hangers, making both slab and beam unified structural components.	-	Features: slab integrated with longitudinal beams, parapet or railing, abutments, wingwalls or occasionally piers

REASONS FOR SELECTION	FIRST EXAMPLE	EXAMPLES	NOTES
Appeared same time as flat-slab span, but more economical for lengths exceeding 25 ft than concrete arch or slab. Span length more limited compared to arches and trusses, needing more piers or bents, so less economical after a point.	-	Little Buffalo River Bridge, AR (1939), Johnson Bridge, WA, Fullersburg Bridge, IL (1924), Jones Beach Causeway Bridge No. 1, NY (1929), Bridge #1912, VA (1925)	Top of T-beam constitutes slab, bottom of T-beam (the stem) appears like a girder when viewed in side elevation. Also, pre-tressed T-beams generally not constructed before late 1950s. Pre-stressed double T-beam often looks like pre-cast channel beam bridge from below.



Figures 3.1, 3.2, 3.3: Examples of reinforced concrete T-beams on a construction site and in finished bridges



Similar final appearance to girder bridges

REINFORCED CONCRETE CHANNEL BEAMS

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
1910s	1920s-30s	Around 1960s	Less than 50 ft	Usually precast but sometimes cast-in-place reinforced

LOCATION	PRIMARY SUPPORT	SECONDARY SUPPORT	DEFINING CHARACTERISTICS
Highway	Stem tension reinforcement located longitudinally at bottom of stem, shear reinforcement or stirrups located higher up	Diaphragms	Features: deck, longitudinal beams, parapet or railing often, abutments, wingwalls and piers

REASONS FOR SELECTION	FIRST EXAMPLE	EXAMPLES	NOTES
Similar to T-beam	-	CR 4048 (Brysonia Rd) Bridge, PA (1948)	When precast, conventionally reinforced or prestressed. Cast-in-place usually features curved underbeam soffit made with U-shaped removable moulds, to appear like jack arch bridges from underneath despite the seam in the middle of the girders. Channel beams often feature diaphragms, giving name "waffle slab"

Figures 4.1, 4.2: Example of reinforced concrete channel beams on a construction site and in a finished bridge

REINFORCED CONCRETE GIRDERS

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
US: 1900-10	1910s-30s. 1930s: Through girder bridges give way to deck girder bridges for need of wider roadways	1940s- fell out of favor for steel I-beams and pre-cast concrete slabs due to cost of scaffolding and framework	15-40 ft long, no wider than 24 ft	Reinforced concrete

LOCATION	PRIMARY SUPPORT	SECONDARY SUPPORT	DEFINING CHARACTERISTICS
Highway	Girders	Monolithic cast-in-place slab and sometimes floorbeams. Deck cast on top of girders in deck girder bridges and cast in between girders in through girder bridges	Features: monolithic deck, girders, parapet or railing, abutments, floorbeams, piers, and sometimes wingwalls. Through girder bridges have natural girder parapets.

REASONS FOR SELECTION	FIRST EXAMPLE	EXAMPLES	NOTES
Easy to construct	France-1893	Beaver Creek Bridge, OR (1912), Main St-Black River Bridge, Mich. (1923), Monroe St Bridge, MI (1929), Old US-131 Bridge, MI (1929), BRG No. 5083, MN (1931)	Another form: continuous reinforced concrete girder: 1950s, pushed lengths to 50-80 ft; not in use after 60s for safety concerns. Nearly impossible to widen Through Girder Bridges.

Figure 5.1: Example of a reinforced concrete girder bridge

REINFORCED CONCRETE RIGID FRAMES

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
US: 1920s	Following WWII	1950s: pre-stressing gain popularity	New lengths: 40-120 ft	Reinforced concrete

LOCATION	PRIMARY SUPPORT	SECONDARY SUPPORT	DEFINING CHARACTERISTICS
Highway, often spanning river and valleys due to slanted vertical supports	Vertical and horizontal components are integral, one solid cast in place piece.	Deck	Features: monolithic sub- and super structure in one continuous fabric, parapet railing

REASONS FOR SELECTION	FIRST EXAMPLE	EXAMPLES	NOTES
Inexpensive, easily constructed, aesthetically appealing for standardized bridge. Good for grade separations. Efficient use of materials in its time.	Designed originally in Germany for buildings but applied to bridges for economical reasons. Arthur Hayden: Bronx River Parkway (1922)	Tekamah City Bridge, Nebraska (1934), Merrit Parkway Comstock Hill Road Bridge (1938), Davidson Freeway Second Ave Bridge, MI (1942), Bridge #1804, VA (1918), Dodge St. Overpass, Neb. (1934)	Last major type of of reinforced concrete bridge developed. Hayden: built approx. 93 rigid frame bridges between 1922-33. Older examples: thicker at the ends of span like shallow arch. Today: looks like inverted U shape and legs are slanted. Junction of pier and deck difficult.

Figure 6.1: Example of a reinforced concrete rigid frame bridge

REINFORCED CONCRETE PRECAST SLABS

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
1900-10, mainly by railroads at first	Following WWII, especially in southeast	1950s: pre-stressing gain popularity	15-30 ft (similar to cast-in-place)	Reinforced concrete

LOCATION	PRIMARY SUPPORT	SECONDARY SUPPORT	DEFINING CHARACTERISTICS
Highway	Precast slab	Piers or abutments	Features: slab, parapet or railing, abutments, wingwalls

REASONS FOR SELECTION	FIRST EXAMPLE	EXAMPLES	NOTES
More modern than concrete cast-in-place deck.	-	-	Tend to work themselves out of line laterally over time because of closed expansion joints over smooth bearing surface.

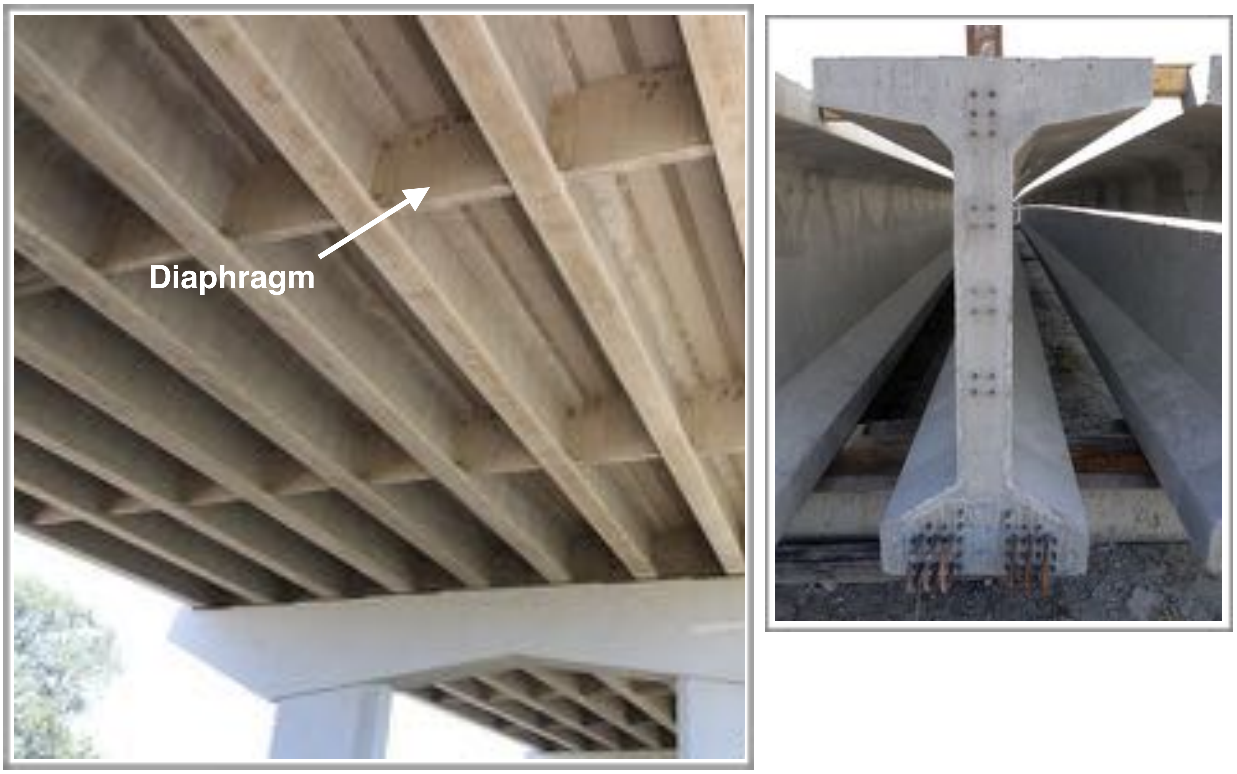
Figure 7.1: Example of reinforced concrete precast slabs on a construction site

PRESTRESSED CONCRETE I-BEAMS

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Eugene Freyssinet (Fr.) built first prestressed bridge in Europe in 1940s. US: 1950	Grew in popularity in mid 1950s	-	130-150 ft, yet transporting precast pieces proved difficult	Prestressed concrete

LOCATION	PRIMARY SUPPORT	SECONDARY SUPPORT	DEFINING CHARACTERISTICS
Crossover structures and stream crossings.	Prestressed concrete I-beams	Slab	Features: slab, longitudinal beams, floor beams, a parapet or railing, abutments piers, and maybe wingwalls

REASONS FOR SELECTION	FIRST EXAMPLE	EXAMPLES	NOTES
Prestressed invention lead to cheaper, longer and stronger spans	Walnut Bridge, Philadelphia (1951). Gustave Magnel and John A Roebling Sons made experiment on Oct. 25, 1949 to prove strength of prestressed beam	Walnut Lane Bridge, PA (1950), Roseville Bridge, OH (1952), US 37 Bridge, OH (1960), Bridge 39 7301 0000 0013, PA (1955), Bridge 67 3009 0180 0721, PA (1955)	-



Figures 8.1, 8.2: Examples of reinforced concrete I-beams on a construction site and in a finished bridge. Also, a visual example of a diaphragm, a common secondary support in bridges.

PRE-STRESSED CONCRETE BOX BEAMS

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Early 1950s	High popularity in 1960s	-	About 50 ft (given the similarities to T and I beams)	Prestressed concrete

LOCATION	PRIMARY SUPPORT	SECONDARY SUPPORT	DEFINING CHARACTERISTICS
Secondary roads	Prestressed concrete box girders	Slab, transverse strands	Features: slab, box-shaped longitudinal beams, parapet or railing, abutments, wingwalls and piers sometimes

REASONS FOR SELECTION	FIRST EXAMPLE	EXAMPLES	NOTES
Despite some issues with fabrication and construction, popularity remained due to speed of construction and minimum section depth.	Duffy's Creek Bridge, TN (1950). 7-wire galvanized were used, and each block had three cores. Special end blocks made for anchoring prestressed strands	Middle Pike Bridge #0630535, OH (1956), Lippincott Road Bridge #1130234, OH (1956), Middleburg Road Bridge #1130412, OH (1954), Hempt Rd Bridge, PA (1952), Scenic Dr Bridge, PA (1950)	Research from highway departments showed that simplified box, I-beam- and double T were efficient to support loads (1962). Often the center of the box is round, with a styrofoam center left from the precasting process.

Figure 9.1: Example of a reinforced concrete box girder being lowered into place on a construction site

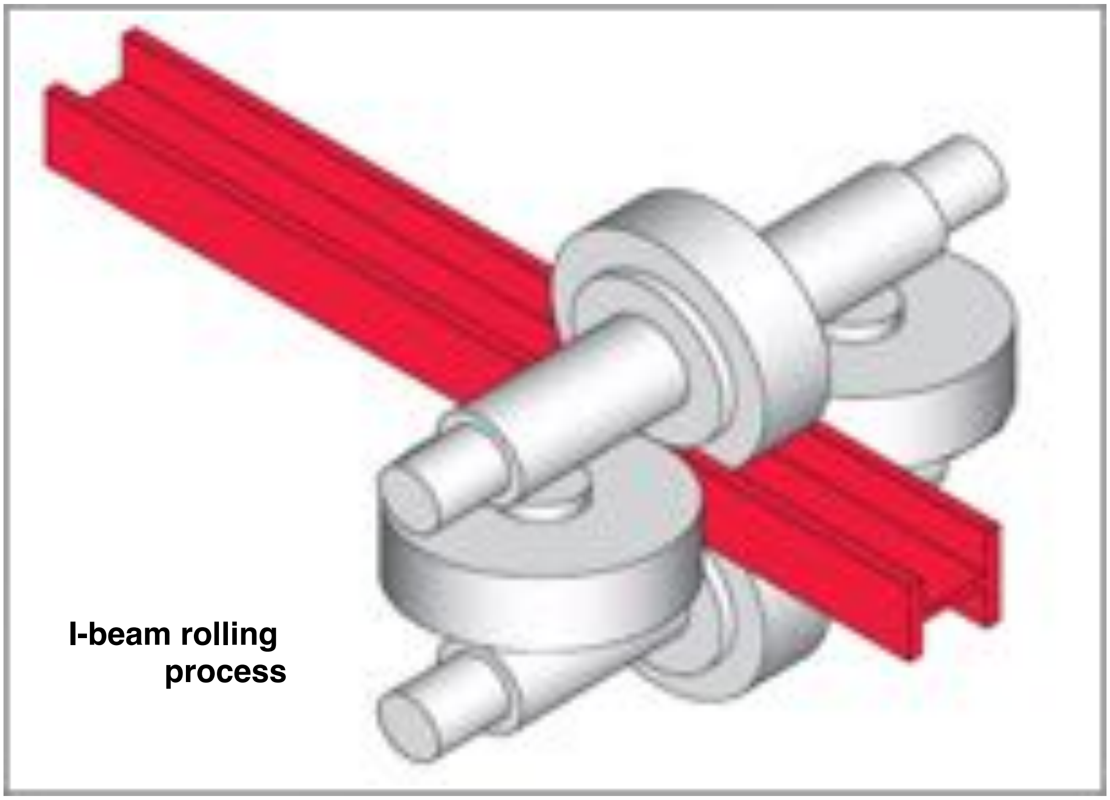
METAL ROLLED MULTI-BEAMS

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Fabricated as early as 1850s-60s. Use in bridges start in 20s-30s	Early 1940s	Early 1960s: ceased to be economical due to prestressed concrete compared to steel prices	Spans grew with the inclusion of cantilever drop-in units	Steel I-beams

LOCATION	PRIMARY SUPPORT	SECONDARY SUPPORT	DEFINING CHARACTERISTICS
Highway	I-beams	Diaphragms	Jack Arch: deck support system of concrete arches under the slab to create arches between bottom flanges of I-beams, helps disperse tension. Features: rolled longitudinal I-beams or wide flange beams, floor beams, original rails, piers, wingwalls, abutments

REASONS FOR SELECTION	FIRST EXAMPLE	EXAMPLES	NOTES
Simpler construction	-	Twin Bridge, Neb. (1900), Brevard Bridge, PA (1913), South Euclid Rd. Bridge, MI (1900), Parryville Bridge, PA (1933), Bridge 021-0182, GA (1929)	Beam: rolled shapes, girder: fabricated girders

Figures 10.1, 10.2, 10.3: Example of a finished metal rolled multi-beam bridge and images showing the metal rolling process



I-beam rolling process

Hot rolled I-beams cooling off

METAL BUILT-UP GIRDER (PLATE-GIRDER)

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Late 19th and early 20th century, less popular due to expense.	1930s	Late 1970s- flaws in orginal welding techniques found using ultrasonic testing. Welding replaced with bolted connections and splices.	-	Steel I-beams

LOCATION	PRIMARY SUPPORT	SECONDARY SUPPORT	DEFINING CHARACTERISTICS
First rail, then higway	I-beam	Floor beams and possibly stringers	Features: riveted or welded metal plate girders, a floor system, abutments and/or wingwalls sometimes

REASONS FOR SELECTION	FIRST EXAMPLE	EXAMPLES	NOTES
Often used for curved portion of bridges	Baltimore and Susquhanna RR by James Millholland at Colton Station, MD (1846), 50 ft span	Francis St Bridge, RI (1894), North Kinney Rd. Bridge, IL (1910), Georgetown Loop Plate Girder Bridge, CO, Bridge 191-0007-0, GA (1944), Peartown Rd Bridge, PA (1909)	Often used for multi-girder bridges; rarely seen long spans or multi-span bridges. Riveted through two-girder bridges, often referred to as "plate girder" bridges

Figures 11.1: Example of metal built-up girder bridges

STEEL RIGID FRAME

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Around 1910	1920-50	Around 1960s	50-200 ft	Steel I-beams

LOCATION	PRIMARY SUPPORT	SECONDARY SUPPORT	DEFINING CHARACTERISTICS
Highway	Inclined rigid frame legs	Web stiffeners, diaphragms, floor systems of floorbeams and maybe stringers	Features: monolithic sub- and superstructure (legs with hori. girders), parapet or railing, piers, wingwalls, abutments.

REASONS FOR SELECTION	FIRST EXAMPLE	EXAMPLES	NOTES
Aesthetically pleasing structures that allow elimination of intermediate supports	-	M-27 Au Sable River Bridge, MI (1935), New Canaan Rd/Route 123 Bridge, CT (1937), US 1 Bridge, City Lane Ave over Amtrak, PA (1935)	Devised at the same time as reinforced concrete bridges, much less common. Chosen as economical choice or to differ aestetically.

Figure 12.1: Example of a steel rigid frame bridge

IV. TYPES OF BRIDGES
C. TRUSS

Although there are many truss designs, this study chose to only look at a few of the original examples. The key to this design is that each component is efficiently designed to act in only compression or tension, so there is no bending within individual truss members. This stability allows the truss to become elemental in other types, often as a deck stiffening agent. Truss bridges can vary greatly in size depending on subtype and material.

SUBTYPES:

- King Post
- Queen Post
- Howe
- (Town) Lattice
- Burr Arch
- Bowstring
- Pratt
- Whipple
- Baltimore
- Pennsylvania
- Parker
- Warren
- Lenticular
- Bailey

KING POST

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Medieval times, illustrated in Palladio's *I Quattro Libri dell'Architectura* and translated into English 1738	Early 19th century	Early to mid 20th century	30 ft, sometimes multiple trusses could lengthen the span	Heavy timbers, roofing to protect the wood

LOCATION	DESCRIPTION	DEFINING CHARACTERISTICS
Secondary roads	Timbers form three sides of equilateral or isosceles triangle, vertical metal or wooden tie rod through center	Triangle shape, metal vertical tie rod or wood post

EXAMPLES	NOTES
Bridge No. 1482, Rock country Minnesota (1908); Blacksmith Shop Covered Bridge, Cornish, NH (1881); Dingleton Hill Covered Bridge, Cornish, NH (1882)	Noted for its derivative importance, multiple king post design includes center triangle with panels extending on either side with diagonals bracing the diagonals of the center triangle; first used as roof gable

Figure 1.1: Example of a king post truss bridge

QUEEN POST

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Medieval times originally, similar history to kingpost	Second half of the 19th century	Early 20th century	30-40 ft	Some metal but mostly wood

LOCATION	DESCRIPTION	DEFINING CHARACTERISTICS
Secondary roads	Similar to the king post but the center is extended to a rectangular panel with two right triangles on either side; center panel is braced by tensile member dividing the panel vertically, braces between the corners, or a pier under the center of the span	Rectangular panel with parallel top and bottom chord with side triangular panels with inclined end posts

EXAMPLES	NOTES
Greenbanks Hollow Covered Bridge, Caledonia County, VT (1886); Copeland Covered Bridge, Saratoga County, BY (1879); Hortense Bridge, Chaffee County, CO (1880)	-

Figure 2.1: Example of a queen post truss bridge

HOWE

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
William Howe patent in July/Aug 1840, first example in 1838 on Western Mass. Railroad	Mid-19th century	Early 20th century	20-50 ft	Heavy wood and iron, sometimes covered; later solely iron

LOCATION	DESCRIPTION	DEFINING CHARACTERISTICS
Railroads in Illinois, Wisconsin and Missouri,	Heavy wood diagonal members in compression and lighter, vertical iron members in tension. Threaded, adjustable iron members secured at the the ends by nuts allowed a method of adjustment.	Heavy wood diagonal intersecting members, lighter vertical iron members, parallel top and bottom chord, struts

EXAMPLES	NOTES
Buskirk Covered Bridge, Washington County, NY (1857); Doe River Bridge, Carter County, TN (1882); Mt. Orne Covered Bridge, Coos County, NH (1911)	Adjustable and thoughtful connections led to stronger design because connections were the weakest part; like king post, first used as roof truss; Ashtabula disaster in 1876 killed 85 people when a cast and wrought iron bridge went down in storm, ASCE then decided to favor all wrought iron as opposed to wrought and cast iron bridges; most widely used wooden bridge type and most profitable bridge patent ever created

Figure 3.1: Example of a Howe truss bridge

(TOWN) LATTICE

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Patented by Ithiel Town in 1820	1840s-70s, metal form from 1950s-90s	Early 20th century	Less than 250 ft	Timber, sometimes covered

LOCATION	DESCRIPTION	DEFINING CHARACTERICTICS
Extensively used in aqueducts, highways and railroads (iron/steel less common for roadways)	Intersecting diagonals forming a web between the top and bottom (parallel) chords with no verticals or posts. The diangonals are in compression and tension	Lattice configuration, no vertical posts, parallel top and bottom chords, end posts, traenail connections; Appeal: no prepatory labor, no large timbers or intricate joints, no straps or ties of iron, all connections with trenails, all web members the same size plank

EXAMPLES	NOTES
Buskirk Covered Bridge, Washington County, NY (1857); Doe River Bridge, Carter County, TN (1882); Mt. Orne Covered Bridge, Coos County, NH (1911)	Earlier wooden trusses have used mortise and tendon joints, here the planks were cut to standard sizes and connected by round wood pins called "trenails," twisting occurs as span lengthen, causing Town to patent a thicker web in 1835; first time in bridge design where licensees needed to pay royalities

Figure 4.1: Example of a Lattice truss bridge

BURR ARCH

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
1804	1820s-50s	Late 19th century	100-120 ft	Timber, sometimes covered

LOCATION	DESCRIPTION	DEFINING CHARACTERISTICS
Extensively used in roadways and railroads	Pegged arch ribs attached to kingpost truss	Combination of arch rib with a truss, attachment of the arch rib to the truss with pegs, parallel top and bottom chords, vertical and diagonal members

EXAMPLES	NOTES
Forksville Covered Bridge, Sullivan County PA (1850); Quinlan's Covered Bridge, Ulster County, NY (1849), Bridgeton Bridge, Parke County, Indiana (1868)	First built by inventor Theodore Burr over Hudson River in NY (destroyed 1909); known for stiffness

Figure 5.1: Example of a Burr truss bridge

BOWSTRING

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
First example: Utica, NY by Squire Whipple in 1840, second all-metal truss bridge in US; patented in 1841	Used in mid-19th century for train sheds, late 19th century very popular for short to moderate spans for farm-to-market road systems	Early 20th century	50-100 ft	Iron

LOCATION	DESCRIPTION	DEFINING CHARACTERISTICS
Train sheds, other curved vault structures, short roadway and canal	Arches of cast iron functioning as primary compression members, vertical and diagonal rods in wrought iron, lower chord or "string" tying the ends of the arch in tension	Relatively heavy arched top chord, seried of X-boxed panels, triangular panels at ends

EXAMPLES	NOTES
Whipple Cast and Wrought Iron Bowstring Truss Bridge, Albany County, NY (1867); White Bridge, Mahoning, OH (1878); North Platte River Bowstring Truss Bridge, Goshen County, WY (1875)	Different from steel tied arch bands primarily due to historical context

Figures 6.1, 6.2: Examples of Bowstring truss bridges

PRATT

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Thomas Pratt, 1842	End of 19th and early 20th centuries	Superseded by Warren truss	Less than 250 ft	Iron

LOCATION	DESCRIPTION	DEFINING CHARACTERISTICS
Roadways and railroads; pony (and half-hip pony), through, deck and bedstead	Vertical compression members of wood and wrought iron diagonals in tension, reverse of earlier Howe truss with diagonals in compression and verticals in tension	Vertical members and endposts handle compression, tend to be relatively heavy and visually prominent, and are composed of angles, channels or rolled sections; diagonal members are in tension and relatively thin, often round or square bars; interior diagonals slant down and in at 45 degrees, while end posts slant out at 45 degreees

EXAMPLES	NOTES
Kennedy Bridge, Blue Earth County, MN, (1883); Burrville Road Bridge, Mercer County, OH (1887); EDL Peloux Bridge, Johnson County, WY (1913)	More expensive than other types but more trustworthy than the Howe design, gained in popularity following move to iron

Figure 7.1: Example of a Pratt truss bridge

WHIPPLE

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Squire Whipple, 1847 patented; first example in 1853 on the Albany and Northern Railroad	1860-1890	Late 19th century	250-300 ft	Iron (cast iron is brittle and good in compression but bad in tension; wrought is equally good in both stresses and handles temperature change better, yet more expensive); known as Murphy-Whipple when entirely wrought iron

LOCATION	DESCRIPTION	DEFINING CHARACTERISTICS
Roadways and railroads	"Trapezoidal truss," "double intersection Pratt," by extending the diagonal members over two panel lengths the depth of the panel would be increased and without altering the 45 degree angle then the span could be longer	Parallel top and bottom chords, double intersection web, inclined endposts, vertical members

EXAMPLES	NOTES
O Street Viaduct, Douglas County, NE (1885); Kentucky Route 49 Bridge, Marion County, KY (1881); Whipple Truss, Hendricks County, IN (1875)	1847: Whipple's *A Work on Bridge Building* explained how the horizontal and vertical forces are balanced and when two forces are known then a determination of stresses in a truss could be determined, first scientific basis for bridge building rather than empirical knowledge; John Murphy made 165 ft span in NJ where pin connections are used throughout, first time; pins were big advancement to previous slow riveting, advancements in reliable and cost-effective field riveting equipment made big change at end of 19th, early 20th meant field-riveting and bolted connections

Figure 8.1: Example of a Whipple truss bridge

BALTIMORE

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
1870s, for heavy locomotives, Baltimore and Ohio Railroad in 1871	Late 19th and early 20th centuries	1920s-30s	Less than 250 ft	Iron

LOCATION	DESCRIPTION	DEFINING CHARACTERISTICS
Railroads, adapted for highways in 1880s	"Petit truss," basically a Pratt with wider sub-divided panels where each diagonal is braced in the middle with sub-diagonals and verical sub-struts to help with maintaining a ecnomic spacing of floor beams in longer spans; optimal slope of diagonals between 45-60 degrees	Parallel top and bottom chords, verticals and diagonals (with substruts), floor beams

EXAMPLES	NOTES
Loosveldt Bridge, Sheridan County, NE (1888); Post Road Bridge, Harford County, MD (1905)	-

Figure 9.1: Example of a Baltimore truss bridge

PENNSYLVANIA

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Design by Pennsylvania Railroad in 1875	Late 19th and early 20th centuries	1920s	Long span railroads and short span highways	At first iron and then steel with rigid riveted connections

LOCATION	DESCRIPTION	DEFINING CHARACTERISTICS
Railroads, adapted for highways in 1880s	"Petit truss," like Pratt truss but basically a Baltimore Truss with a polgonal top (like in the Parker)	Top and bottom chords, vertical and diagonal members (including substruts), floor bottom chords

EXAMPLES	NOTES
Leaf River Bridge, Green County, MS (1907); Old Colerain Pennsylvania Through Truss Bridge, Hamilton County, OH (1894); Four Mile Bridge over Big Horn River, Hot Springs County, WY (1927-28)	-

Figure 10.1: Example of a Pennsylvania truss bridge

PARKER

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Charles Parker patented in 1870	Late 19th and early 20th centuries	1950	Pony: 30-60 ft, Through: 100-300 ft	Steel with riveted connections

LOCATION	DESCRIPTION	DEFINING CHARACTERISTICS
Railroads, adapted for highways in 1880s	Pratt truss with polygonal top chord, requiring less depth at the ends and therefore shorter panels that save material (yet different lengths for each panel cause higher fabrication costs)	Top and bottom chords, vertical and diagonal members (including substruts), floor bottom chords

EXAMPLES	NOTES
Walnut Street Bridge, Chattanooga Hamilton County, TN (1891); Rifle Bridge, Garfield County, CO (1909); Enterprise Bridge, Dickinson Count, KS (1924-25)	Benefits: simple cast iron connections and inclined end posts; camelback variation: exactly 5 slopes

Figure 11.1: Example of a Parker truss bridge

WARREN

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
1890s	Highways in 1920s-30s, railroads in 1930s	1950	Intermediate length highway spans	Wrought iron and pin connections

LOCATION	DESCRIPTION	DEFINING CHARACTERISTICS
Highways (many steel, field-riveted or bolted pony trusses)	Only diagonal members connecting the top and bottom chords; diagonals in both compression and tension as they make equilateral triangles; all members tend to be thick and visible; sometimes verticals added	Parallel top and bottom chords, inclined end posts, diagonals, floor beams

EXAMPLES	NOTES
Clear Creek Bridge, Butler County, NE (1891); Romness Bridge, Griggs County, ND (1912); Williams River Bridge, Windham County, VT (1929)	-

Figure 12.1: Example of a Warren truss bridge

LENTICULAR

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
Germany patent: 1856, US patent: 1878; dates back to 1617 when Faustus Verantius wrote about tied arch and lenticular designs	All in US by Berlin Iron Bridge Company of Connecticut, built hundreds in New England and Midwest	1900	Short to Intermediate lengths	Iron

LOCATION	DESCRIPTION	DEFINING CHARACTERISTICS
Highways	"Parabolic truss," like a Pratt Truss with top and bottom chords curved over the entire length of the structure	Curved top and bottom chords, vertical and diagonal members, floor beams

EXAMPLES	NOTES
Washington Avenue Bridge, New Haven County, CT (1880); Lover's Leap Lenticular Bridge, Litchfield County, CT (1895); Neshanic Station Bridge, Somerset County, NJ (1896)	-

Figure 13.1: Example of a Lenticular truss bridge

BAILEY

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
1941/42, used in WWII by British and US forces	Still used in construction today	-	Less than 200 ft	Timber, steel alloys

LOCATION	DESCRIPTION	DEFINING CHARACTERISTICS
Temporary crossings for canals, rivers, railroads	Light, prefab bridge with little need of tools or knowledge to erect, often a design similar to Warren trusses	Easily erected, transportable pieces, uncomplicated design

EXAMPLES	NOTES
River Arno, Florence, on original piers of Ponte San Trinità (1944); Old Finch Avenue Bailey Bridge, Scarborough, Ontario, Canada (1954)	-

Figures 14.1, 14.2: Examples of Bailey truss bridges

CANTILEVERED

BEGIN	HIGH POINT	END	LENGTH	MATERIALS
1866: Heinrich Gerber	Still used today	-	Over 1,500 ft	Steel

LOCATION	DESCRIPTION	DEFINING CHARACTERISTICS
Larger railroad and highway bridges	Either a design where the arms are centered on the piers and the outside halves (called anchor arms) balance the connecting inside halves, or a suspended truss span where the piece is lowered into place via crane	Thicker truss at pier that thins out into cantilever, inside arms meet in center or connect to suspended truss, outer arms act as "anchor arms"

EXAMPLES	NOTES
Poughkeepsie-Highland Railroad Bridge, NY (1978); High Bridge, Jessamine County, KY (1876); Forth Bridge, Edinburgh, Scotland (1882)	Famous Benjamin Baker experiment photo explaining suspended truss spans

Figure 15.1: Example of a cantilevered truss bridge

IV. TYPES OF BRIDGES
D. SUSPENSION

Short History

The idea of the suspension bridge was born from the natural event in which a vine connects two sides of a void. Primitive bridges involved this type of construction with the addition of multiple ropes for stability. The concept evolved around 1800, when American engineer James Finley realized that the deck would need to be a flat surface supported by curved cables in order to provide transport for carriages. He built his first suspension bridge in 1808. In 1820, Samuel Brown created the first modern suspension bridge in Europe, the Union Suspension Bridge over the River Tweed, which still exists today. What followed was decades of competition to build the longest bridge in the world in multiple countries. It was not until the middle of the nineteenth century, however, that engineers began using exacting math to design bridges, as opposed to the previous method of “intuition.” With the development of the Deflection Theory, the 1904 Manhattan Bridge used applied math to become the first “truly modern suspension bridge.” The next development was the rise in popularity of the long bridge with the thin deck. This design was applied to many new bridges at the time: the George Washington Bridge, the Bronx-Whitestone Bridge, the Golden Gate and the Tacoma Narrows. Soon there after, however, these bridges began to move in strong winds, which caused the Tacoma Narrows Bridge to collapse into the water. Bridges were corrected and new designs began an aesthetic that included stiff decks. Today the competition for the longest bridge is still alive but it is met with many more safety precautions and a smarter application of materials. The suspension bridge continues to be a popular and iconic bridge design for picturesque cityscapes.[1]

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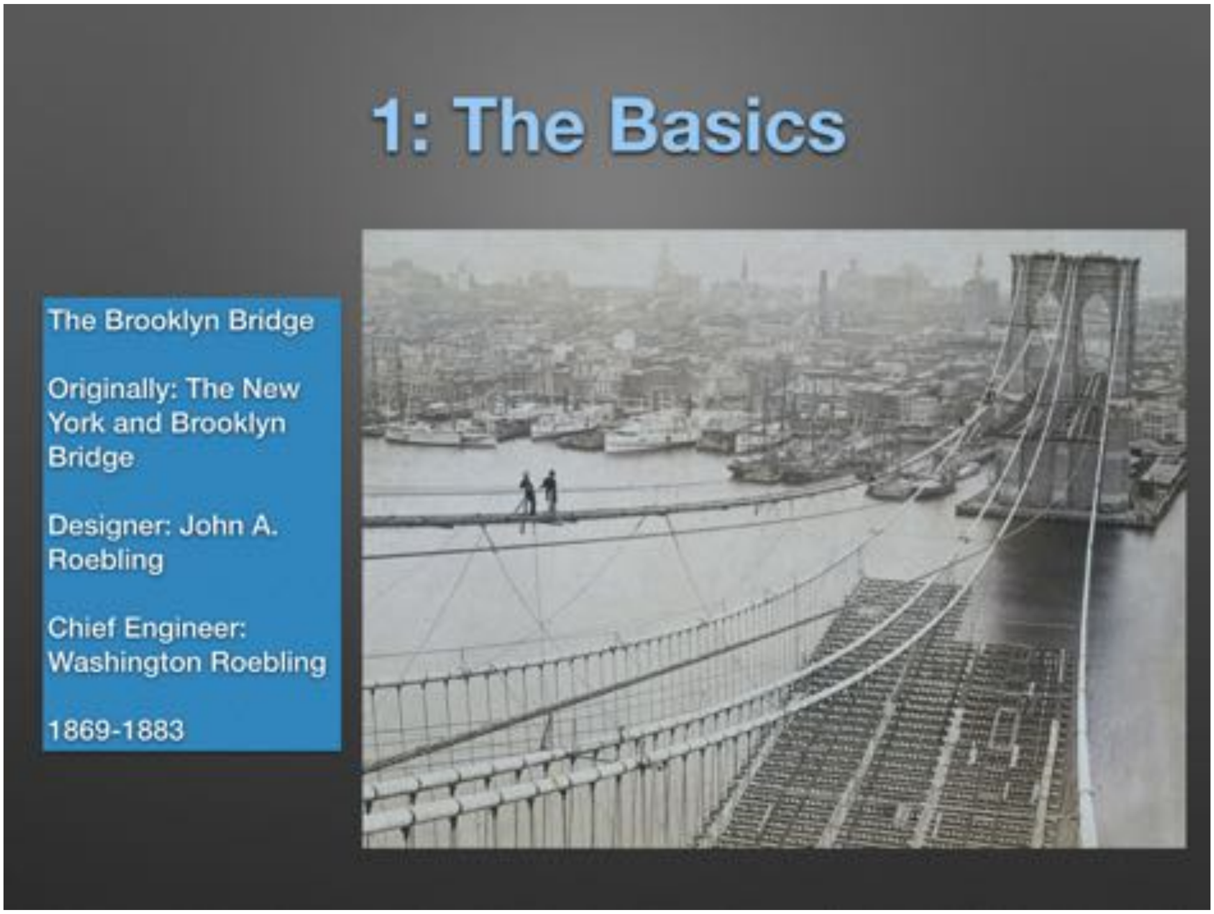
[1] Harry H. West, “The Ups and Downs of Suspension Bridges: And the Highs and Lows of Their Builders,” (lecture, Civil Engineering, Penn State: University Park, State College, PA, April 4, 2014).

25 Things to Know About the Brooklyn Bridge

By Cody Chase



1: The Basics

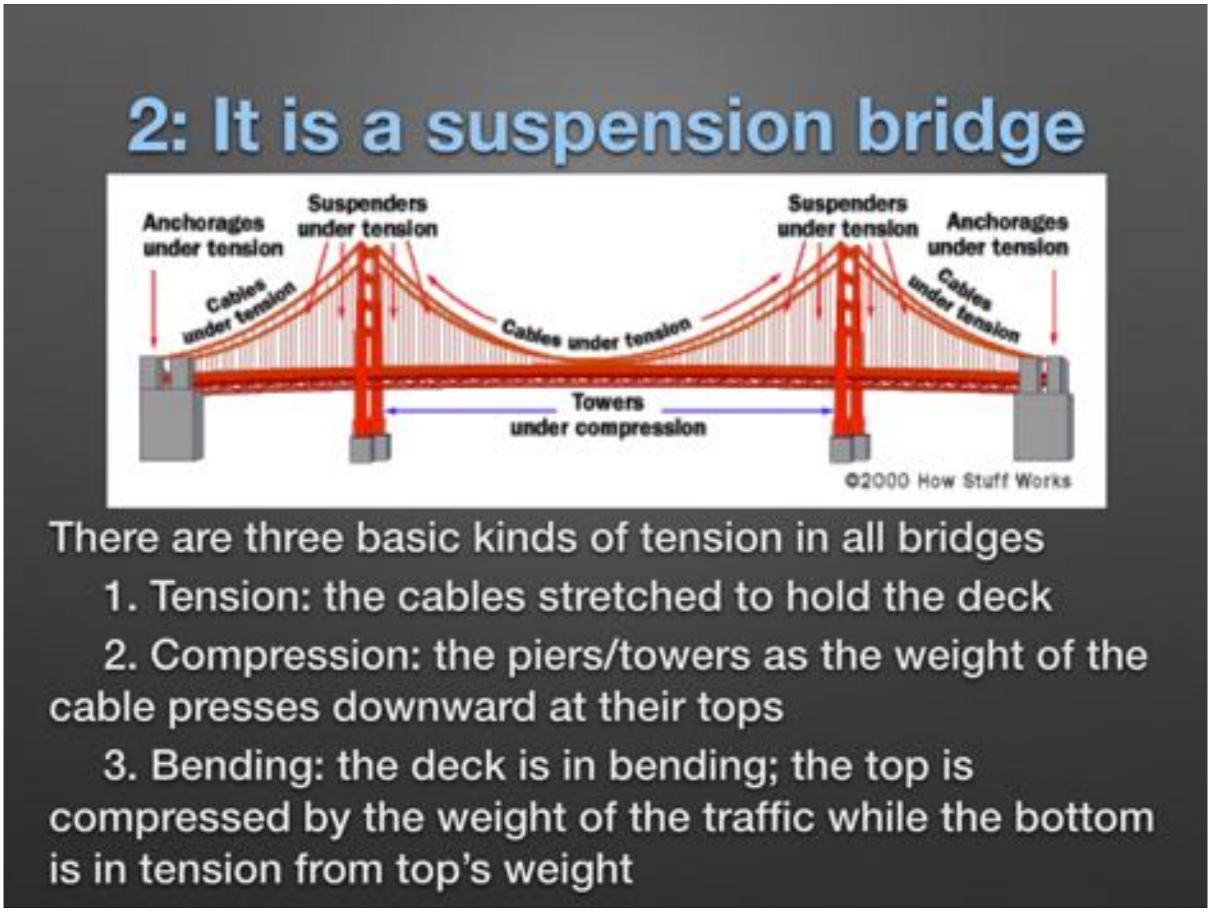
The Brooklyn Bridge

Originally: The New York and Brooklyn Bridge

Designer: John A. Roebling

Chief Engineer: Washington Roebling

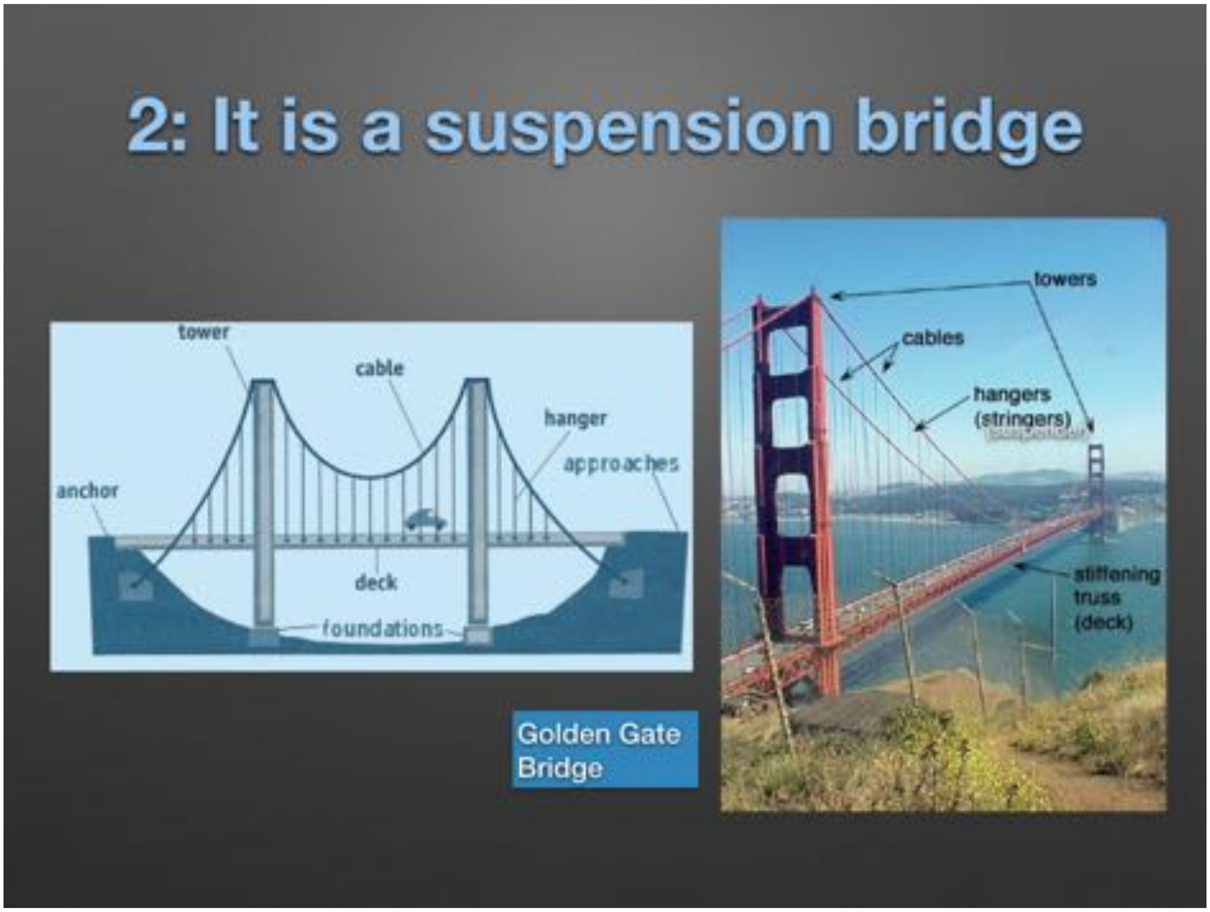
1869-1883



2: It is a suspension bridge

There are three basic kinds of tension in all bridges

1. Tension: the cables stretched to hold the deck
2. Compression: the piers/towers as the weight of the cable presses downward at their tops
3. Bending: the deck is in bending; the top is compressed by the weight of the traffic while the bottom is in tension from top's weight



2: It is a suspension bridge

Golden Gate Bridge

2: It is a suspension bridge

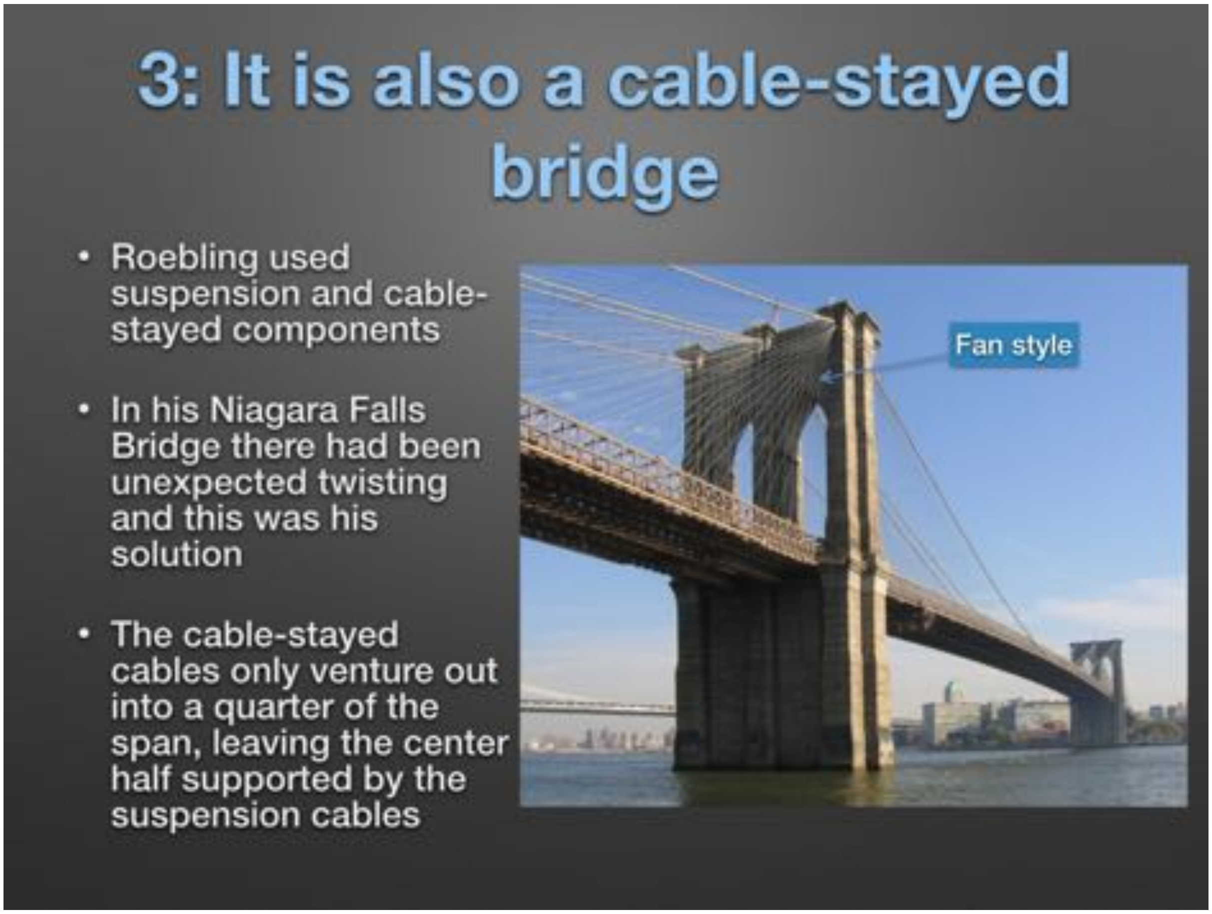
- The bridge has 4 main cables
- From these cables hang the suspenders, linking to the deck
- Roebling wanted the cables to make a beautiful sweeping arch so he placed the suspenders very close: every 7.5 feet
    - Golden Gate Bridge suspenders: 50 ft

3: It is also a cable-stayed bridge

- Cable-stayed is a type of wire suspension
- Often chosen for its natural elegance
- Cannot support spans as long as a suspension bridge
- Designs: mainly fan or harp, with some new asymmetrical designs

Dame Point River Bridge (harp)

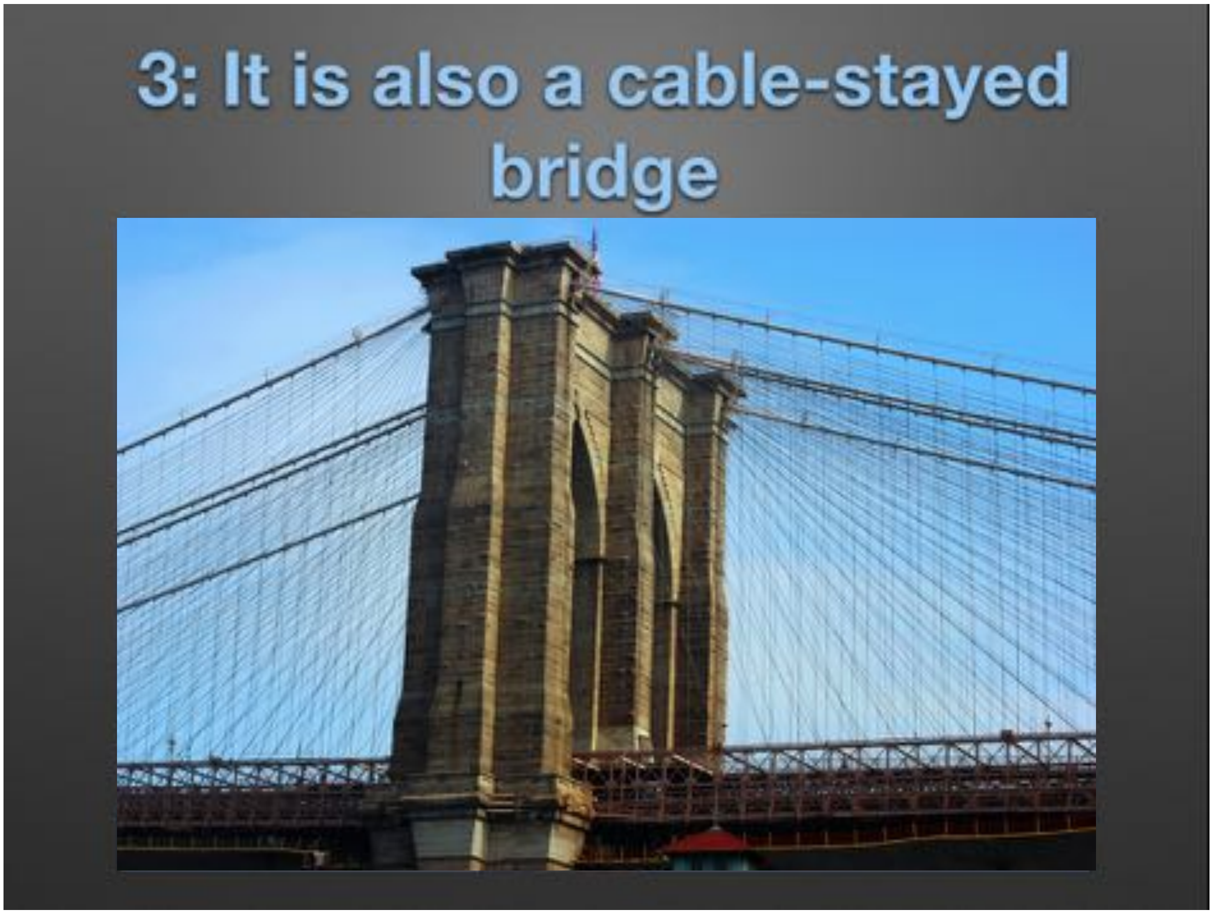
Millau Viaduct (fan)



3: It is also a cable-stayed bridge

- Roebling used suspension and cable-stayed components
- In his Niagara Falls Bridge there had been unexpected twisting and this was his solution
- The cable-stayed cables only venture out into a quarter of the span, leaving the center half supported by the suspension cables

Fan style



3: It is also a cable-stayed bridge

3: It is also a cable-stayed bridge with truss decking

- Strengthening the edge of the deck helps with twisting
- Carries the load between the suspenders
- 14 ft deep truss

4: The materials

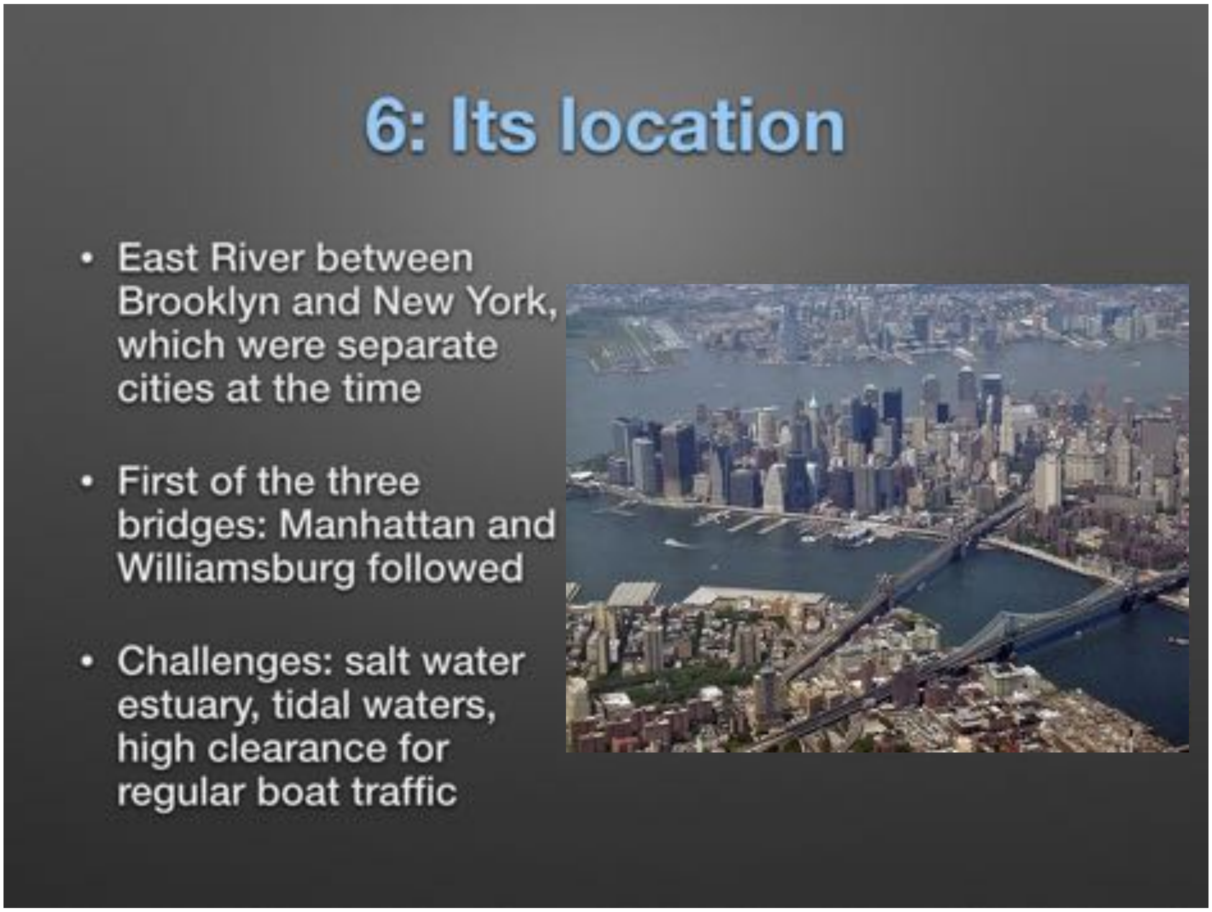
- Underwater: wooden blocks filled with concrete
- Piers: stone, granite quarried in Maine (stone is best for compression)
  - The largest bridges at this time were stone arch
- Cables and trusses: steel as per Roebling's design
- Deck: reinforced concrete
- Pedestrian pathway: wooden decking

5: Its place in history

- Union Bridge over the River Tweed, 1820
  - Connects England and Scotland
  - First vehicular suspension bridge
  - Span: 423 ft
- Menai Suspension Bridge, Wales, 1826
  - Span: 577 ft
  - Longest bridge in the world until the Brooklyn Bridge

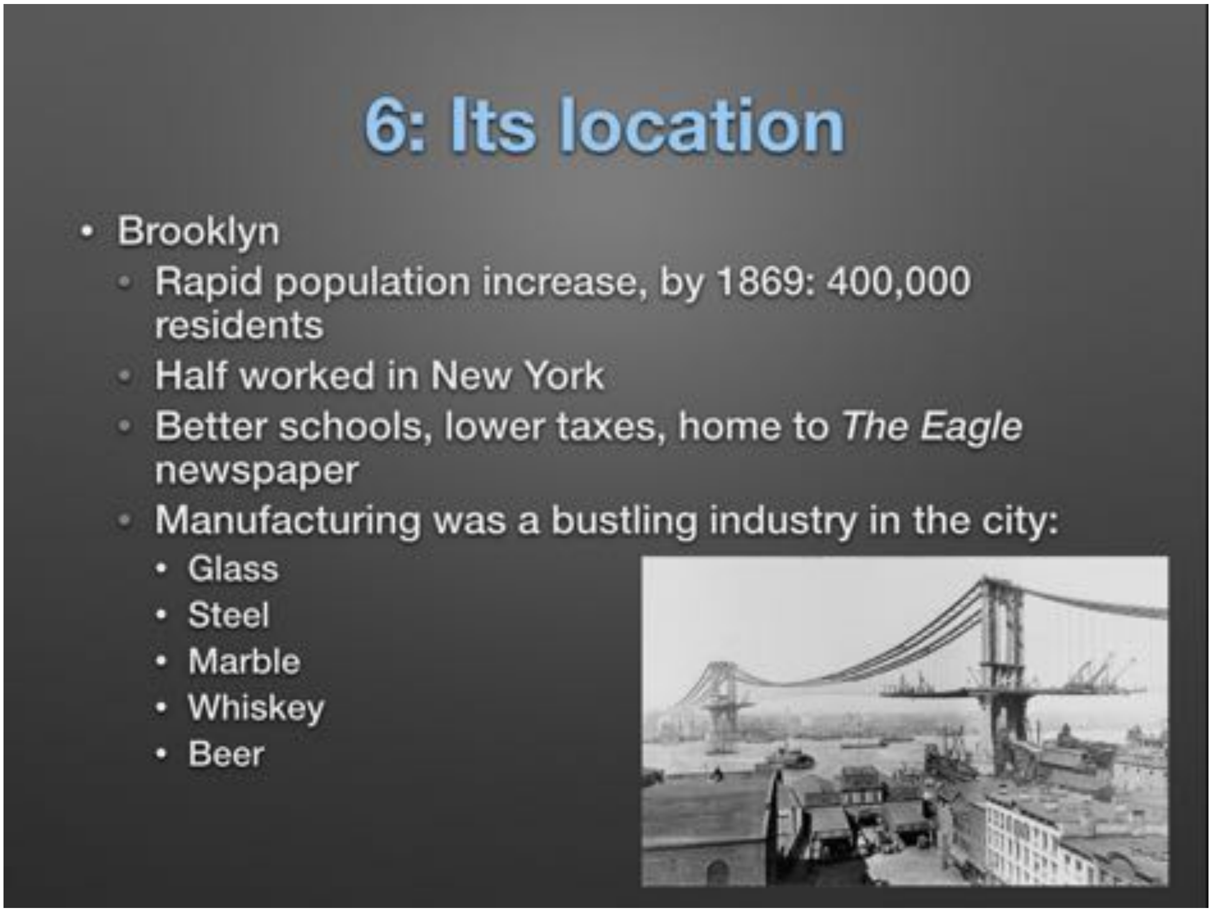
5: Its place in history

- Over twice the span of the longest bridge at the time, the Menai Straits Bridge
- Span: 1,595 ft, 6 in
- Entire length: 5,989 ft, over 1 mile



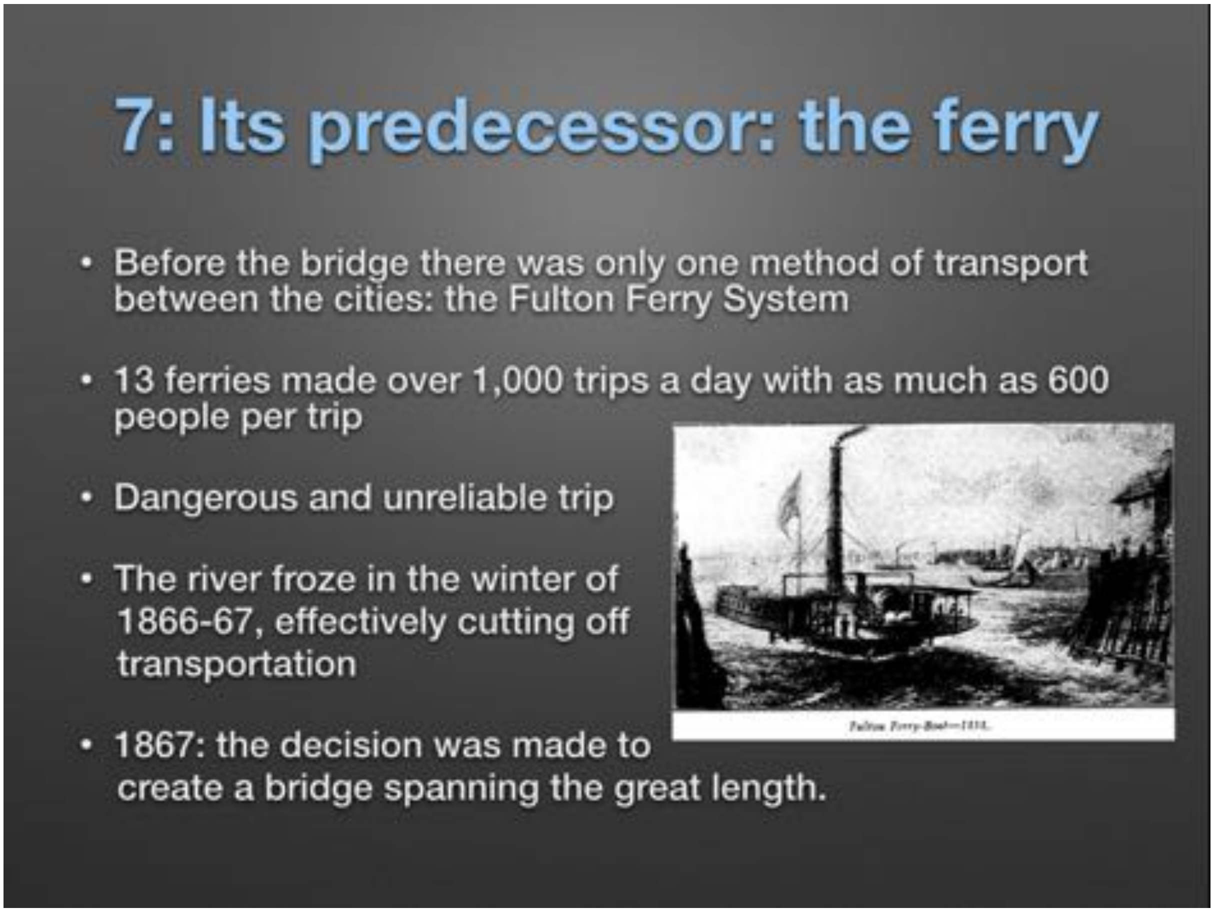
6: Its location

- East River between Brooklyn and New York, which were separate cities at the time
- First of the three bridges: Manhattan and Williamsburg followed
- Challenges: salt water estuary, tidal waters, high clearance for regular boat traffic



6: Its location

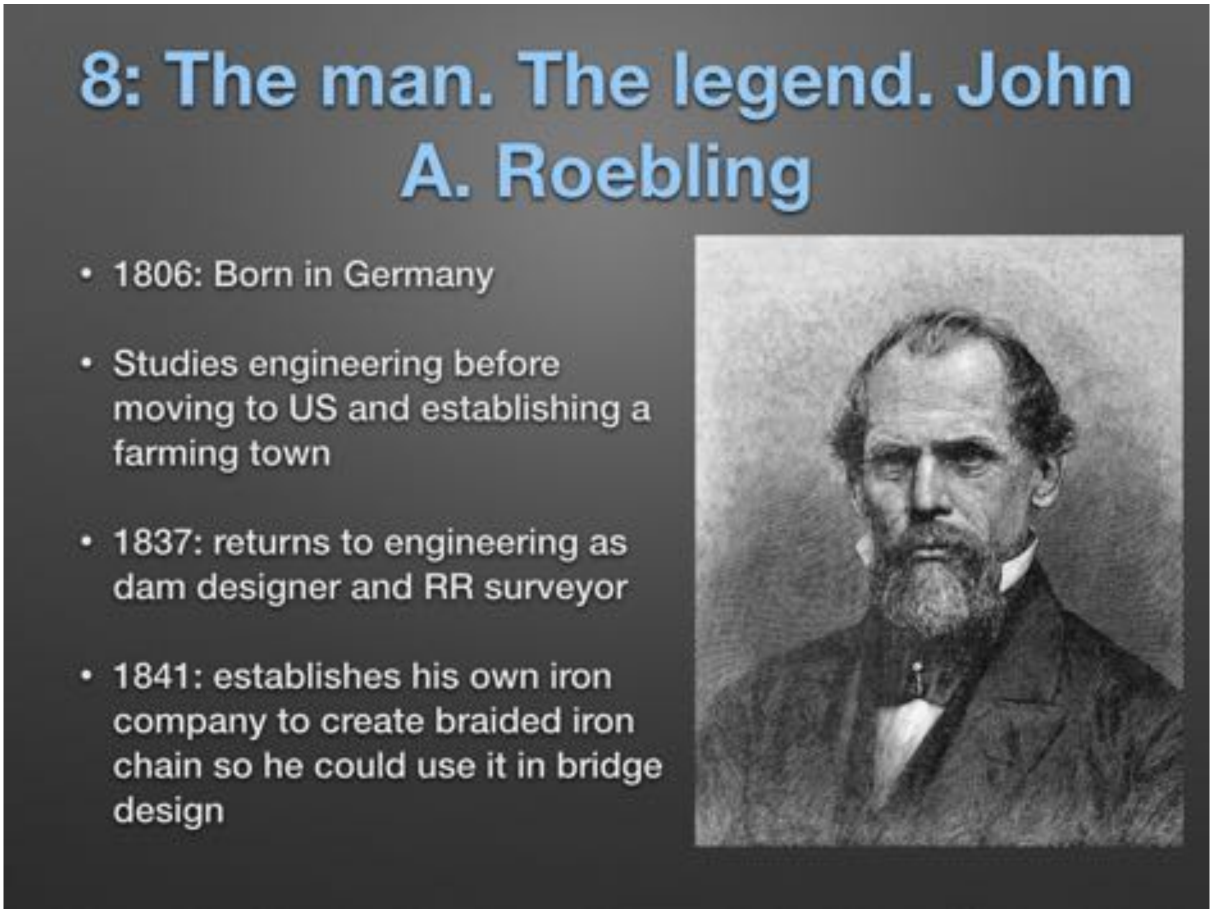
- Brooklyn
  - Rapid population increase, by 1869: 400,000 residents
  - Half worked in New York
  - Better schools, lower taxes, home to *The Eagle* newspaper
  - Manufacturing was a bustling industry in the city:
    - Glass
    - Steel
    - Marble
    - Whiskey
    - Beer



7: Its predecessor: the ferry

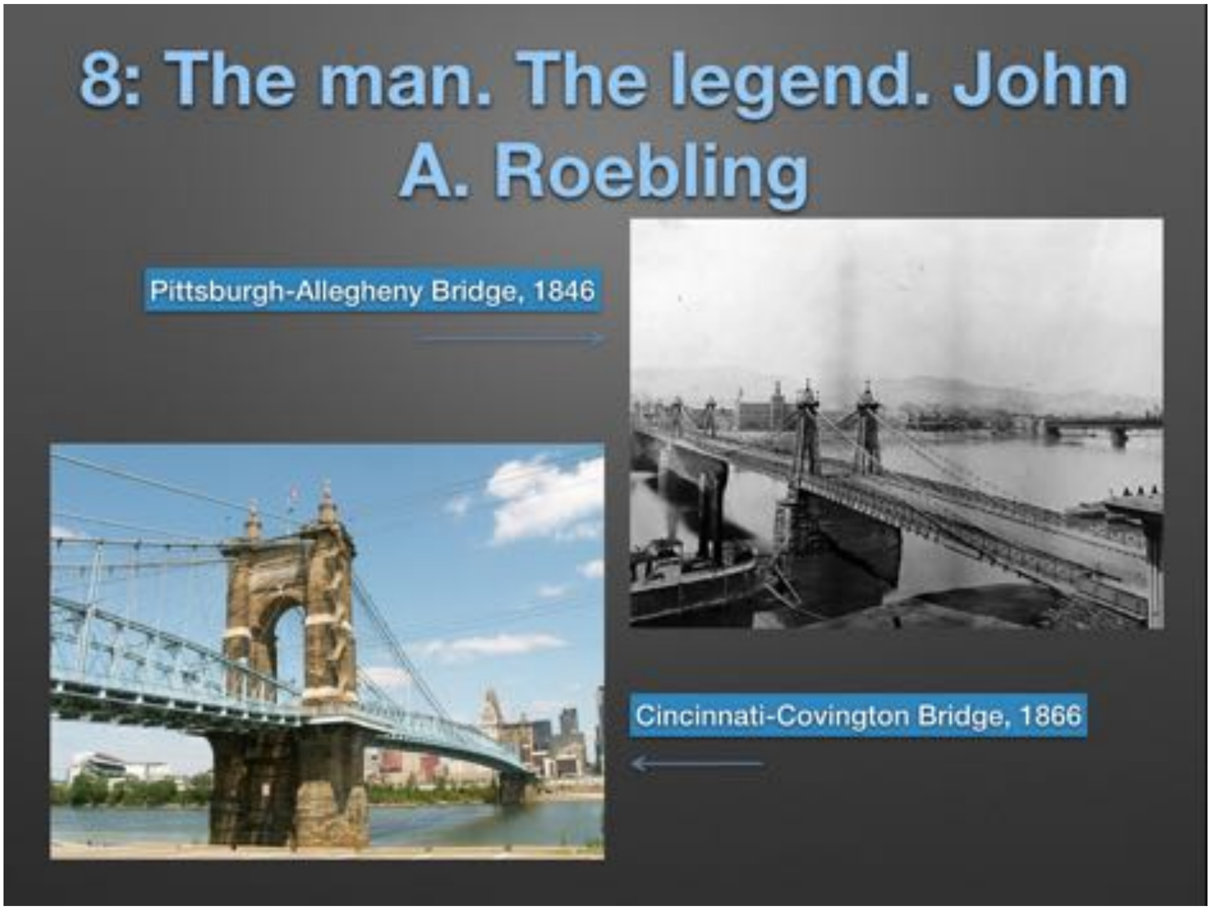
- Before the bridge there was only one method of transport between the cities: the Fulton Ferry System
- 13 ferries made over 1,000 trips a day with as much as 600 people per trip
- Dangerous and unreliable trip
- The river froze in the winter of 1866-67, effectively cutting off transportation
- 1867: the decision was made to create a bridge spanning the great length.

Fulton Ferry-Boat—[illegible]



8: The man. The legend. John A. Roebling

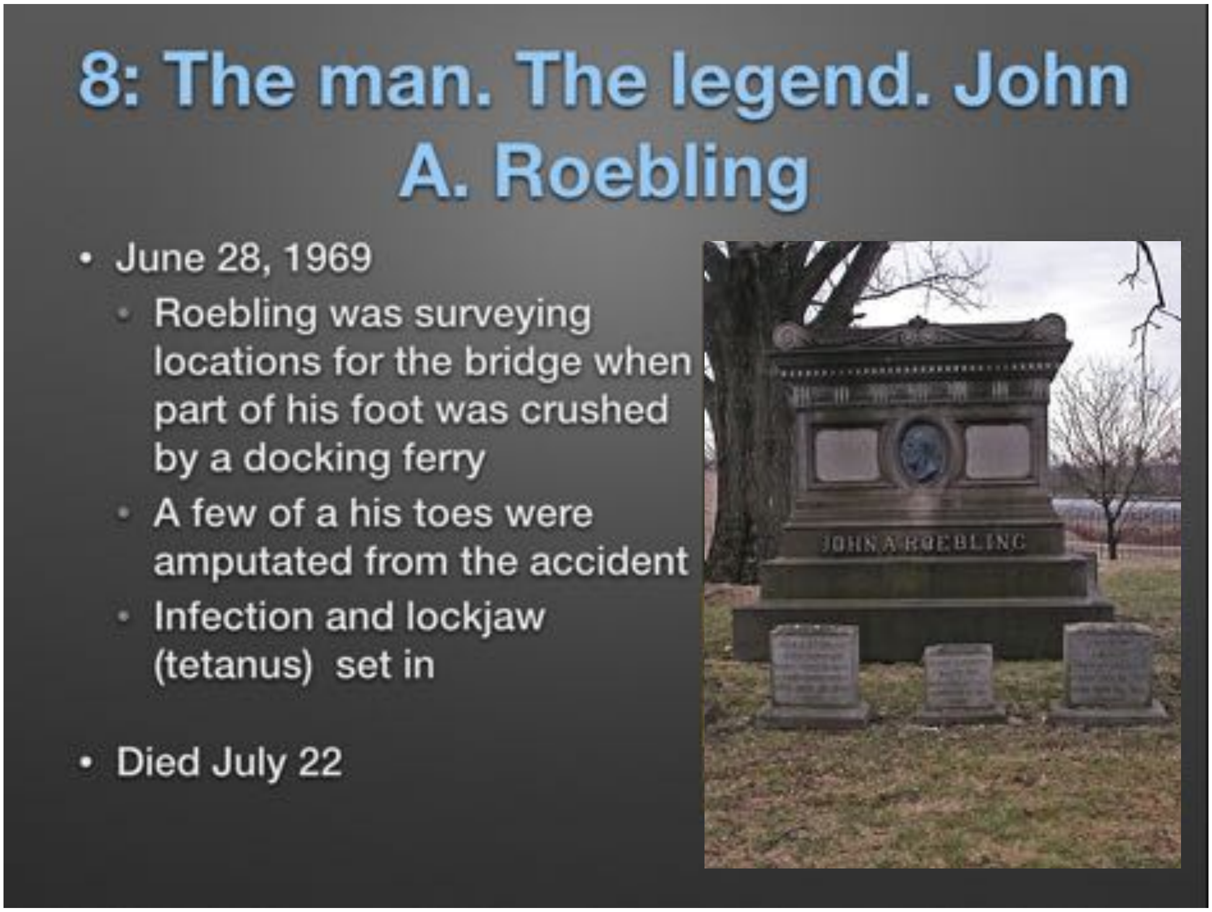
- 1806: Born in Germany
- Studies engineering before moving to US and establishing a farming town
- 1837: returns to engineering as dam designer and RR surveyor
- 1841: establishes his own iron company to create braided iron chain so he could use it in bridge design



8: The man. The legend. John A. Roebling

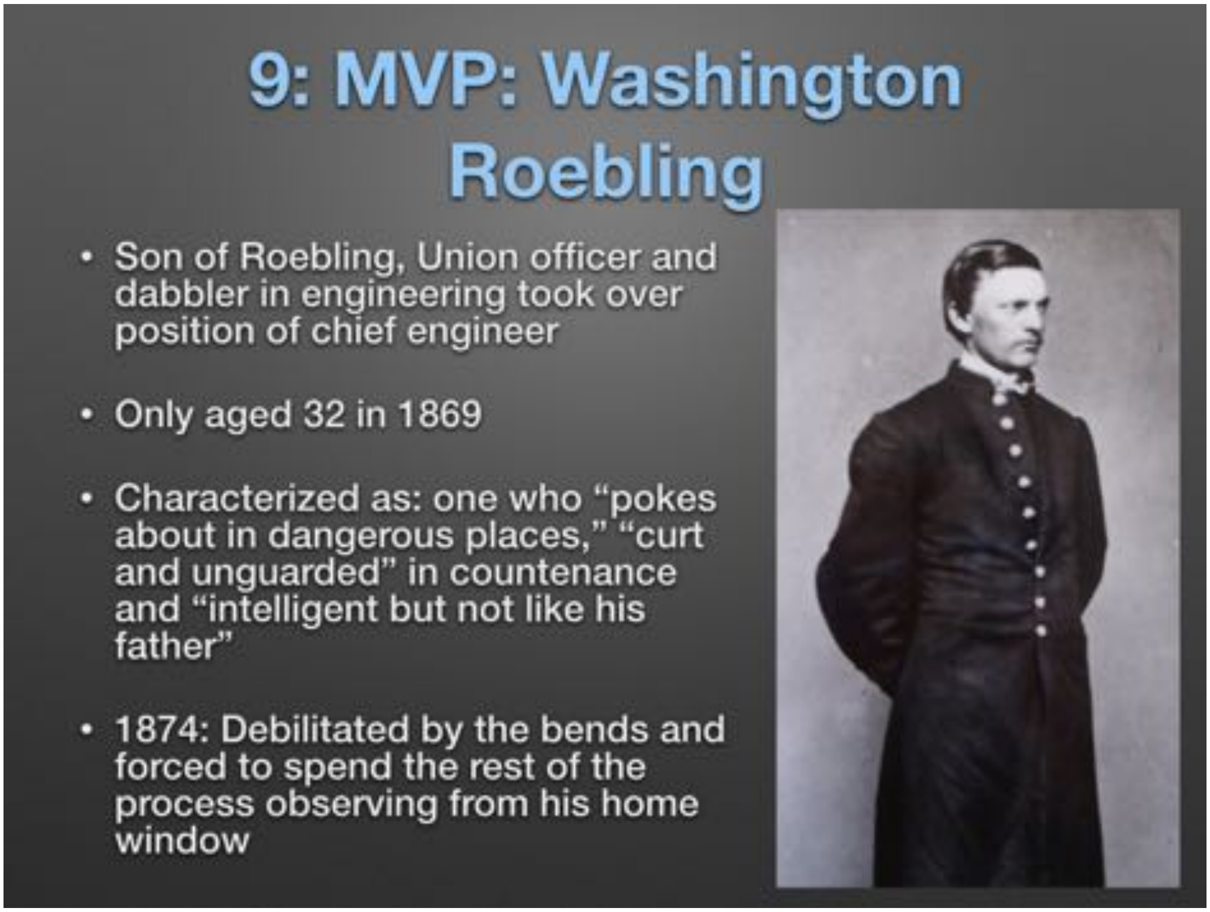
Pittsburgh-Allegheny Bridge, 1846

Cincinnati-Covington Bridge, 1866



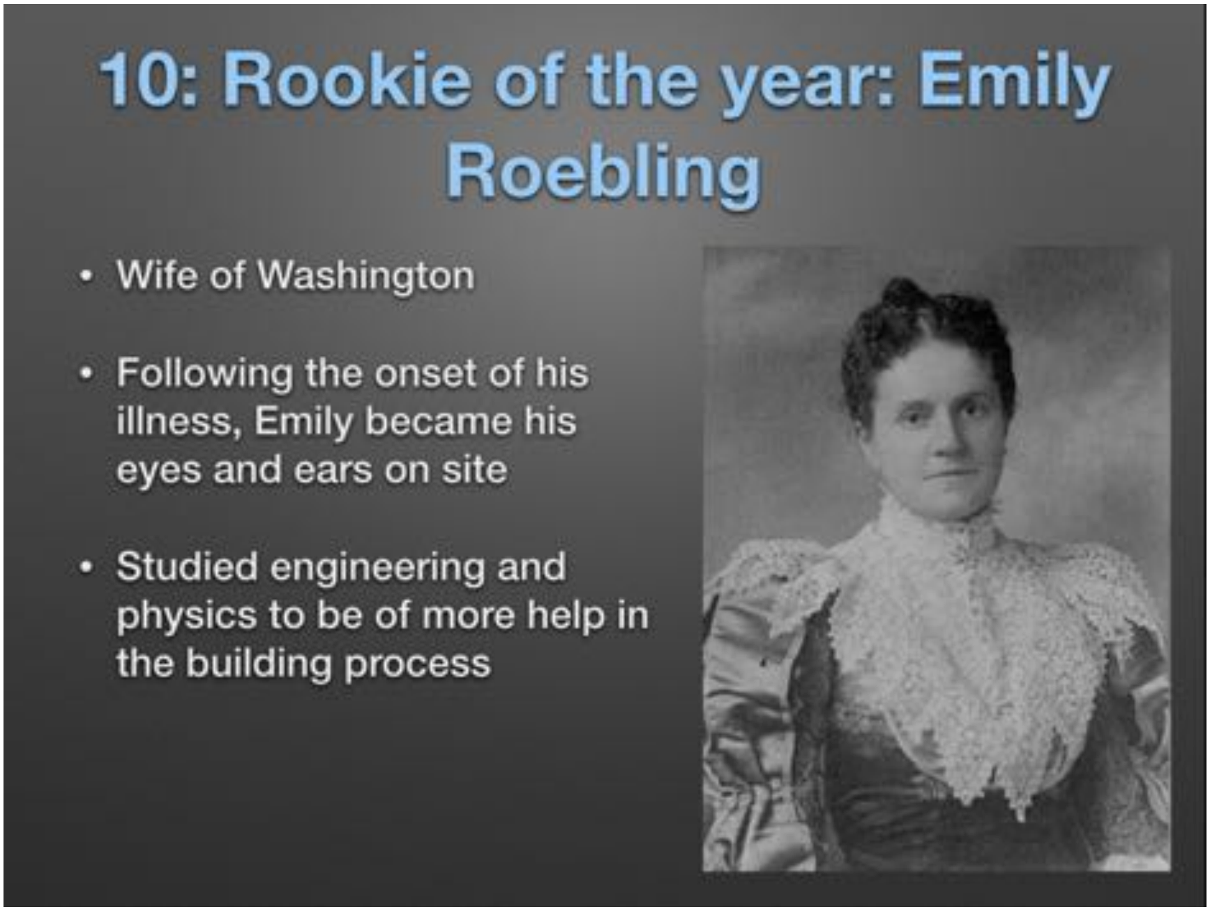
8: The man. The legend. John A. Roebling

- June 28, 1969
  - Roebling was surveying locations for the bridge when part of his foot was crushed by a docking ferry
  - A few of a his toes were amputated from the accident
  - Infection and lockjaw (tetanus) set in
- Died July 22



9: MVP: Washington Roebling

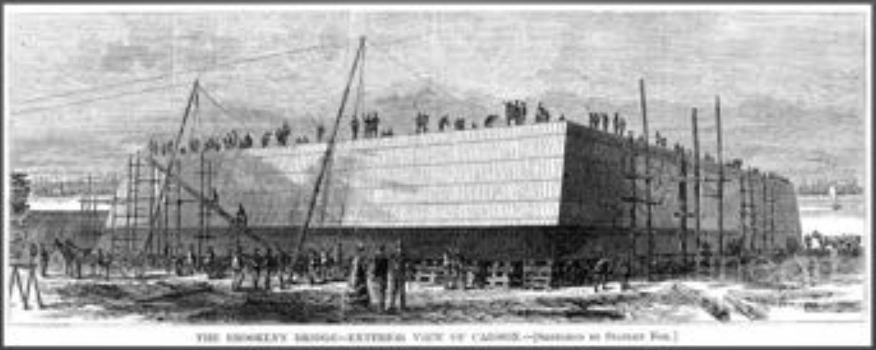
- Son of Roebling, Union officer and dabbler in engineering took over position of chief engineer
- Only aged 32 in 1869
- Characterized as: one who “pokes about in dangerous places,” “curt and unguarded” in countenance and “intelligent but not like his father”
- 1874: Debilitated by the bends and forced to spend the rest of the process observing from his home window



10: Rookie of the year: Emily Roebling

- Wife of Washington
- Following the onset of his illness, Emily became his eyes and ears on site
- Studied engineering and physics to be of more help in the building process

11: The caissons



- Building method used as early as 1831 in Europe
- Large wooden boxes underwater with a removable bottom as an airtight chamber
- Workers would work in the space pumped with pressurized air as they dug out the riverbed

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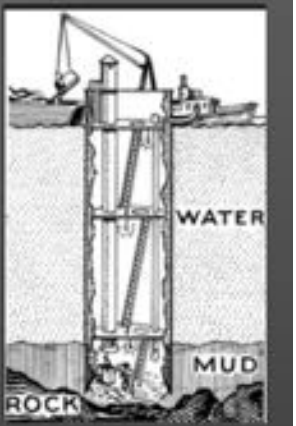
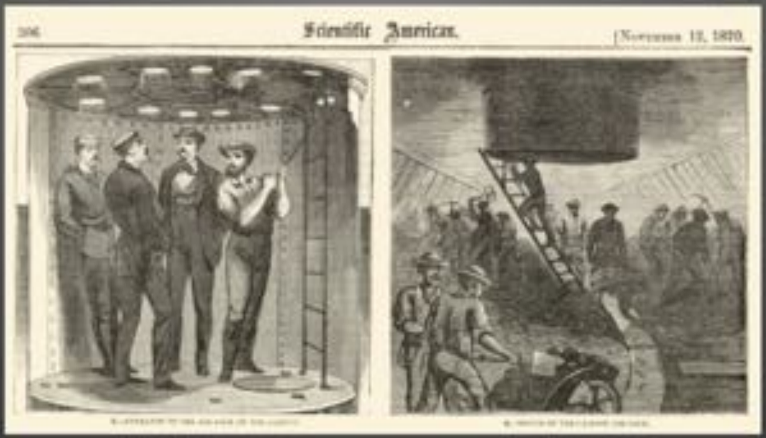
11: The caissons



- First launched on March 19, 1870
- The Brooklyn caisson was the biggest ever
  - 168ft x 102ft with a 15ft thick timber ceiling
- About 2,500 men worked in the caissons mainly Irish, German and Italian immigrants
- Due to the highly dangerous, difficult and frankly painful work in the extremely high pressure space about 100 men quit a week
- Conditions included mud 3ft deep and sometimes removing rocks as large as 100ft3
- 40 men/chamber for 8 hours a day @ $5, 3 shifts a day
- Brooklyn caisson had more rocks to dig out; NY caisson had more sand, meaning deeper digging and higher pressure

11: The caissons



- At first the bends or "caisson's disease" was thought to be a reaction to the underwater soil or air quality
- After a while there was the introduction of a chamber to assimilate the workers to the high pressure before and after their work

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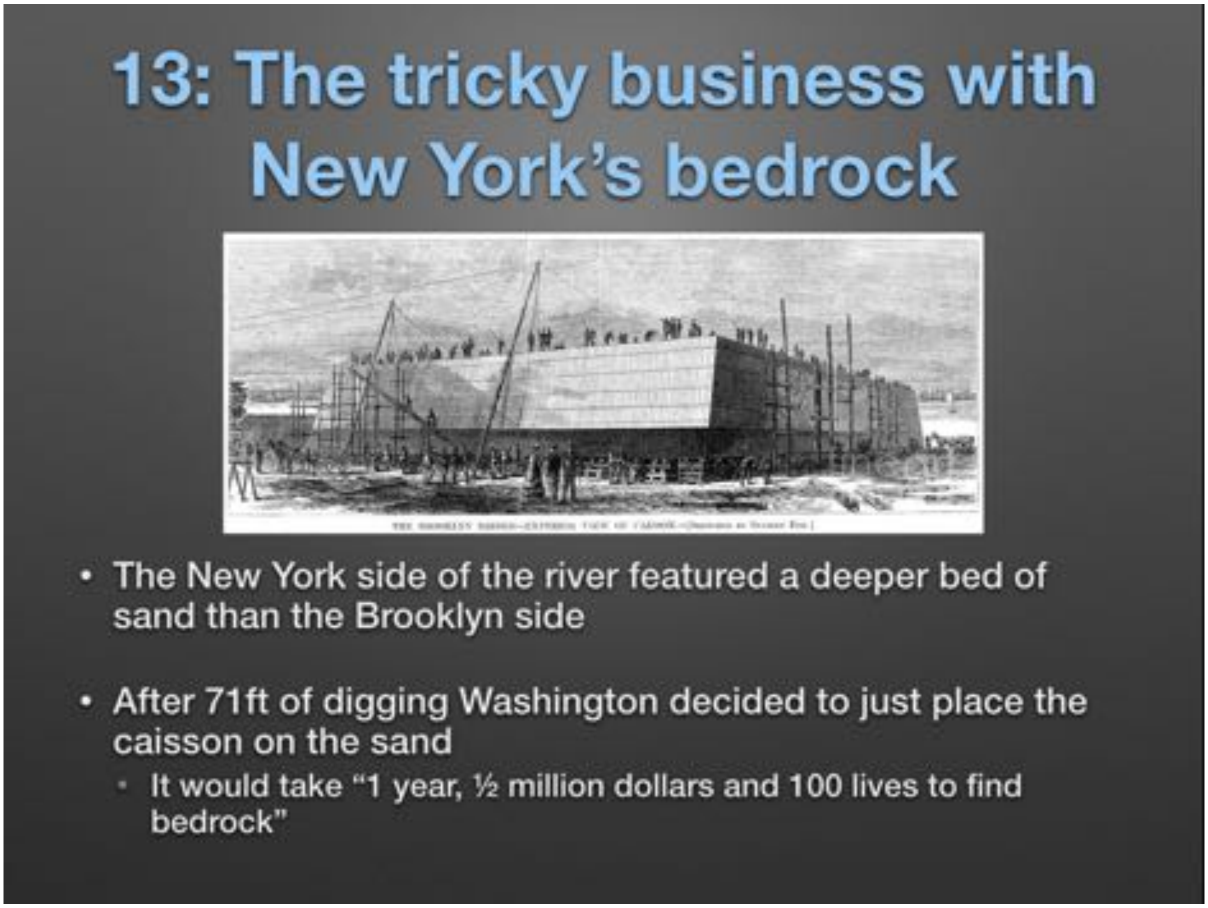
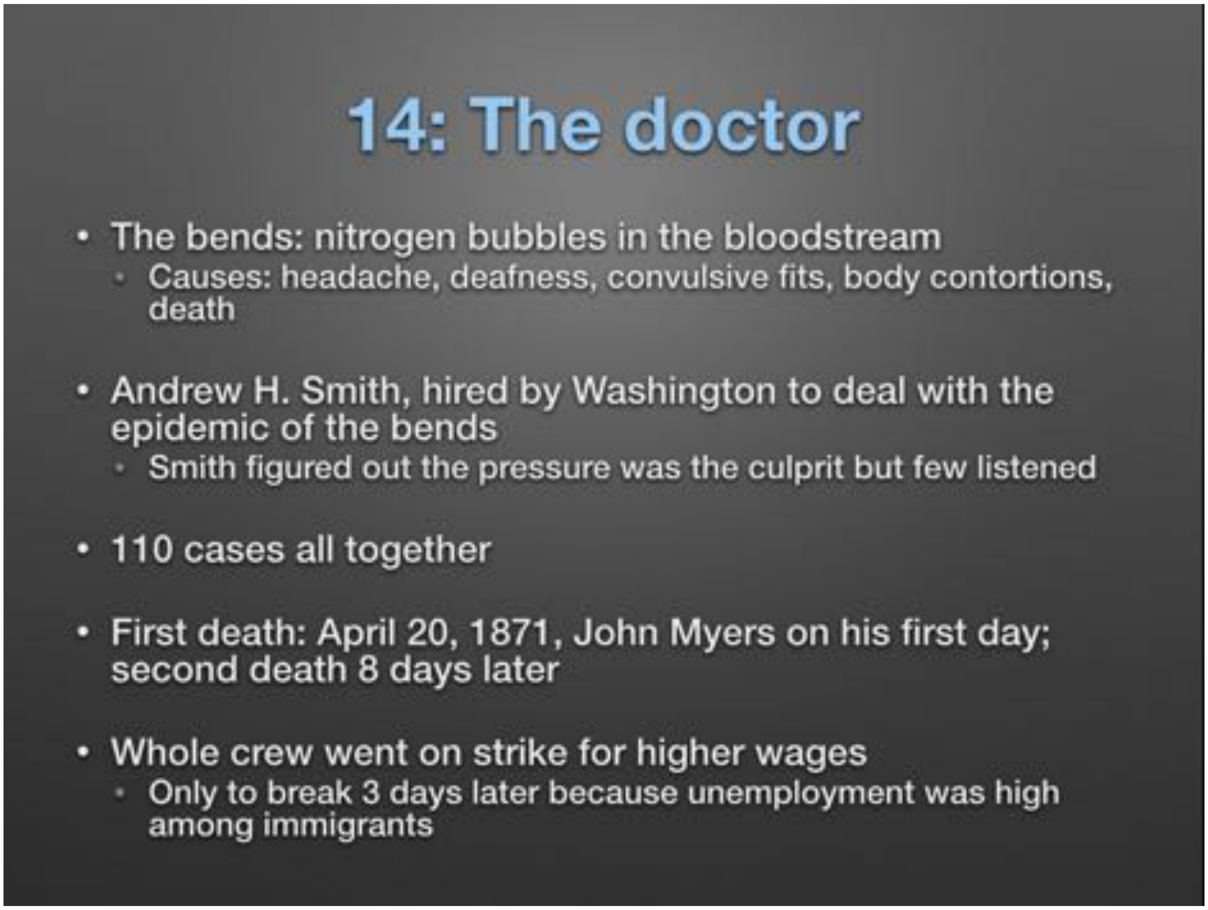
12: The fire that happened underwater

- December 1, 1870, New York caisson
  - A candle was held too close to the timber ceiling and caught fire in between Chambers 1 and 2
  - It wasn't discovered until 9:30pm, hours after its onset, water and fire extinguishers could do nothing
  - 4-5 fires before, so not uncommon but quickly put out
  - 80 workers in panic as the layers of the ceiling burned
  - 8am: workers evacuated
  - 1:30pm caisson had been completely flooded to put out the fire, 1.35 million gallons of water
  - March 1, 1871- repairs completed all the while work continued



13: The tricky business with New York's bedrock

- The New York side of the river featured a deeper bed of sand than the Brooklyn side
- After 71ft of digging Washington decided to just place the caisson on the sand
  - It would take "1 year, ½ million dollars and 100 lives to find bedrock"



14: The doctor

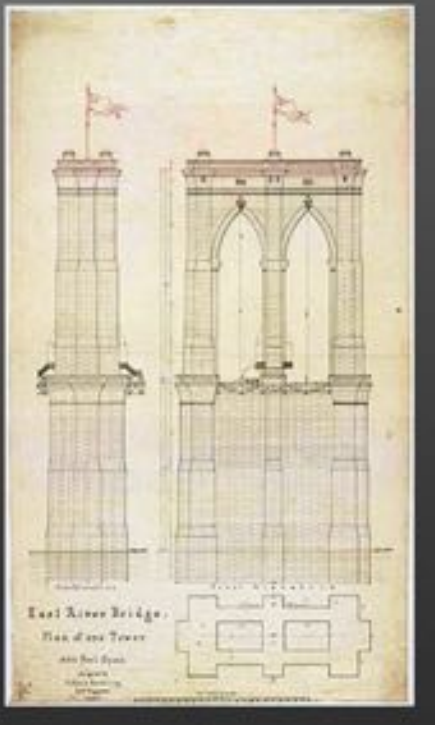
- The bends: nitrogen bubbles in the bloodstream
  - Causes: headache, deafness, convulsive fits, body contortions, death
- Andrew H. Smith, hired by Washington to deal with the epidemic of the bends
  - Smith figured out the pressure was the culprit but few listened
- 110 cases all together
- First death: April 20, 1871, John Myers on his first day; second death 8 days later
- Whole crew went on strike for higher wages
  - Only to break 3 days later because unemployment was high among immigrants

14: The doctor

- 10 rules for battling the bends
  - Never enter a caisson on an empty stomach
  - Diet of meat and coffee
  - Put on extra clothing when leaving
  - Avoid the cold
  - No exercise for the first hour out
  - Use liquor sparingly
  - 8 hours of sleep before and after
  - See bowels are opened everyday
  - Never enter when sick
  - Report all sickness to the office

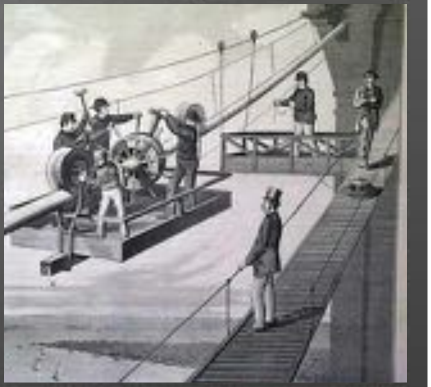
15: The towers

- Began ascent in summer of 1872
- Both designed to rise above high water level at 278ft
- Stone was used since it is the perfect material for compression



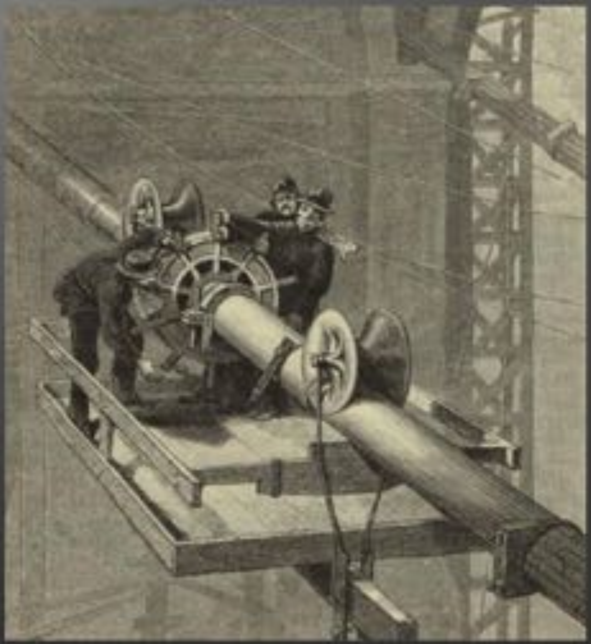
16: Laying the cable

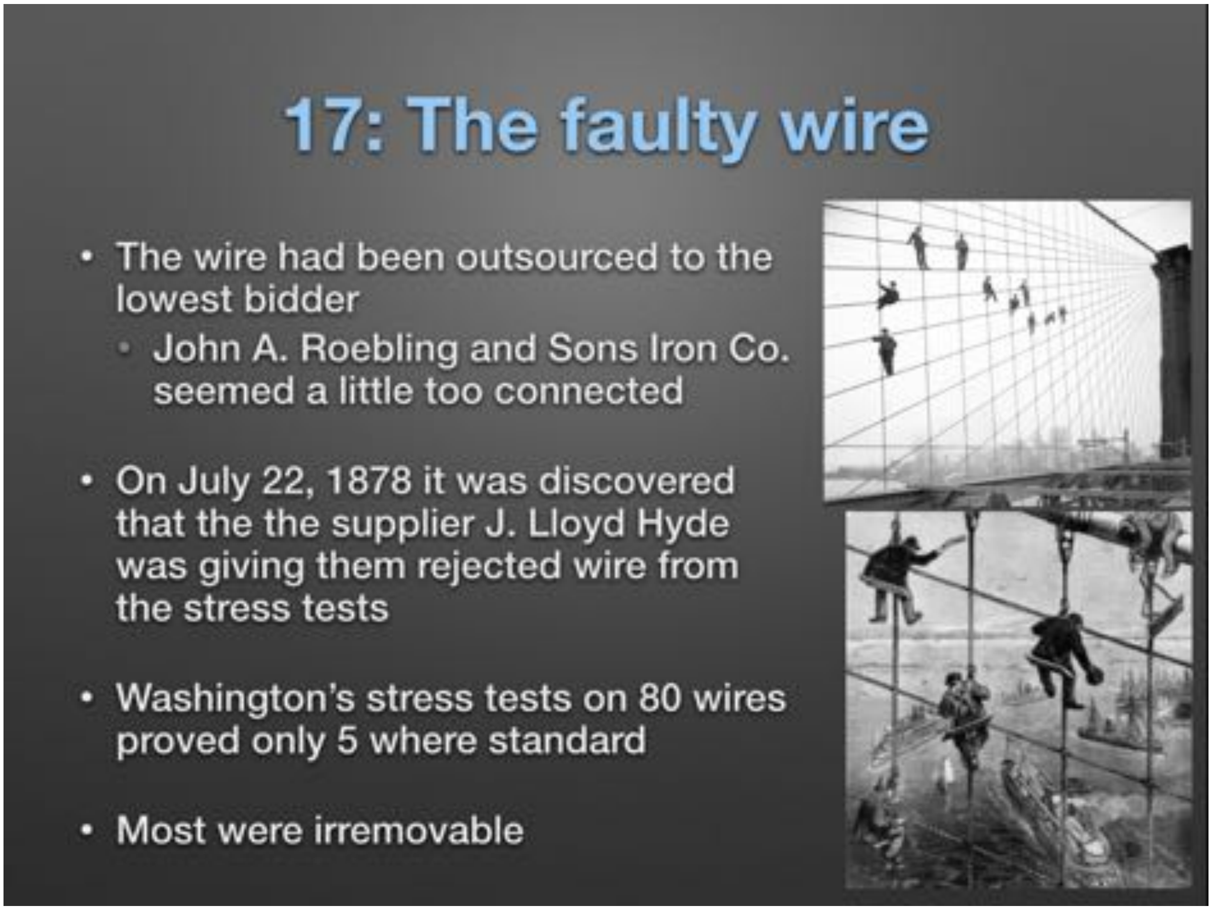
- August 14, 1976: the first rope was thrown between the towers to begin cable work
- In total, 6.8 million pounds of steel wire was used
- The process involved a small cart on a pulley that ran back and forth like a spider laying layer upon layer of cable, which would be bunched at certain intervals



16: Laying the cable

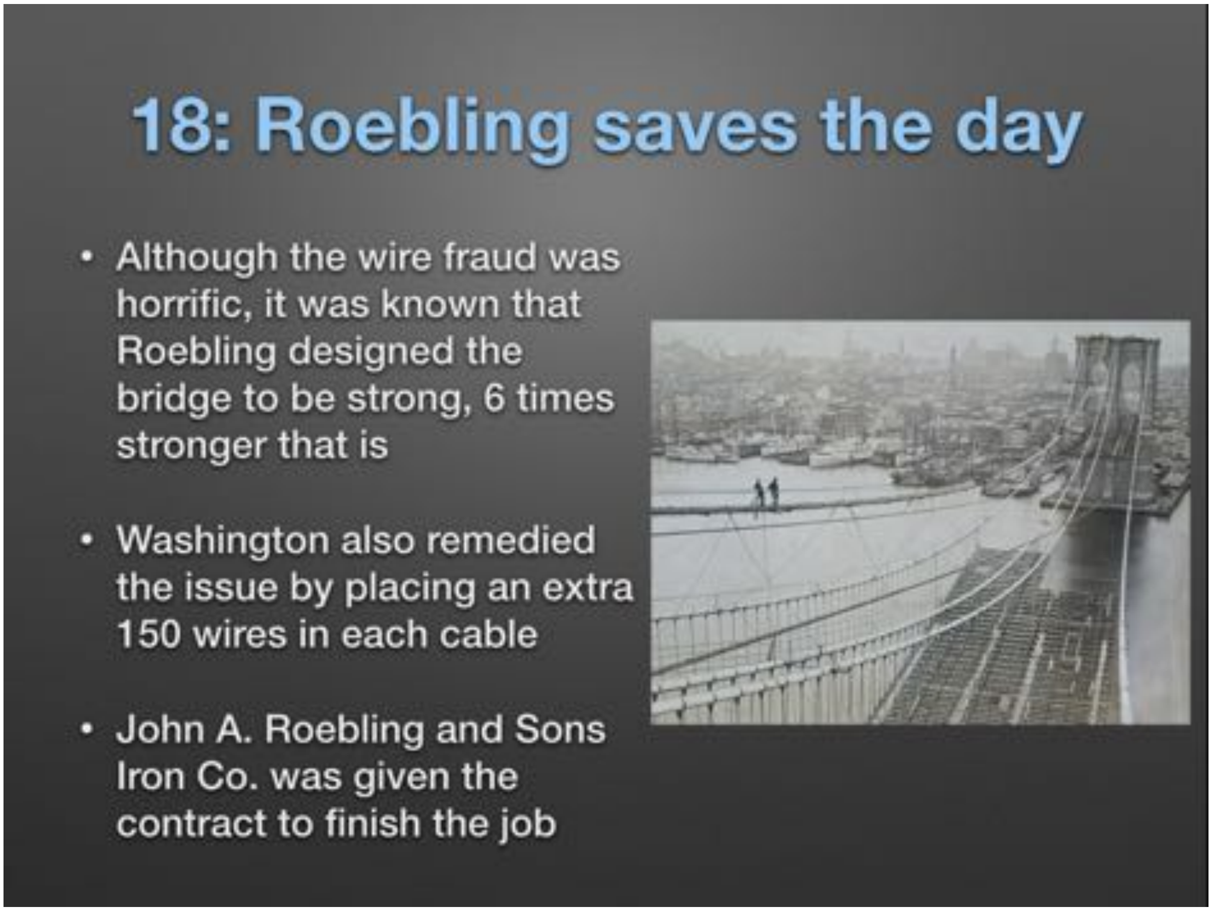
- The “buggies” would travel back and forth to combine the small wire, some as small as a human hair
- Washington hired sailors for the work for their ability to work on high lines





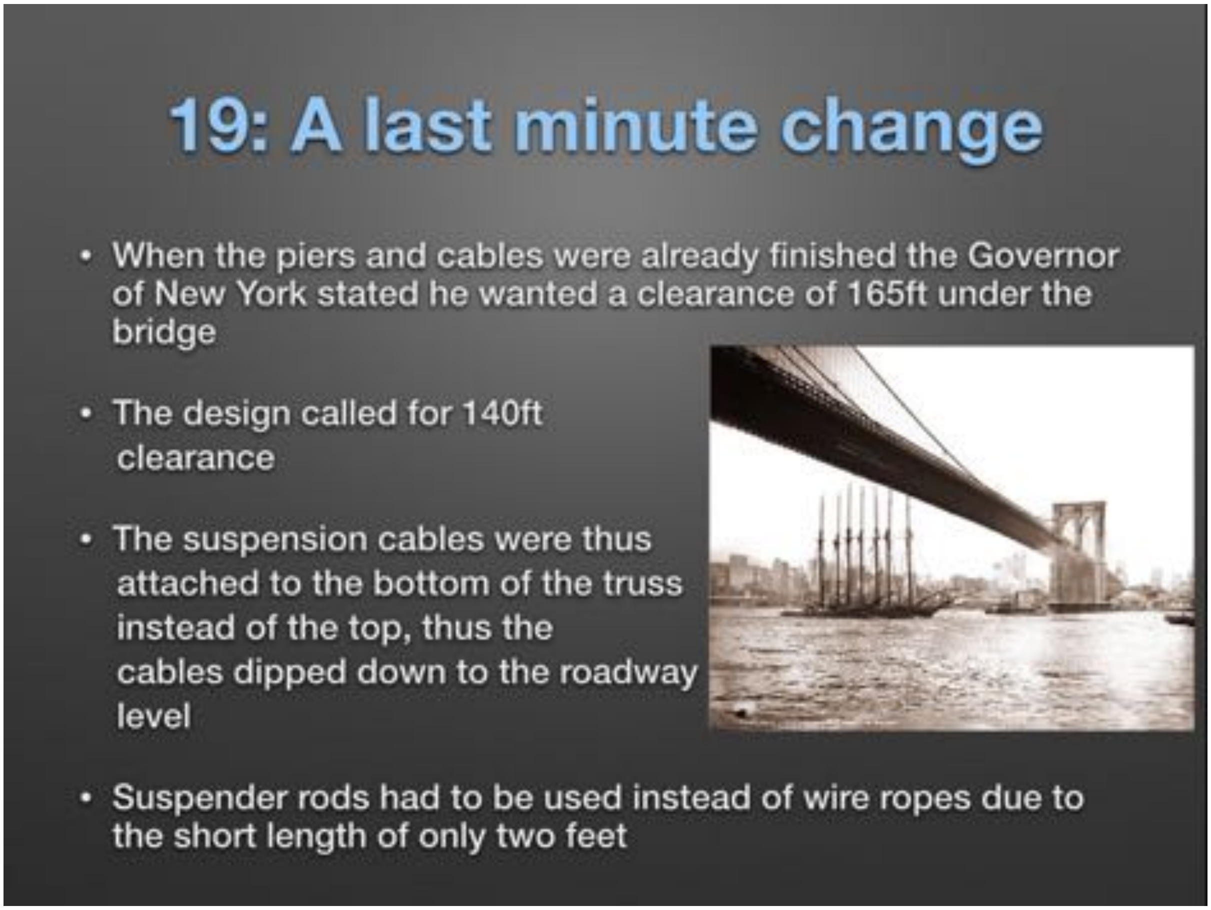
17: The faulty wire

- The wire had been outsourced to the lowest bidder
  - John A. Roebling and Sons Iron Co. seemed a little too connected
- On July 22, 1878 it was discovered that the the supplier J. Lloyd Hyde was giving them rejected wire from the stress tests
- Washington's stress tests on 80 wires proved only 5 where standard
- Most were irremovable



18: Roebling saves the day

- Although the wire fraud was horrific, it was known that Roebling designed the bridge to be strong, 6 times stronger that is
- Washington also remedied the issue by placing an extra 150 wires in each cable
- John A. Roebling and Sons Iron Co. was given the contract to finish the job



19: A last minute change

- When the piers and cables were already finished the Governor of New York stated he wanted a clearance of 165ft under the bridge
- The design called for 140ft clearance
- The suspension cables were thus attached to the bottom of the truss instead of the top, thus the cables dipped down to the roadway level
- Suspender rods had to be used instead of wire ropes due to the short length of only two feet

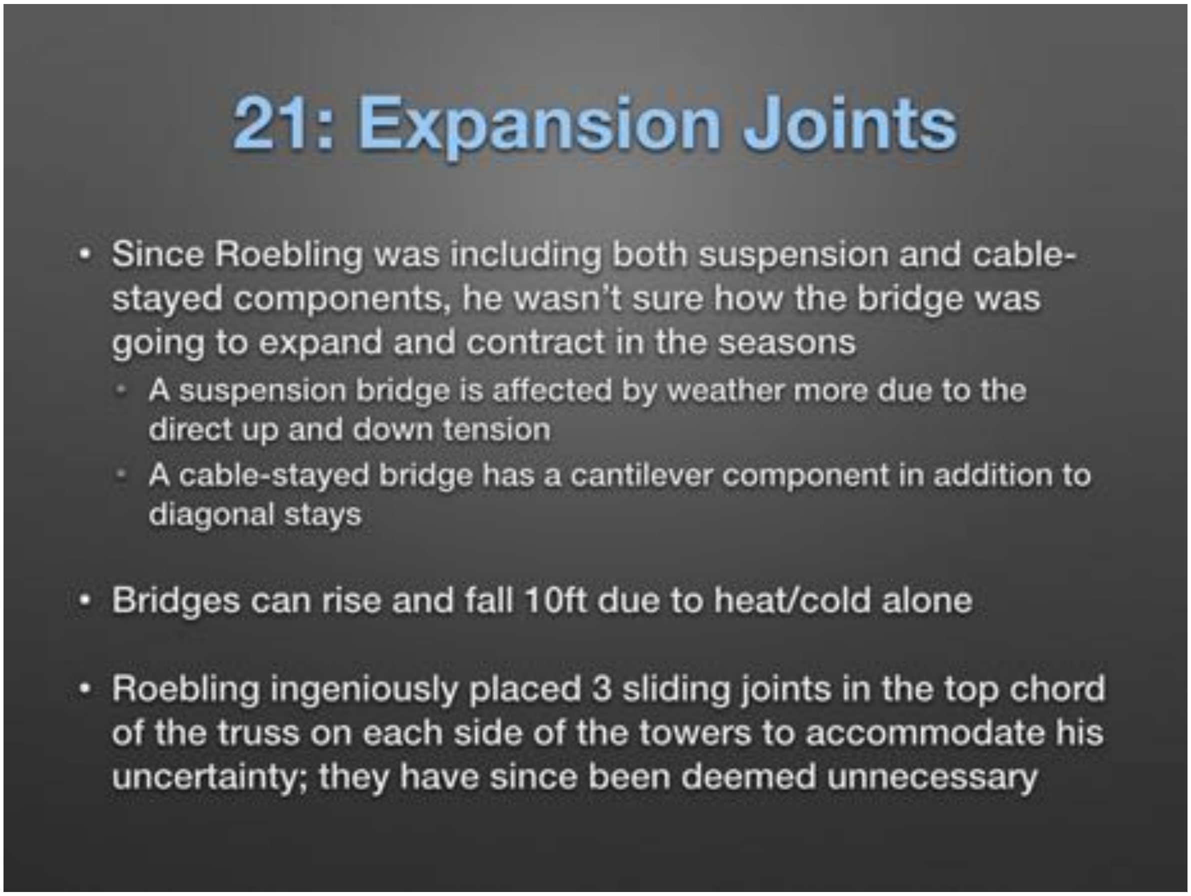
19: A last minute change

Golden Gate Bridge
*Note the cables that meet the deck at the top as is the usual

George Washington Bridge
*Fun Fact: Originally the towers were to be clad in stone but they ran out of money. The basic structural design was deemed aesthetically pleasing in itself and remains today

20: Opening Day

- The bridge opened on May 24, 1883
- It took 14 years, $15 million (3 times budget), 27 lives and many injuries to complete
- The opening procession was led by President Chester A. Arthur
- 150,000 people and 108,000 vehicles crossed the bridge that day



21: Expansion Joints

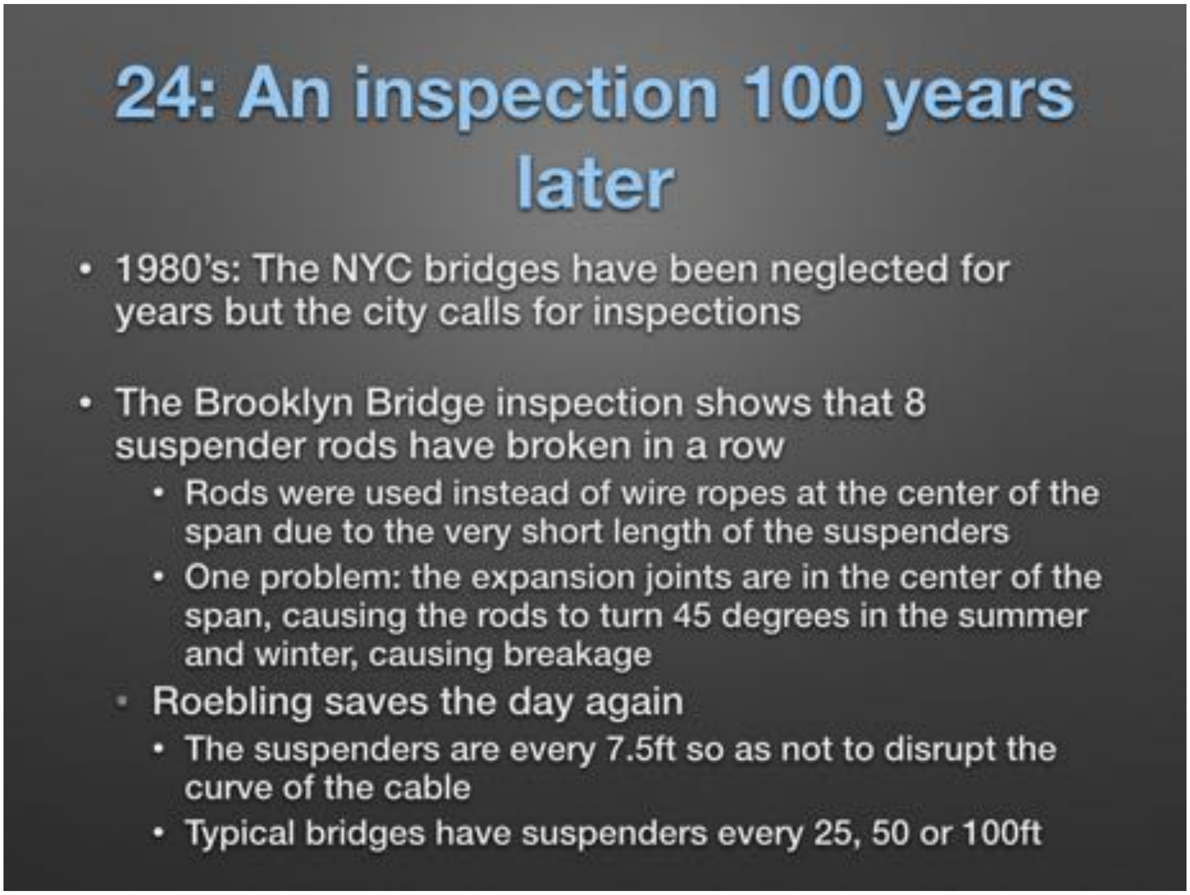
- Since Roebling was including both suspension and cable-stayed components, he wasn't sure how the bridge was going to expand and contract in the seasons
  - A suspension bridge is affected by weather more due to the direct up and down tension
  - A cable-stayed bridge has a cantilever component in addition to diagonal stays
- Bridges can rise and fall 10ft due to heat/cold alone
- Roebling ingeniously placed 3 sliding joints in the top chord of the truss on each side of the towers to accommodate his uncertainty; they have since been deemed unnecessary

22: The stampede

- May 30, 1883: One week after its opening the bridge was overcrowded with over 100,000 pedestrians
- Mass panic set in causing a stampede to get off the bridge
- 12 died and dozens were injured in the event

23: A second stampede

- In May 1884 P.T. Barnum led a group of 21 elephants across the bridge to prove its strength



24: An inspection 100 years later

- 1980's: The NYC bridges have been neglected for years but the city calls for inspections

- The Brooklyn Bridge inspection shows that 8 suspender rods have broken in a row
  - Rods were used instead of wire ropes at the center of the span due to the very short length of the suspenders
  - One problem: the expansion joints are in the center of the span, causing the rods to turn 45 degrees in the summer and winter, causing breakage
- Roebling saves the day again
  - The suspenders are every 7.5ft so as not to disrupt the curve of the cable
  - Typical bridges have suspenders every 25, 50 or 100ft

25: Today's Brooklyn Bridge

- Today the bridge is an iconic piece of New York and also world bridge architecture
- Roebling originally placed focus on raising the pedestrian platform to create the best view of the city and he has achieved it
- The bridge remains in great condition and continues to serve hundreds of thousands every day

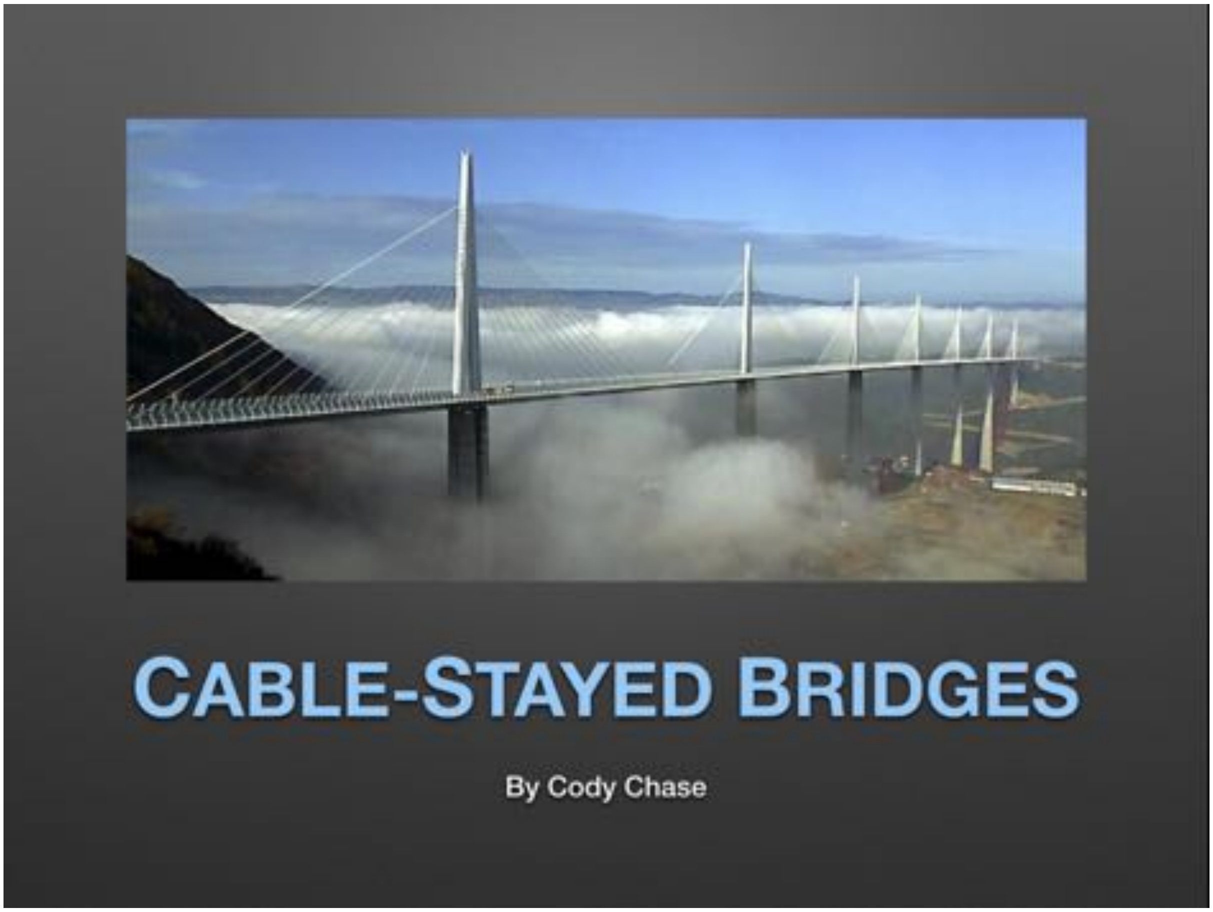
IV. TYPES OF BRIDGES

E. CABLE-STAYED

Cable-stayed bridges are the newest type on this list. Born from the same idea as suspension bridges, cable-stayed designs eliminate the longitudinal cables to allow simply the tower and suspender cable elements. These bridges provide a fresh and modern feel, giving designers a wide range of opportunity for unique creations.

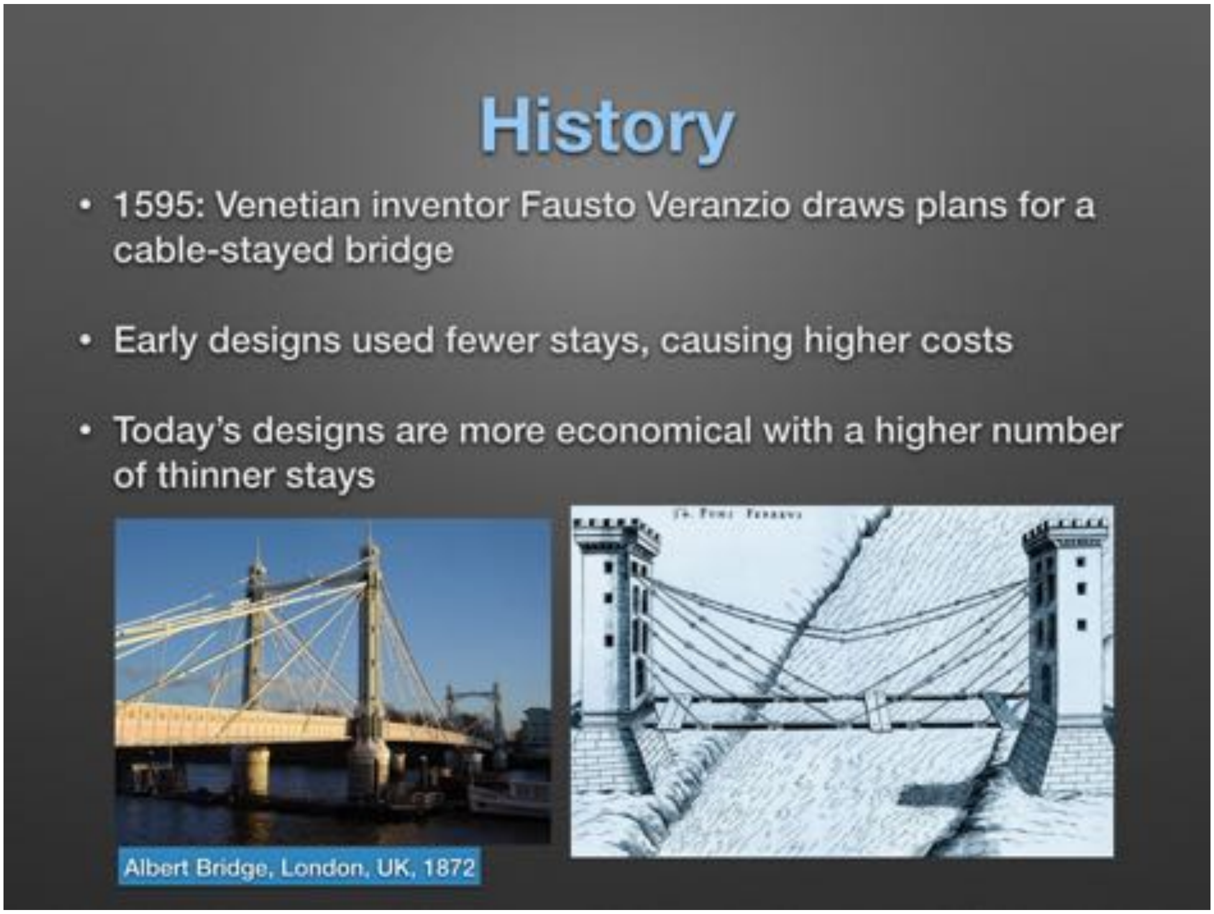
SUBTYPES:

- Side-Spar
- Multispan
- Extradosed
- Cradle
- Other



CABLE-STAYED BRIDGES

By Cody Chase



History

- 1595: Venetian inventor Fausto Veranzio draws plans for a cable-stayed bridge
- Early designs used fewer stays, causing higher costs
- Today's designs are more economical with a higher number of thinner stays

Albert Bridge, London, UK, 1872

3: It is also a cable-stayed bridge

- Cable-stayed is a type of wire suspension
- Often chosen for its natural elegance
- Cannot support spans as long as a suspension bridge
- Designs: mainly fan or harp, with some new asymmetrical designs

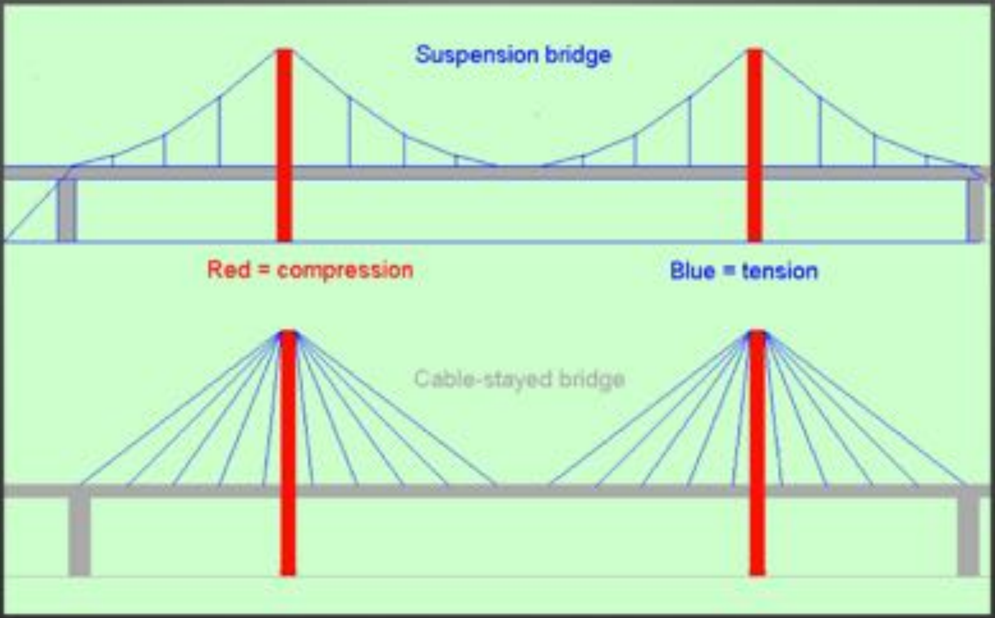
Dame Point River Bridge (harp)

Millau Viaduct (fan)

The First Modern Example

The first steel-decked cable-stayed:
Franz Dischinger's Strömsund Bridge, Sweden, 1956

Cable-Stayed vs. Suspension



1: The Basics

The Brooklyn Bridge

Originally: The New York and Brooklyn Bridge

Designer: John A. Roebling

Chief Engineer: Washington Roebling

1869-1883

Cable-Stayed vs. Suspension

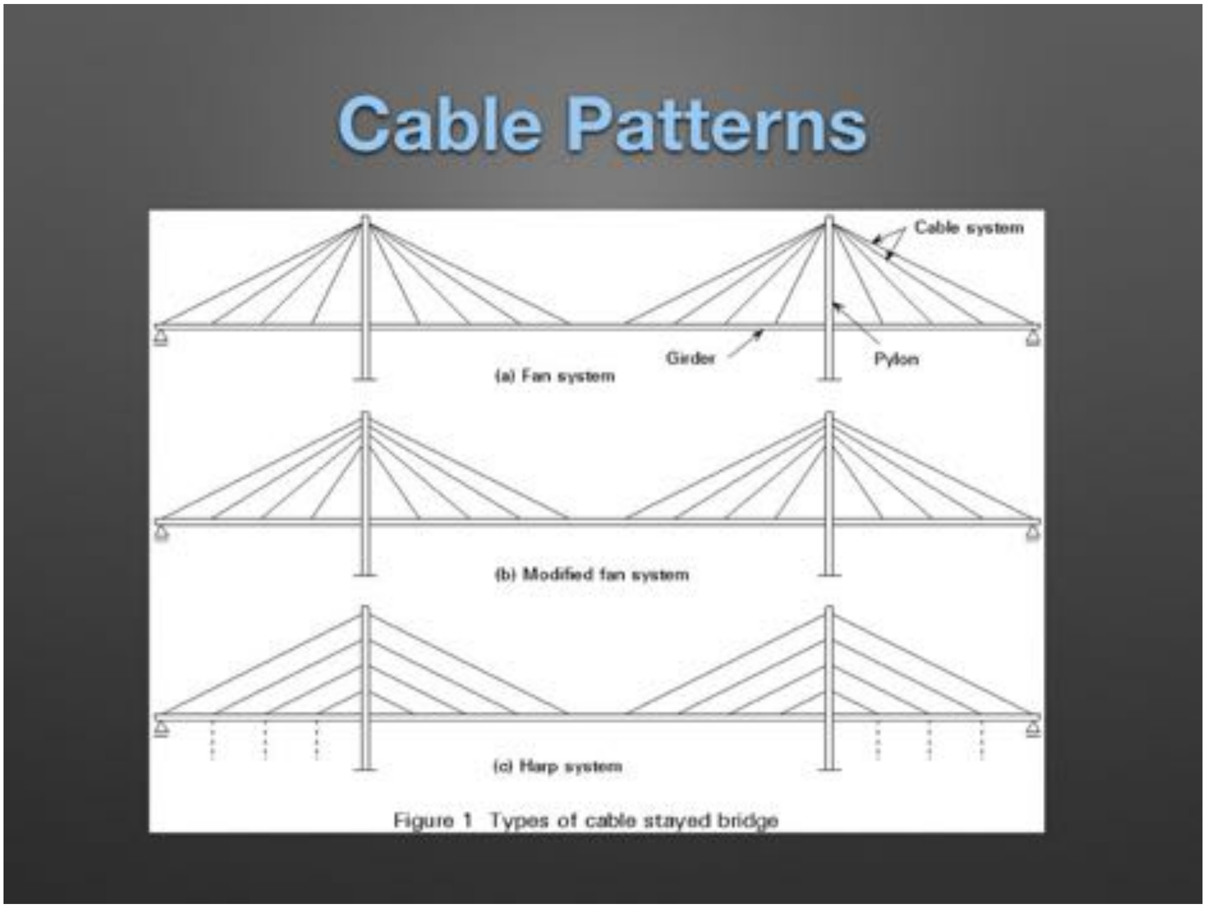
- No need for strong anchors at the ends, most of the stress is let out through the pylons
- Thicker deck to combat horizontal compression so better in winds
- Shorter than a suspension bridge span, longer than a girder span

- Anchored at either end, difficult when there is poor footing on the banks
- Thinner deck that simply hangs from suspenders
- Longest span length of all bridge types

Cable-Stayed vs. Suspension

John Roebling added the cable stays to the Brooklyn Bridge design after his previous Niagara Bridge experienced flexing.

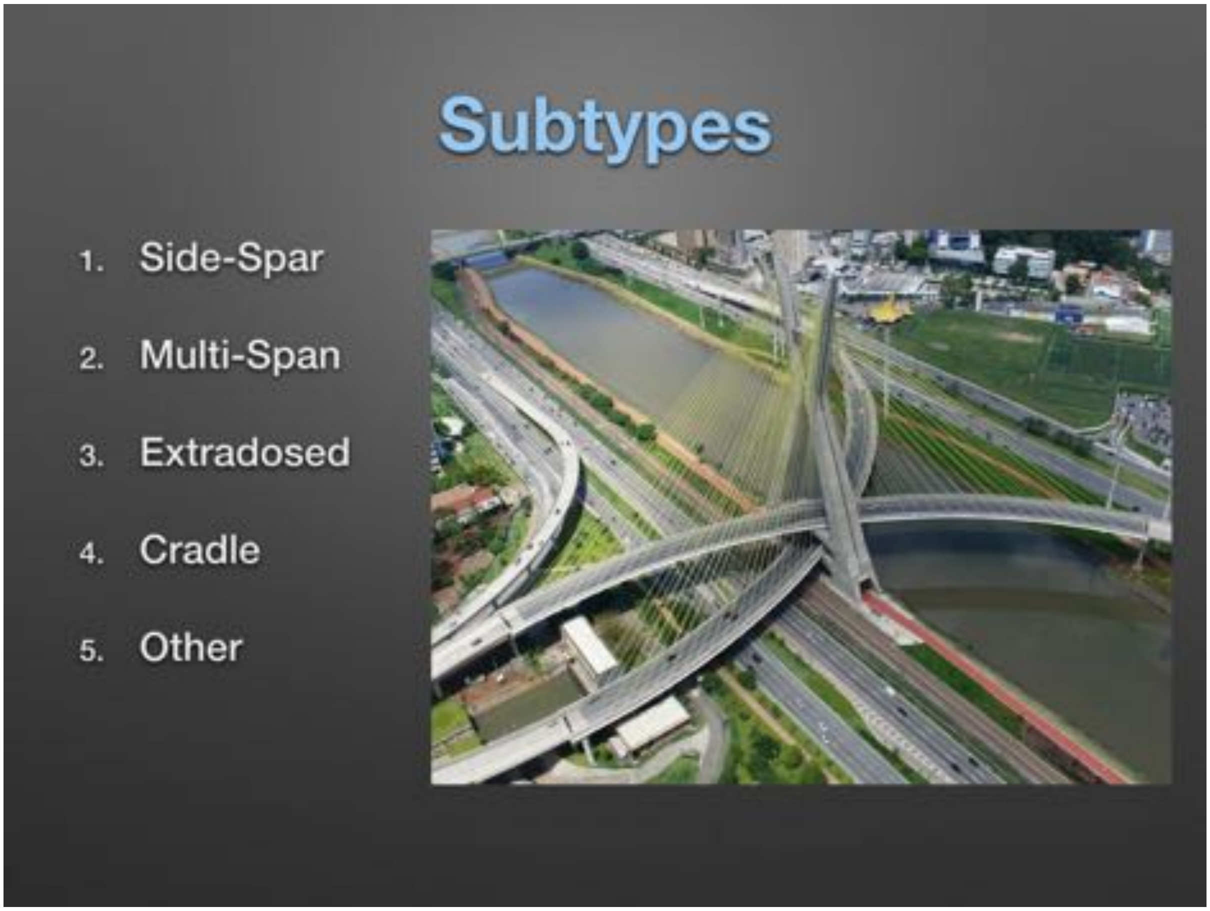
*The combined suspension and cable-stayed elements make the bridge 6x stronger.



Cable Patterns

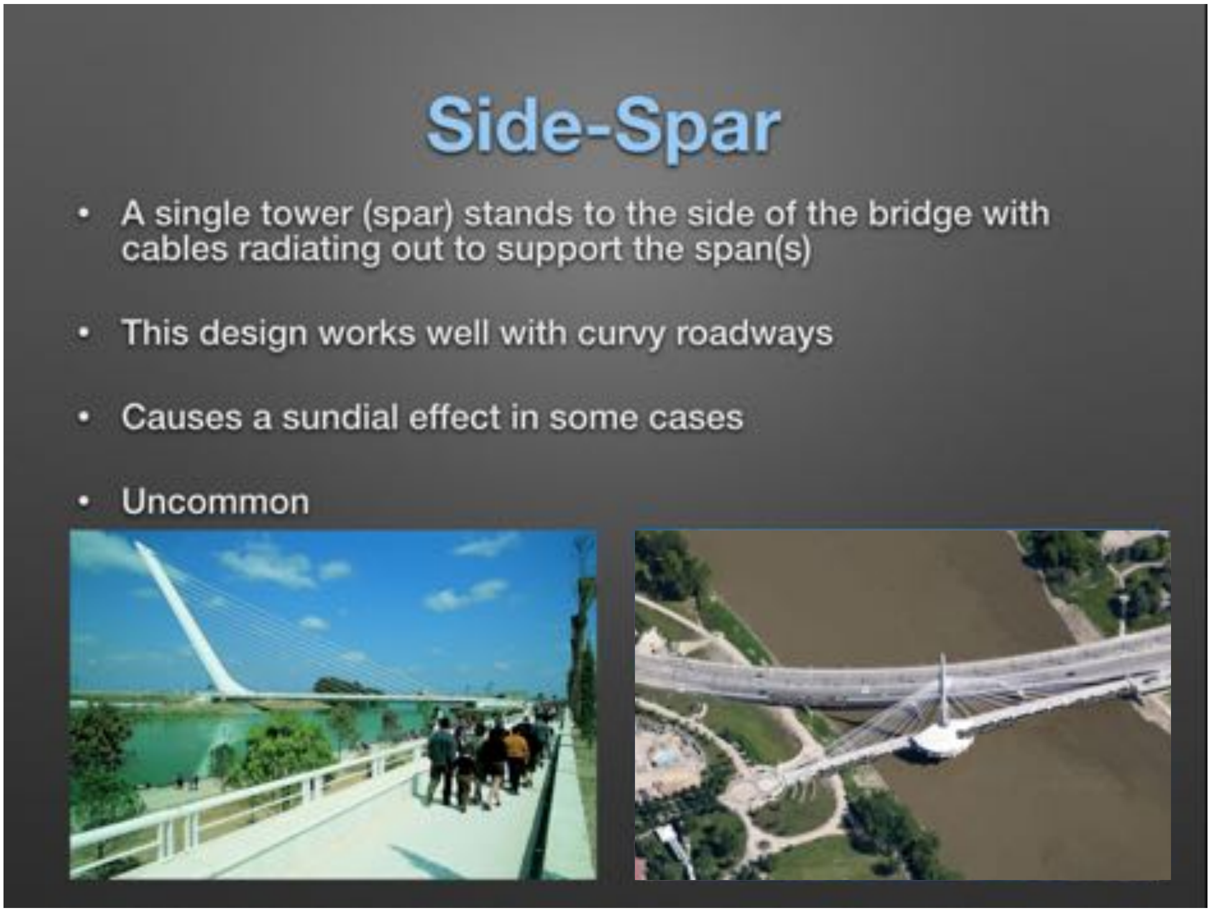
Figure 1 Types of cable stayed bridge

Tower Types



Subtypes

1. Side-Spar
2. Multi-Span
3. Extradosed
4. Cradle
5. Other



Side-Spar

- A single tower (spar) stands to the side of the bridge with cables radiating out to support the span(s)
- This design works well with curvy roadways
- Causes a sundial effect in some cases
- Uncommon

The First Modern Example

The first steel-decked cable-stayed: Franz Dischinger's Strömsund Bridge, Sweden, 1956

Jerusalem Chords Bridge

Jerusalem Chords Bridge

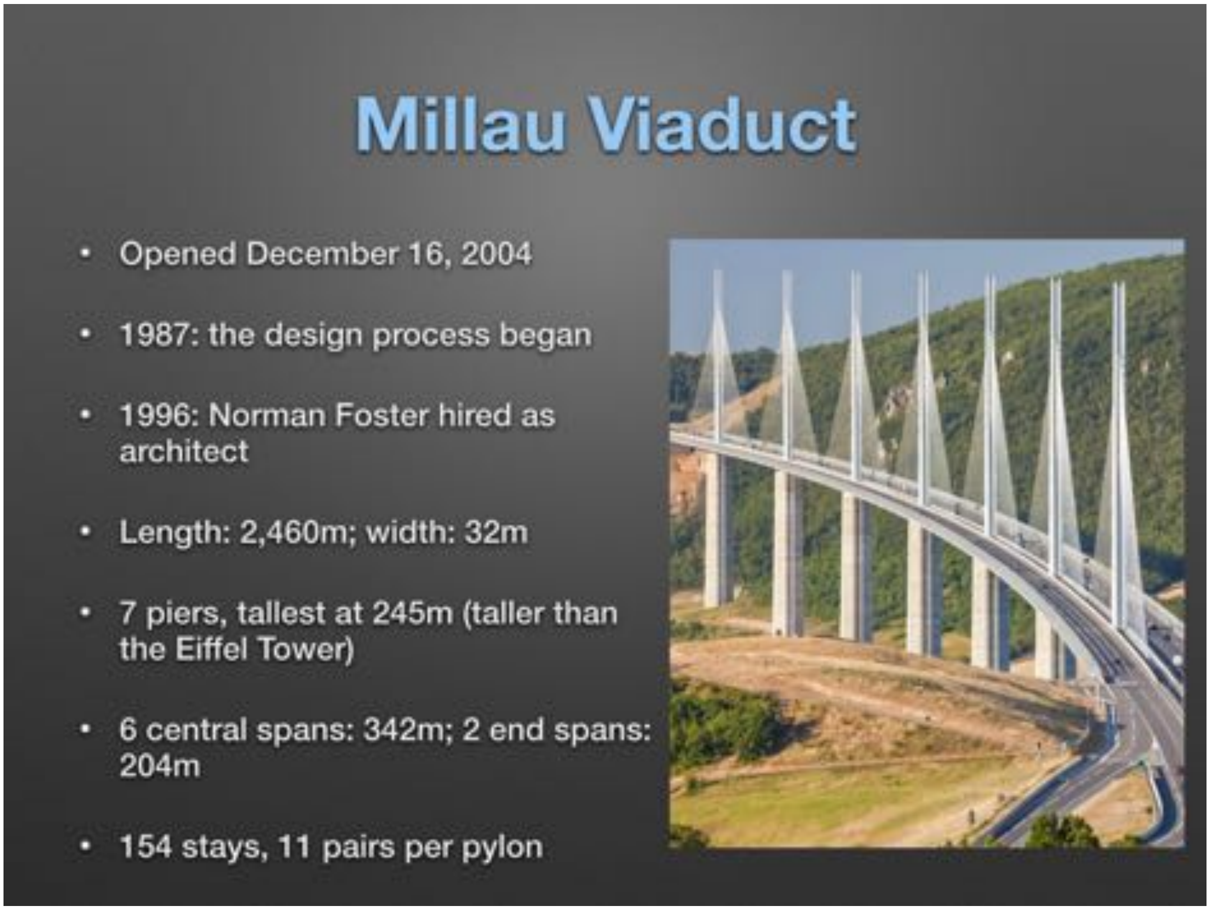
- Opened: June 25, 2008
- Light rail and pedestrians
- Cantilever-spar bridge (with a side spar)
- Architect: Santiago Calatrava
- 160m span, 118m spar, 66 cables
- Exterior: Jerusalem stone, steel, concrete, glass
- "Jerusalem's shrine of modern design" –Time Magazine

Rion-Antirion Bridge

Rion-Antirion Bridge

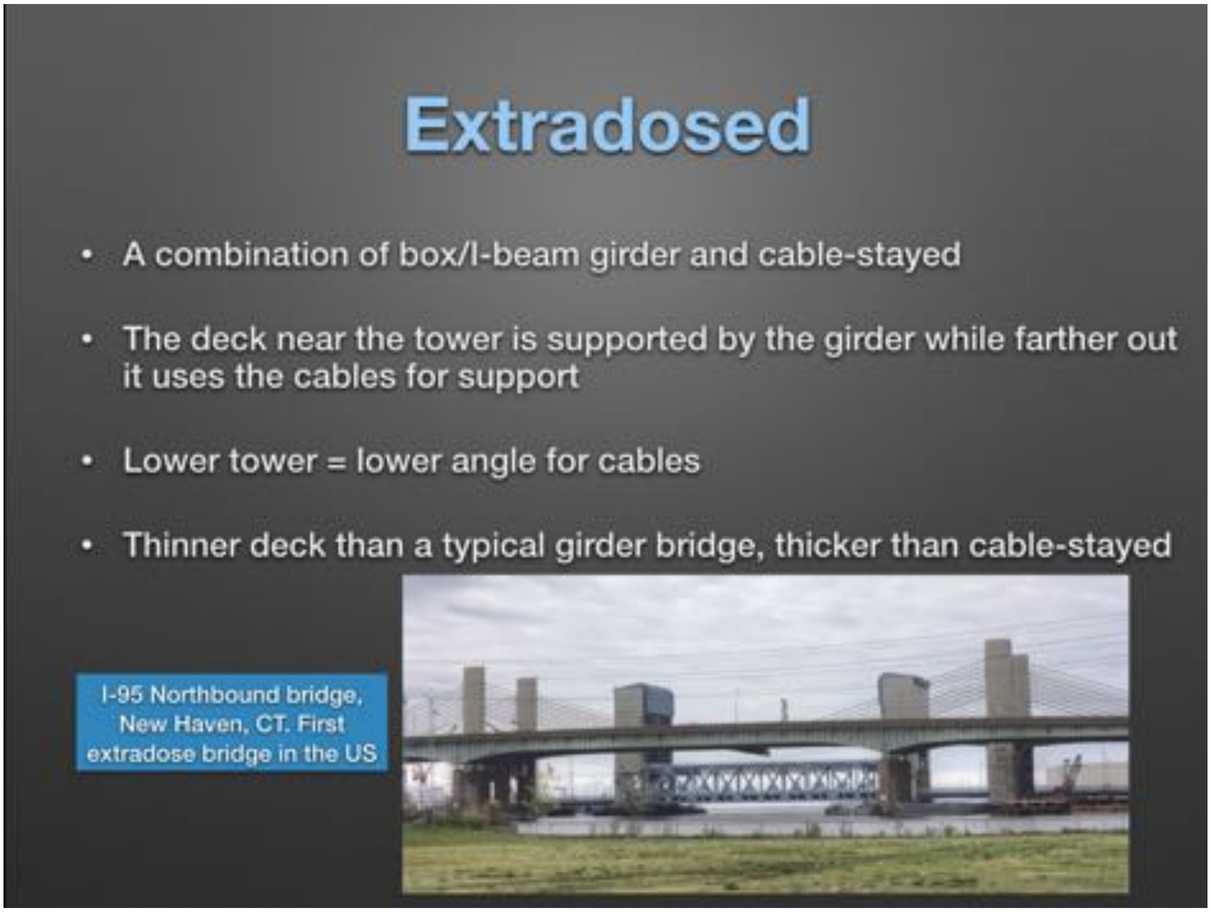
- Gulf of Corinth, connects Greece to Peloponnese, completed 2004
- Longest continuously suspended deck in the world
- Issues: absence of bedrock, high velocity winds, high seismic activity
- 27m wide deck acts as a pendulum to deal with earthquakes
- 5-span deck, constructed with cantilever technique

Millau Viaduct



Millau Viaduct

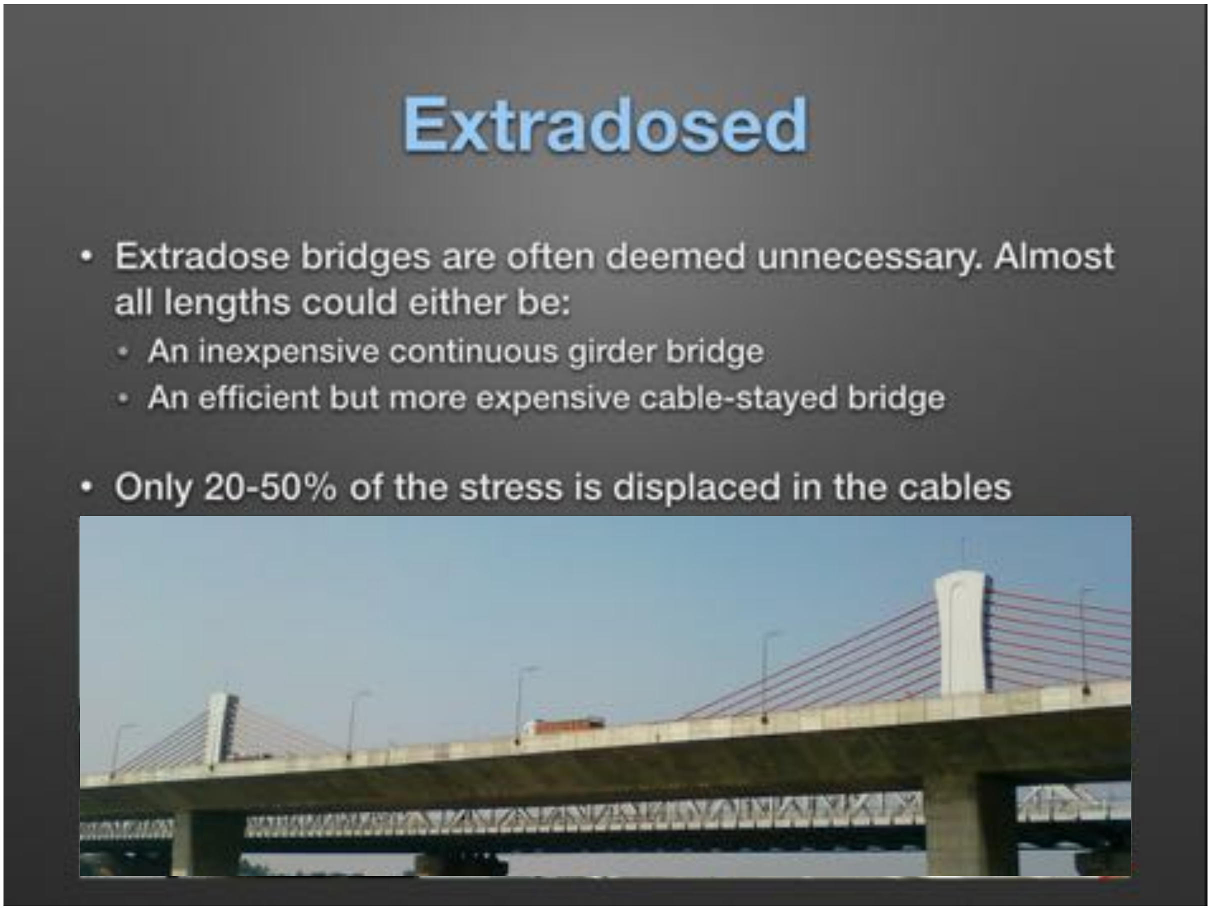
- Opened December 16, 2004
- 1987: the design process began
- 1996: Norman Foster hired as architect
- Length: 2,460m; width: 32m
- 7 piers, tallest at 245m (taller than the Eiffel Tower)
- 6 central spans: 342m; 2 end spans: 204m
- 154 stays, 11 pairs per pylon



Extradosed

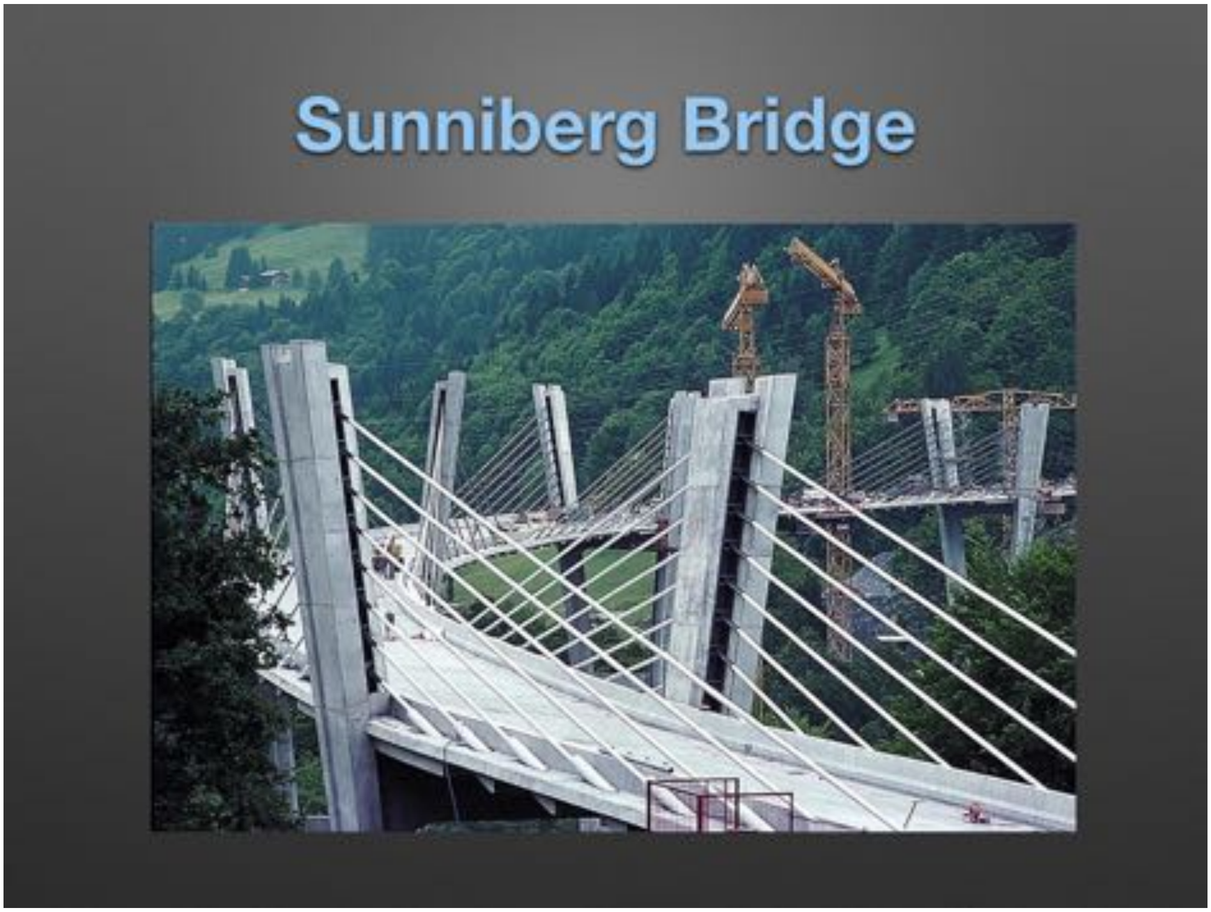
- A combination of box/I-beam girder and cable-stayed
- The deck near the tower is supported by the girder while farther out it uses the cables for support
- Lower tower = lower angle for cables
- Thinner deck than a typical girder bridge, thicker than cable-stayed

I-95 Northbound bridge, New Haven, CT. First extradose bridge in the US



Extradosed

- Extradose bridges are often deemed unnecessary. Almost all lengths could either be:
    - An inexpensive continuous girder bridge
    - An efficient but more expensive cable-stayed bridge
- Only 20-50% of the stress is displaced in the cables



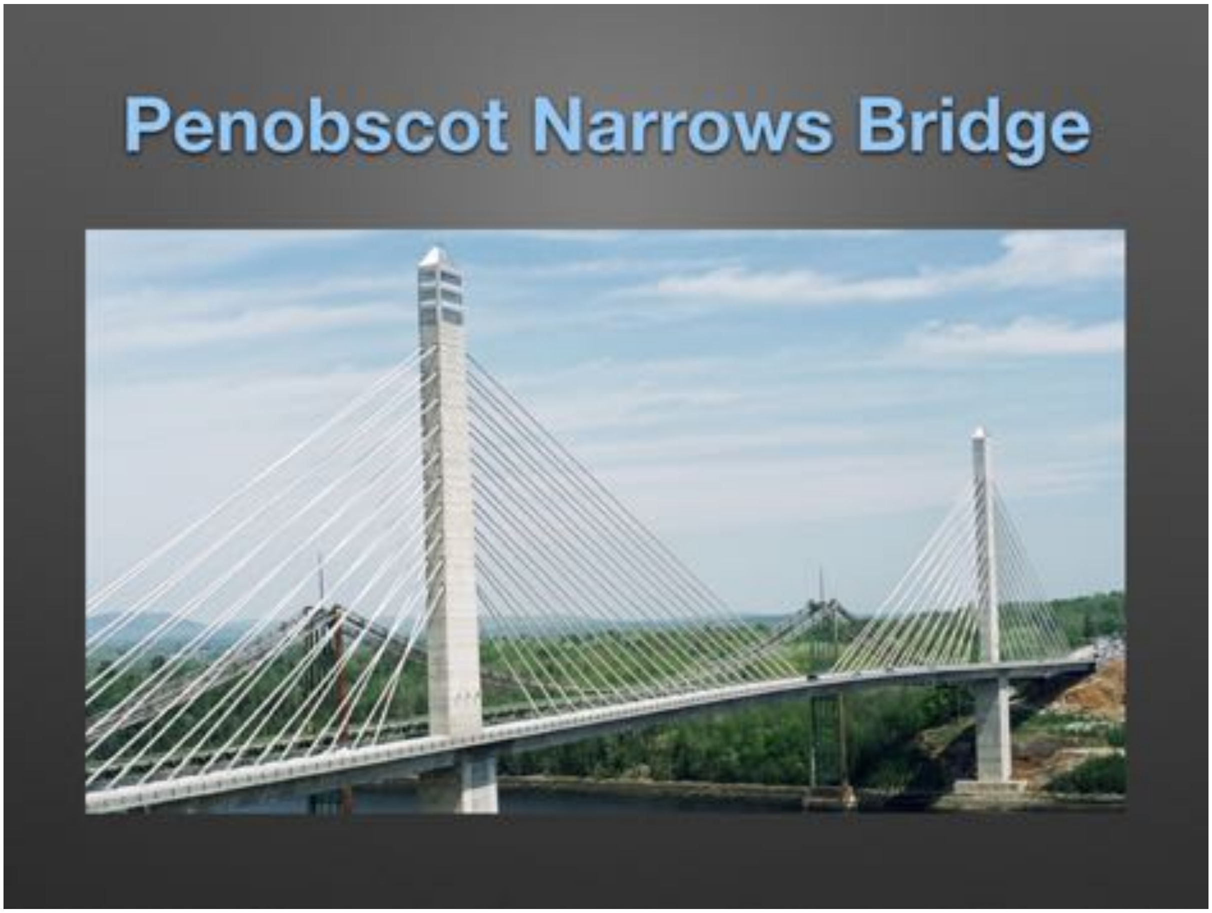
Sunniberg Bridge

Sunniberg Bridge

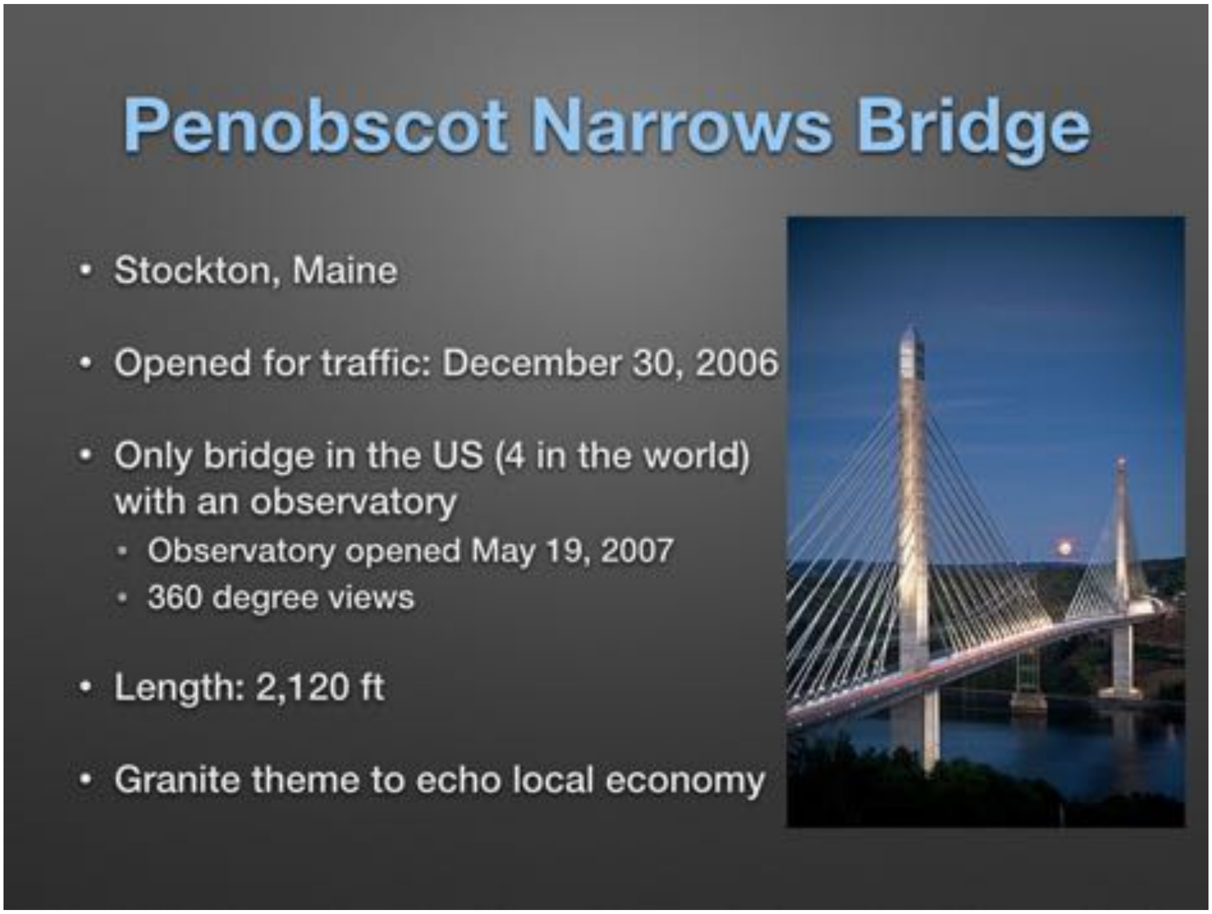
- Klosters, Switzerland, 1998
- IABSE: Outstanding Structure Award (2001)
  - " a delicate expression of structural art responding to a sensitive landscape"
- Length: 26m, width: 12m, pylons: 77m tall
- No expansion joints at the ends to allow the bridge to "breathe" with weather

Cradle System

- Eliminates anchorages in pylon
  - The stay attaches to the deck, go through the tower, and attaches again on the other side to the deck
- Epoxy coated steel strands that are easy to remove and repair
- Easier construction and 100+ year service life
- New type, very few in existence currently



Penobscot Narrows Bridge



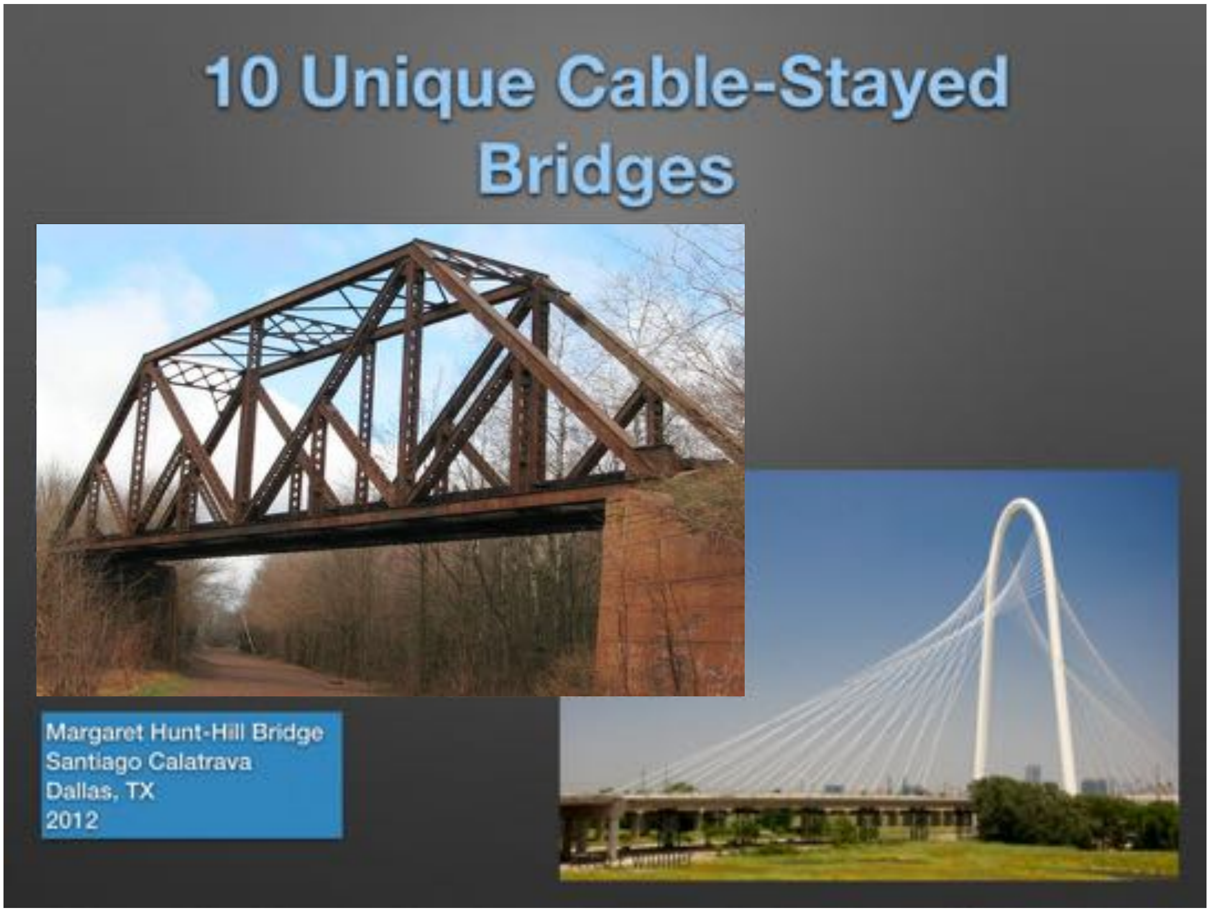
Penobscot Narrows Bridge

- Stockton, Maine
- Opened for traffic: December 30, 2006
- Only bridge in the US (4 in the world) with an observatory
  - Observatory opened May 19, 2007
  - 360 degree views
- Length: 2,120 ft
- Granite theme to echo local economy

Zakim Bridge

Zakim Bridge

- "Bunker Hill Bridge"
- Boston, Massachusetts, crosses the Charles River
- Part of the $15 Billion "Big Dig" project
- 10 lanes, 2 outside the pylons; first unsymmetrical cable-stayed in the US
- Length: 1,432ft, width: 183ft, clearance: 40ft
- Northbound opened March 30, 2003; Southbound opened December 20, 2003



10 Unique Cable-Stayed Bridges

Margaret Hunt-Hill Bridge
Santiago Calatrava
Dallas, TX
2012

Erasmusbrug (Erasmus Bridge), Ben van Berkel, Rotterdam, Netherlands, 1996

Fred Hartman Bridge, Houston, TX, 1995

Russky Bridge, Vladivostok, Russia, 2012

Juscelino Kubitschek Bridge, Alexandre Chan and Mário Vila Verde, Brasilia, DF, Brazil, 2002

Most SNP, Jozef Lacko, Arpád Tesár, Ivan Slamen, and Ladislav Kušnír, Bratislava, Slovakia, 1972

Octavio Frias de Olivera Bridge, João Valente Filho, Sãn Paulo – SP, Brazil, 2008

Zhivopisny Bridge, Moscow, Russia, 2007

Baluarte Bridge, Durango, Mexico, 2008

Puente del Alamillo, Santiago Calatrava, Seville, Spain, 1992

IV. TYPES OF BRIDGES
F. MOVEABLE SPAN

Moveable span bridges are unique in that their design is decided by the best way for both water and road traffic to proceed unimpeded. Moveable spans can vary greatly in design and size, making them the most unique type on this list.

SUBTYPES:

- Swing
- (Vertical) Lift
- Bascule
- Retractable
- Tilt
- Submersible
- Folding
- Rolling
- Transporter

MOVEABLE SPAN BRIDGES

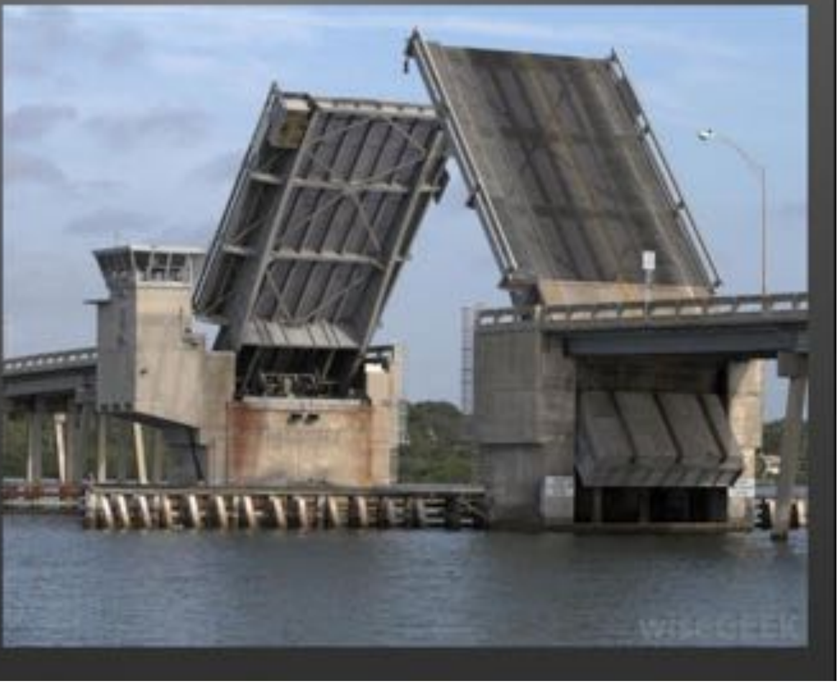
By Cody Chase

Basics

- Best option in cases where high clearance is desired but a limited budget or lack of space makes a long approach with tall piers impossible
  - Spans typically limited to under 500 ft
- Most are either girder or truss designs
- Often operated by bridge-tenders, video cameras or even the watercourse users
- In most cases opening the bridge halts vehicular traffic, US law requires set daily times for bridge opening

Subtypes

1. Swing
2. (Vertical) Lift
3. Bascule
4. Retractable
5. Tilt
6. Submersible
7. Folding
8. Rolling
9. Transporter



Swing

- Moveable span spins on a central pin/pivot (often at 90°) to allow water traffic to pass
  - Most designs include a central pier, but a few have the span pivot from one side
  - Subtypes: center-pivot, rim bearing, shear-pole draw, and jack-knife draw
- Earliest moveable type in America: mainly 1890s-1920s
- Advantages: clear, two-way traffic, moveable span protected by central berm
- Disadvantages: limits water channel space, slow to open

(Vertical) Lift

- Moveable span lifts vertically, while remaining parallel with the deck, to allow boat traffic to pass underneath, usually with the assistance of towers
  - Subtype: table lift- hydraulic lifts push the span up from below
- Originally patented by Squire Whipple in 1872, further developed by J.A.L. Waddell
- Advantages: generally cheaper, counterweights only have to equal the weight of the deck (as opposed to heavier weights for other types) so spans can be longer
- Disadvantage: height restriction

Arthur Kill Vertical Lift Bridge, Elizabethport, NJ and Staten Island, NY, 1959
*longest lift span in the world: 558 ft truss

(Vertical) Lift

Thames River Bridge (Amtrak), New London and Groton, CT, originally a 1919 Warren through truss bascule design, changed to a lift bridge in 2008

Bascule

- Moveable span, or “leaf,” is lifted in an upward swing and balanced by a counterweight, either in a single- or double-leaf design
  - Subtypes: simple trunnion (Milwaukee, Chicago), multiple trunnion (Strauss), rolling lift (Sherzer), Rall rolling lift
- “Bascule”: French for seesaw
- Advantages: opens quickly, relatively little energy is used
- Disadvantages: larger counterweights are needed to balance the lifted span

Simple trunnion

Multiple trunnion

Bascule

Pegasus Bridge, Caen and Ouisteham, France, original design in 1944, changed to rolling bridge in 1994
*Theodor Rall patented the design in 1901, no hinge point means greater clearance

Retractable

- Moveable span is rolled or slid back to the side span in order to create a gap for water traffic
- also known as a “thrust” bridge
- Advantage: one of the best designs in regards to vertical clearance
- Disadvantage: requires a lot of flat horizontal space

Carroll Street Bridge, Brooklyn, NY 1889

Tilt

- A curved moveable span tilts on fixed points using hydraulic lifts
- Rare design reserved mainly for pedestrian bridges

Gateshead Millenium Bridge, UK, 2001

*Also a Suspended Deck Arch Bridge

Submersible

- Moveable span is lowered below the water level so water traffic can pass above
- Advantages: no height limit (especially for sailboats), aesthetically pleasing
- Disadvantage: depth restriction

Corinth Canal Bridge, Greece, 1988
*Two submersible bridges designed for the canal, each sinking 26 ft below water level

Folding

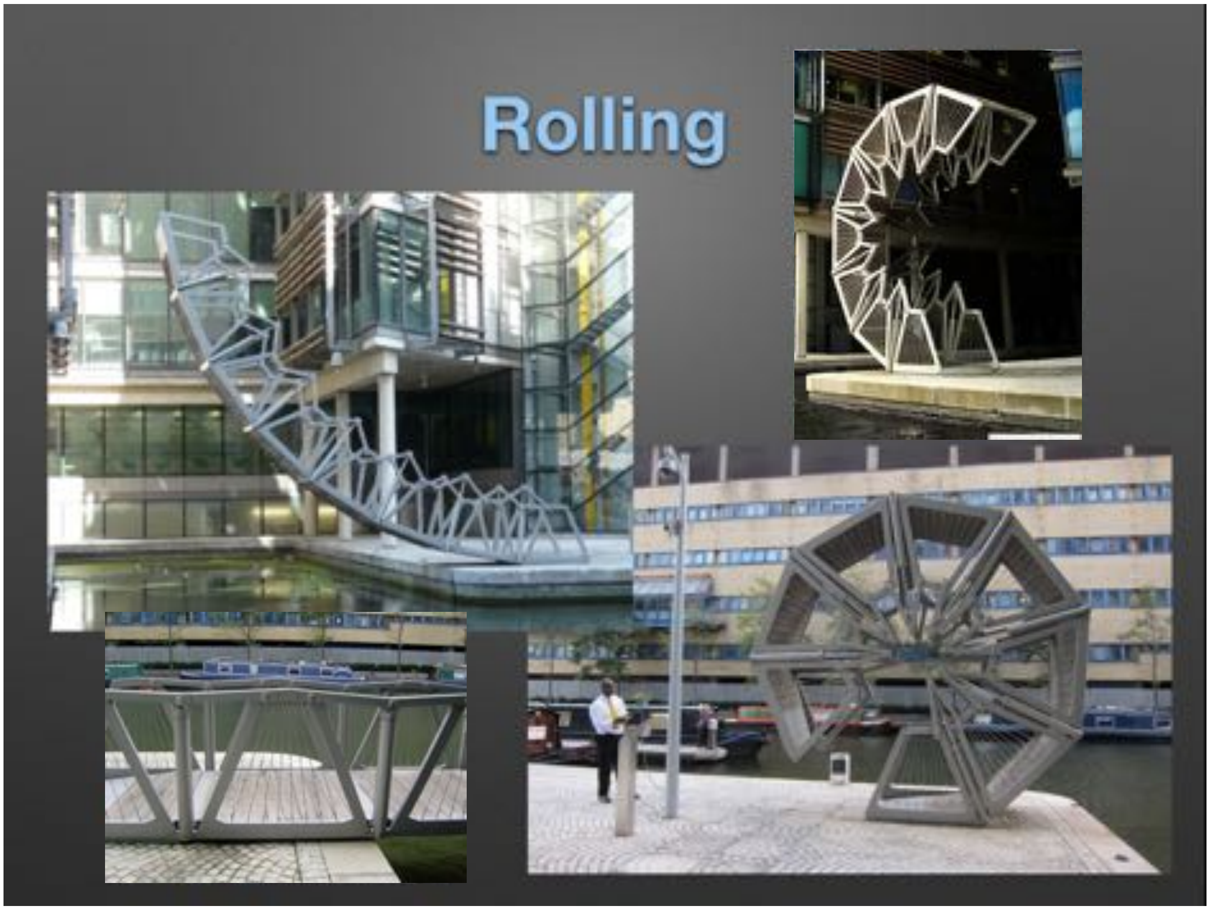
- Movable span folds to one side, allowing a gap for passing water traffic

Hörn Bridge, Kiel, Germany, 1997

19: A last minute change

Golden Gate Bridge
*Note the cables that meet the deck at the top as is the usual

George Washington Bridge
*Fun Fact: Originally the towers were to be clad in stone but they ran out of money. The basic structural design was deemed aesthetically pleasing in itself and remains today



Rolling

Transporter

- Movable span exists as a gondola, a steel frame cart on steel cables that carries vehicles across the gap
  - Inverse of the other types where the vehicles usually have the natural right of way

Newport Transporter Bridge, Wales, UK, 1906

V. FAILURES

This section speaks to the importance of historical knowledge so mistakes do not repeat themselves. The sheer size of these iconic structures often blind designers to the reality of modern structural limitations, before, during and after construction. These are the four main reasons for failure:

- Misuse of materials
- Poor construction methods
- Impossible designs
- Post-construction mishaps

Tacoma Narrows Bridge collapse, Puget Sound, Washington, 1940.

The reasons for bridge failure have not changed much since the time of antiquity. The issue lies in the constant desire for new materials and building techniques, which must be balanced with studies in physics and aerodynamics. Pushing the limits of design wins contests but it also blinds builders to small issues that may later become much larger ones. Through the breakdown of the process, however, there seem to be four main areas of neglect that tend to lead to the big failures. There is the misunderstanding of materials, their own weight and capabilities in tensile and compressive stress; bad construction methods where temporary and unfinished structures are not properly used; cases with lofty designs that are not executed properly, or just impossible to begin with; and the basic usage issues: insufficient maintenance, misuse, and extreme weather.

Materials are constantly changing and evolving, even today there is experimentation to create stronger steel, more environmentally-friendly concrete, and wood serums to resist rotting. It was no different in antiquity. Although their structures were not as long as some today, their feats are to be commended considering their limited technology. Today there are many ancient Roman structures that still stand, some of which are bridges and viaducts. But the truth is that most of Rome's bridges were timber, despite today's evidence of stone and concrete constructions. The fact of the matter is that it is better to use a material suited to the needs of the bridge, rather than something "iconic," because every material has strengths and weaknesses.

Two cautionary tales are that of timber and iron in the mid-1800s. Both materials have their merits and yet neither proved to be too successful in railroad infrastructure. American railroads were expanding and owners only needed a few hundred miles of track across the countryside to make a considerable profit. No one wanted to spend the money on expensive tubular iron truss or iron arch bridges, timber and iron truss hybrids were just enough for lightweight rail. By the 1850s, however, trains were becoming heavier and yet no one felt the need to update the bridges accordingly. This caused the famous bridge disaster of Ashtabula, Ohio in 1876.

The Lake Shore and Southern Michigan Railroad needed a bridge to span the 700-foot wide gorge of the Ashtabula, so they built up the embankments and spanned a 150-foot Howe truss in the space. In an awful storm on December 29 the Pacific Express was crossing the bridge when the driver felt a huge shudder and then a grinding sound, which later turned out to be his wheels on the stone abutment. The rest of the train, eleven cars, had crashed into the river on top of each other and immediately set aflame. Ninety people were crushed to death and the few survivors had to wait for help in the middle of the freezing river amidst the burning train cars. The span had completely broken off and fallen into the river. The blame was placed on the designer and the fact that little was known about the tensile strength of cast and wrought iron.[2]

The news was devastating and public outrage over the safety of bridges was raised. The decade had been filled with an average of forty bridge failures per year, most of which were smaller timber bridges with few fatalities. In the ten years following this disaster, however, there were two hundred bridge collapses. This marked the end of iron bridges in the United States, urged reforms in bridge safety, and instated mandatory inspections by the American Society of Civil Engineers.[3]

The time that the bridge is under construction is the most dangerous time for error. Temporary supports used without stress tests, human error, and neglect of procedure run rampant, and often the unfinished bridge is used too soon as a construction platform. The year of 1998 was a big bridge construction year and as a result, almost every month there was some kind of accident, sometimes with fatalities.[4] In Japan, the $8.8 billion bridge crossing the Kurushima River had an accident when lowering a fifty-ton temporary platform. Three cables snapped, tipping the surface

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[2] David Bennett, *The Creation of Bridges: From Vision to Reality: The Ultimate Challenge of Architecture, Design, and Distance,* (Edison, N.J.: Chartwell Books, 1999), 158-60.

[3] *Ibid*.

[4] *Ibid*, 153.

enough to cause seven workers to fall two hundred feet to their deaths.[5] In the same year, the construction of the Injaka Bridge in South Africa experienced a collapse of two 88-foot spans, killing fourteen workers and visitors and injuring more. The designer, a twenty-seven-year-old with great promise, was among the fatalities.[6] A third disaster occurred in West Virginia when a temporary bridge fell during demolition, causing one death.[7] All of these cases prove that all over the world construction is made into a much more dangerous venture than it should be, especially in places where supervision and inspection are disregarded. While there are numerous tests to create a safe product for the public, the intermediary platforms are given less attention and therefore place workers at a higher risk throughout the course of construction.

Almost two years to the day after the Ashtabula Bridge disaster was the Tay Bridge collapse in Dundee, Scotland. The bridge was the longest in the world, a series of wrought iron lattice girders with some raised spans for higher clearance. Queen Victoria made a special visit to the bridge to meet the designer, Thomas Bouch, and later even knighted him alongside Henry Bessemer, the inventor of steel. The bridge had no new or interesting design techniques; it was a simple and elegant design that performed admirably. That is, until December 28, 1878, when a train attempted to pass the bridge in a snowstorm, only to disappear in the middle and land in icy waters. There were seventy-five deaths and no survivors. (Only forty-six bodies were ever found.) In response, front page headlines across Britain stated the “bridge was doon.” There were two main opinions for the failure, one being that the inspector tasked with filling the “Beaumont Eggs” was incompetent. It was his job to find and fill the holes in the cast iron with beeswax and iron filings. If he had done a better job perhaps the riveting would have been stronger. Another reason is that Bouch only designed for 20 pounds per square foot, compared to the American standard of 50 pounds per square foot. Had there been more stress tests during construction then perhaps the bridge would have been better equipped and braced for such wind conditions.[8]

Another famous bridge disaster with a devastating construction failure is the Quebec Bridge in Canada in 1907. With the turn of the century came a new material, steel. The confidence in its abilities inspired greater and more daring designs. Designer Theodore Cooper envisioned the cantilever truss steel bridge but was advised to be sparing in tonnage for the sake of price. This was the first strike. The second was that the chief engineer started to notice a deflection in the south cantilever and telegrams to

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[5] *Ibid*, 155.

[6] *Ibid*, 156.

[7] *Ibid*.

[8] *Ibid*, 160-164.

the designer went unanswered. The chief engineer called off construction and left town to speak to Cooper, leaving the contractor who called for work to continue, the third strike. On August 29, 1907 a crane was placed out onto the noticeably deflecting cantilever. With a loud sound of the tearing of metal, 19,000 tons of steel went into the river, killing 75 workers. Blame was placed on the weak trusses, poor attention to riveting, and lack of knowledge of the material. It has been recorded as the biggest bridge disaster in history, and mainly due to a lack of attention during construction.[9]

The preservation of funds is a very real issue in bridge design. From the 1950s to late 1970s a certain type of design called “fracture critical” bridges became very popular. The major flaw of these bridges was that if one major design component breaks then the whole bridge can fail. The design eliminates structural redundancy, which is a frivolous expenditure to some eyes. These bridges are still designed today, but mainly reserved for smaller highway bridges. This form of cheap and quick construction does not bode well for accidents and certainly not for the long term.[10]

Another element to bridge failure is the desire to create the next award-winning and iconic bridge. In the words of David Bennett,

> It has become increasingly clear that over the centuries as stronger materials are developed and new construction technologies evolve that the limiting factors are not technological nor economic restraints, but the human ability to effectively communicate with one another and to decide on priorities.[11]

It is true that today’s challenges are not so much material in nature but in the design process and communication of knowledge.

The 1849 Wheeling Bridge over the Ohio River in Ohio was the longest bridge in the world when it was built, a suspension bridge with a 1,000-foot span. The designer Charles Ellet was experienced but also ambitious, causing him to underestimate the effects of wind. So when a storm hit in mid-afternoon on May 17, 1854 people evacuated the approaches of the bridge for the usual light undulating movements were turning into a wildly bouncing and twisting deck. The bridge was designed to handle its own weight and the broad force of the wind but not the vibration in the suspenders and cables. It broke and splashed into the water. It was this event that caused John

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[9] *Ibid*, 164-167.

[10] CBS News, “Thousands of U.S. bridges vulnerable to collapse,” last modified May 25, 2013, http://www.cbsnews.com/news/thousands-of-us-bridges-vulnerable-to-collapse/.

[11] Bennett, 170.

Roebling to cleverly design diagonal stays in addition to suspenders for the Brooklyn Bridge, ensuring stability and strength.[12]

History, however, is doomed to repeat itself. The tale of the Wheeling Bridge was forgotten and nearly one hundred years later a similar event occurred over the Puget Sound in Washington. It is perhaps the most famous bridge collapse of our time, the Tacoma Narrows Bridge. At the time of construction the Golden Gate and Oakland Bay Bridges had just been completed and the style in the United States was sleek and beautiful suspension bridges. It opened July 1, 1940 and featured a 2,800-foot span. The bridge was a success: the tolls brought in more than expected and the bridge acquired the loving name of “Galloping Gertie” due to the slight undulations that were common in breezy weather. While driving on the bridge it could happen that a car down the road would disappear for a moment due to the galloping action. One day, four months after its opening, the bridge was really moving in the forty-four mph winds and the bridge was emptied. Suspenders broke, dropping a 600-ft section of deck into the water, before the rest broke off and followed suit. The event was captured on film, a fascinating and unbelievable sight to see. Leon Moiseff, whose resume included the Manhattan Bridge and the Golden Gate, was the designer. He was respected and knowledgeable and yet so taken with new design that he neglected the lessons of the past. The same undulations had occurred with the Wheeling Bridge and yet no connections were drawn. The materials, construction techniques, design and date may be different but the effects of wind on an inadequately stiffened span are the same, and the signs should have been recognized. In order for future bridges to be successful, modern day bridge designers must look to the past for the mistakes to avoid. Luckily, the lesson was learned in time to save other bridges — deck stiffening trusses were added to the Golden Gate and Bronx Whitestone Bridges.[13]

The final cause for bridge failure is what happens to the bridge after it has been completed. Not all of the weight falls onto the shoulders of the creators; a fair amount must be accorded to the users and maintainers. If a bridge was developed for horse-drawn carriages and cows then it may not hold up against the eighteen-wheeler trucks of today. Painting to counteract rust, car accidents involving the structure, and weather damage must be tended to. Some things like earthquakes,[14] hurricanes and tornadoes are very difficult to combat but current research practices are working towards better solutions.

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[12] *Ibid*, 157.

[13] *Ibid*, 168-169.

[14] *Ibid*, 173.

When the Ashtabula Bridge disaster occurred there was a big public response, the magazines *Iron Age* stated: “We know there are plenty of cheap, badly built bridges, which engineers are watching with anxious fears, and which, to all appearances, only stand by the grace of God!”[15] That was in 1876, but similar concerns exist today. Many bridges were built for Eisenhower’s Interstate Highway System starting in 1956, and have since been long neglected. Few see the importance since failures are not as common as they used to be, but this issue could become a regular problem again soon.

In the United States there is a sufficiency rating system on a scale of 100. If a bridge scores under 80 it should be given federal funds to repair, while a score under 50 should allow for the replacement of the bridge. Today some active bridges around the country have a single-digit score and yet continue to be neglected. The phrase “functionally obsolete” refers to the bridges that were designed to codes that are no longer up to par, and last year the Federal Highway Administration counted 84,748 bridges in the United States and Puerto Rico that were functionally obsolete, with 66,749 that were structurally deficient. Combined this number is one quarter of the country’s 607,000 bridges. While discussion has been raised on higher tolls and a tax on gas, nothing has been done to address this issue.[16] If left unchecked, the small funds that cannot be spared to fix old bridges will become large funds needed to build new bridges.

Bridges are a necessity in daily life and yet seem to be often neglected in the big scheme of things. They are not a square building on solid ground devised for shelter; bridges are, by necessity, precariously placed structures that are highly susceptible to extreme weather and tasked with the job of carrying extremely heavy loads all the time. People often forget the vulnerability due to size, but on a larger scale the same issues exist. If we wish to keep our bridges in the air we must understand and respect the maintenance required of us as the users of these engineering marvels.

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[15] *Ibid*, 159.

[16] CBS News.

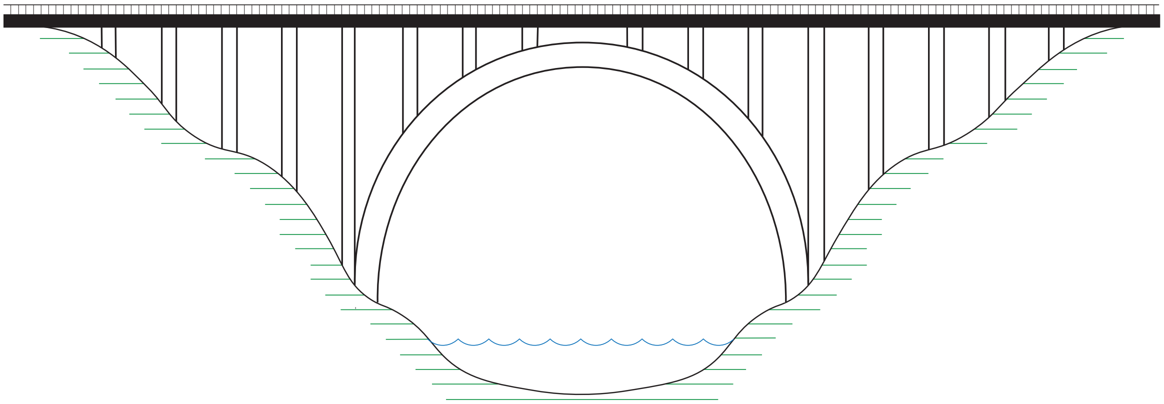
VI. ILLUSTRATOR MODELS

- Arch, True/Round
- Arch, Segmental
- Beam/Stringer/Girder, Reinforced Concrete Girder
- Beam/Stringer/Girder, Reinforced Concrete Rigid Frame
- Cable-Stayed, Fan Style Cables
- Cable-Stayed, Harp Style Cables
- Suspension
- Truss, Howe
- Truss, Burr
- Truss, Bowstring
- Truss, Lenticular

TYPE: ARCH

Subtype: True/Round

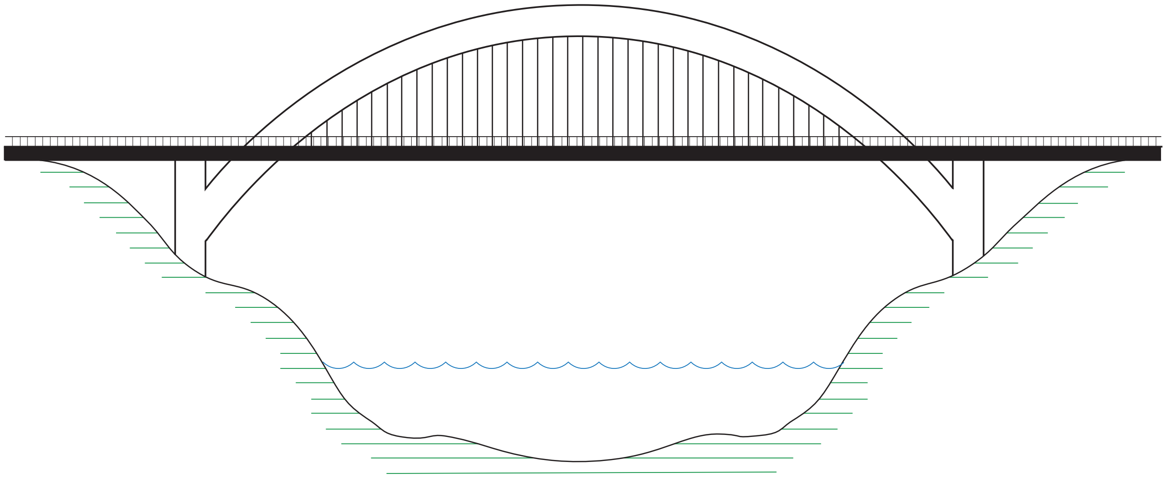
Other Classifications: Deck Bridge, Open Spandrels



TYPE: ARCH

Subtype: Segmental

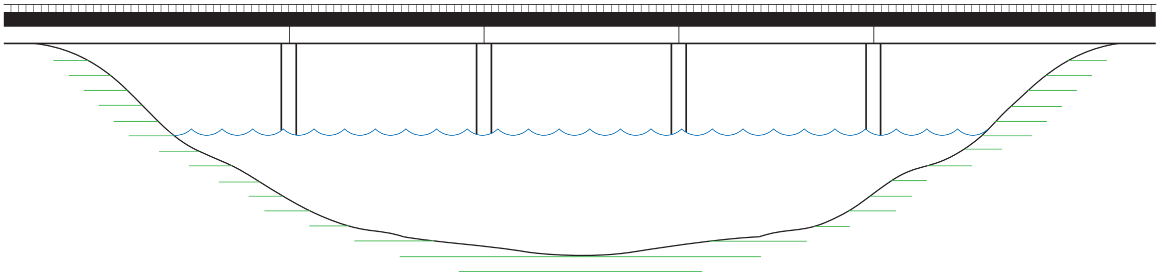
Other Classifications: Through Bridge



TYPE: Beam/Stringer/Girder

Subtype: Reinforced Concrete Girder

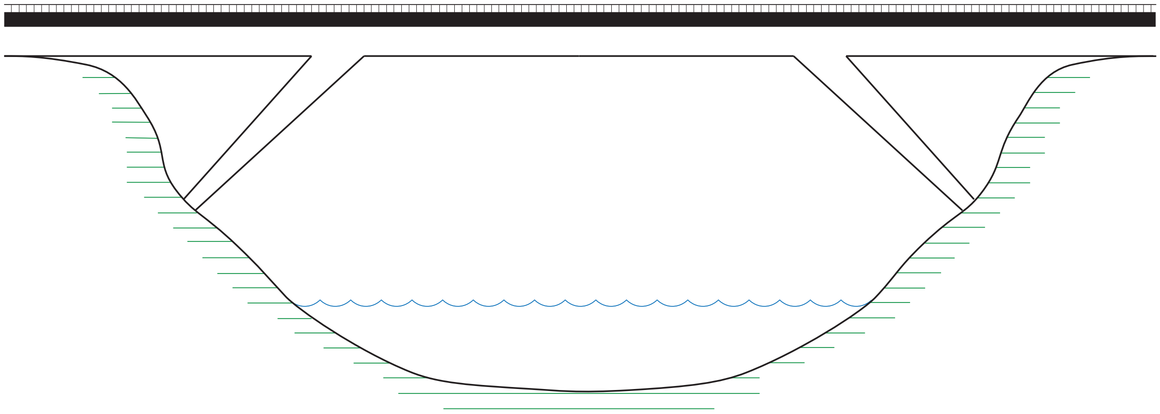
Other Classifications: N/A



TYPE: Beam/Stringer/Girder

Subtype: Reinforced Concrete Rigid Frame

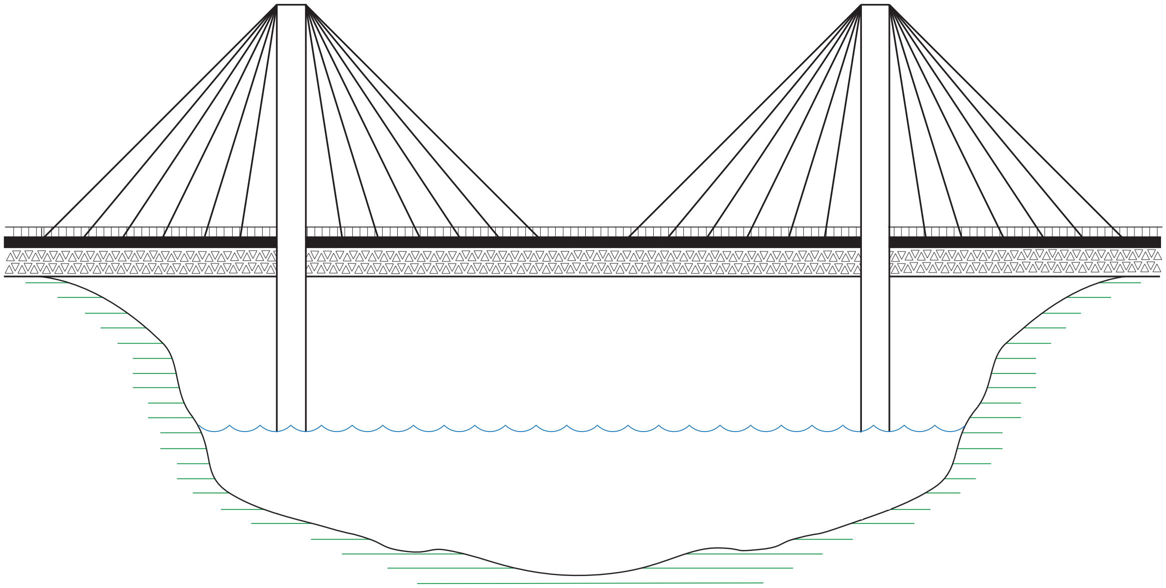
Other Classifications: N/A



TYPE: Cable-Stayed

Subtype: Fan Style Cables

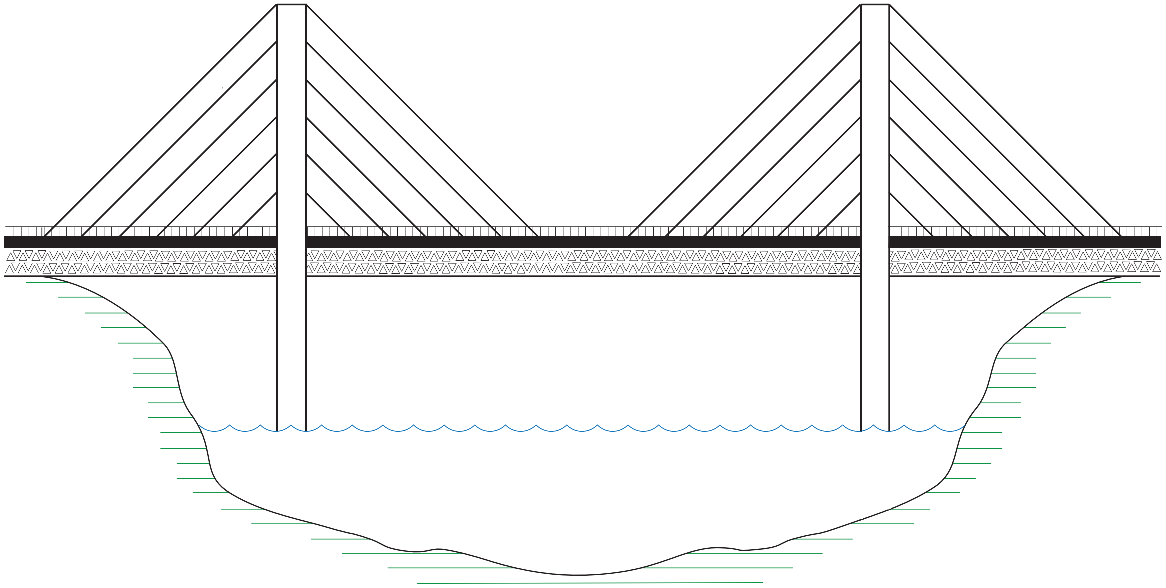
Other Classifications: Truss-Stiffened Deck



TYPE: Cable-Stayed

Subtype: Harp Style Cables

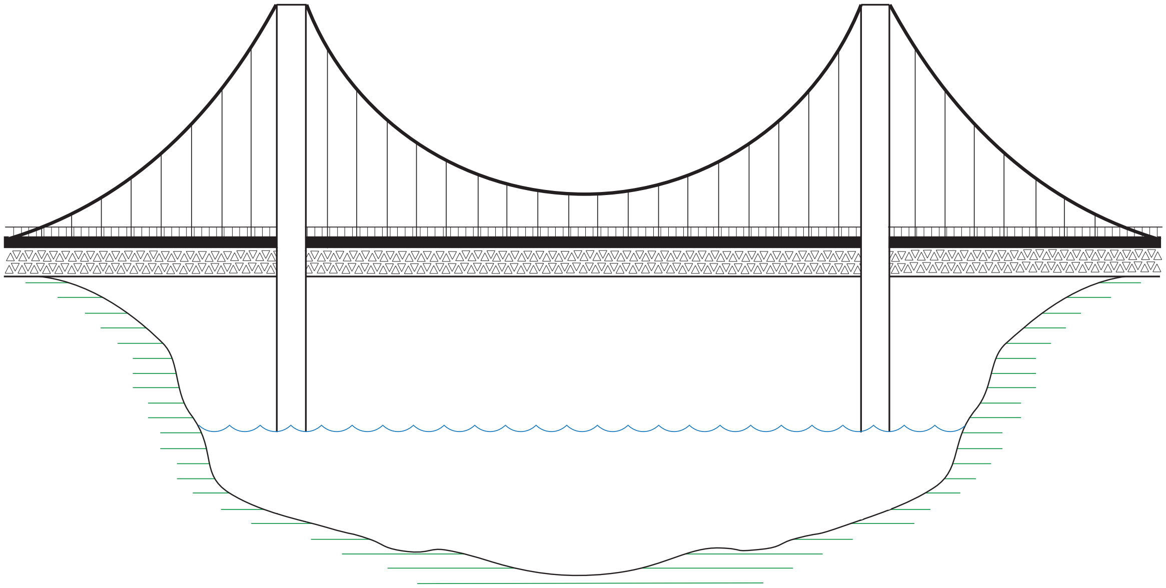
Other Classifications: Truss-Stiffened Deck



TYPE: Suspension

Subtype: N/A

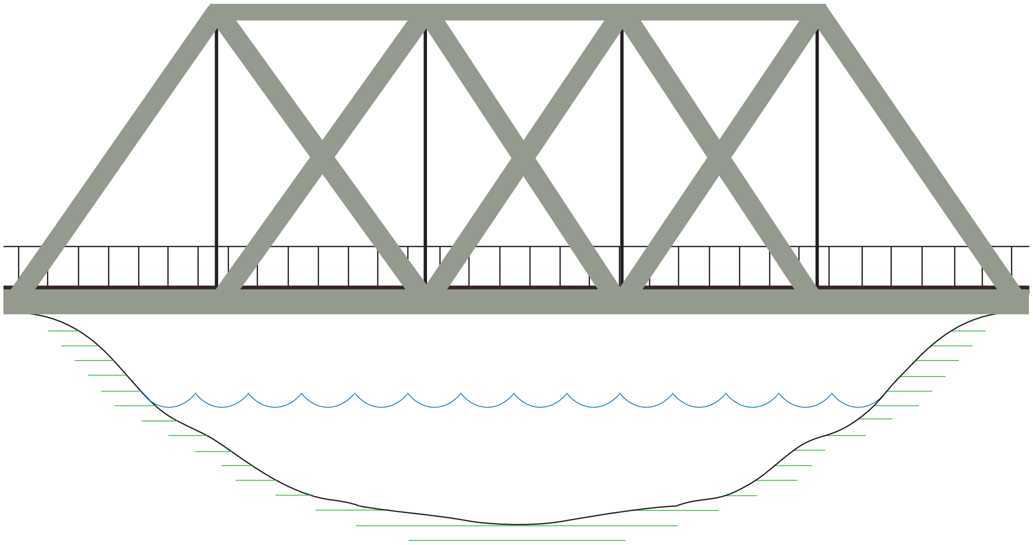
Other Classifications: Truss-Stiffened Deck



TYPE: Truss

Subtype: Howe

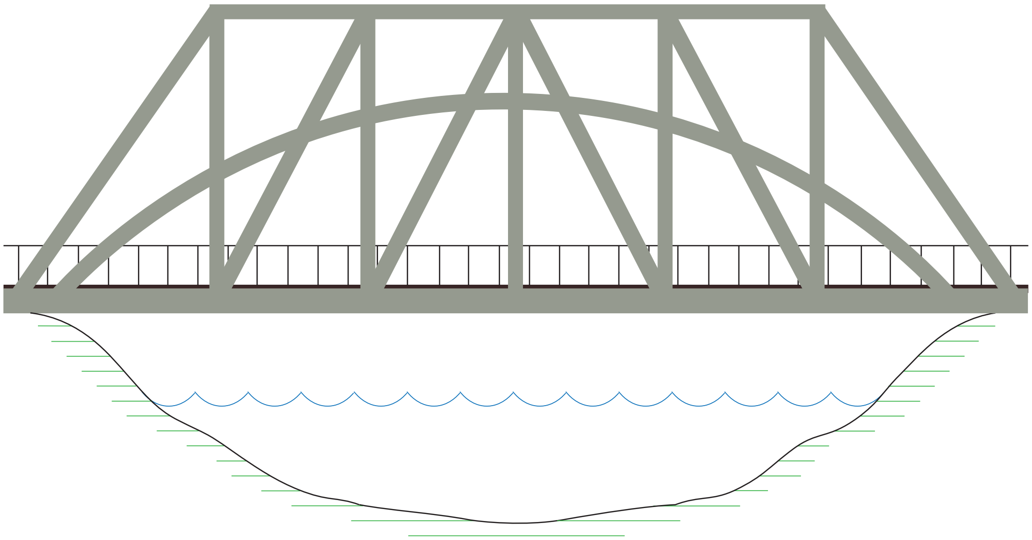
Other Classifications: Through Bridge



TYPE: Truss

Subtype: Burr

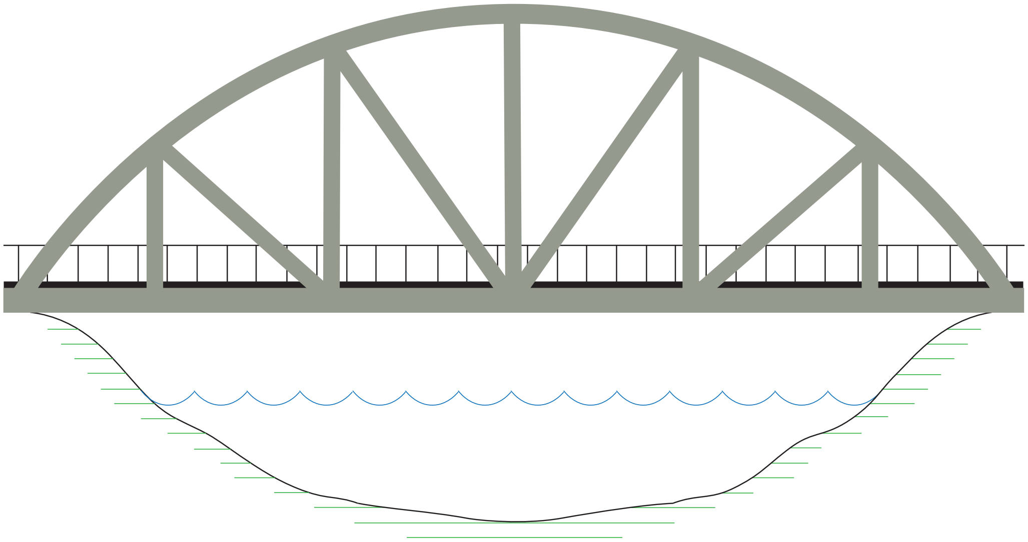
Other Classifications: Through Bridge



TYPE: Truss

Subtype: Bowstring

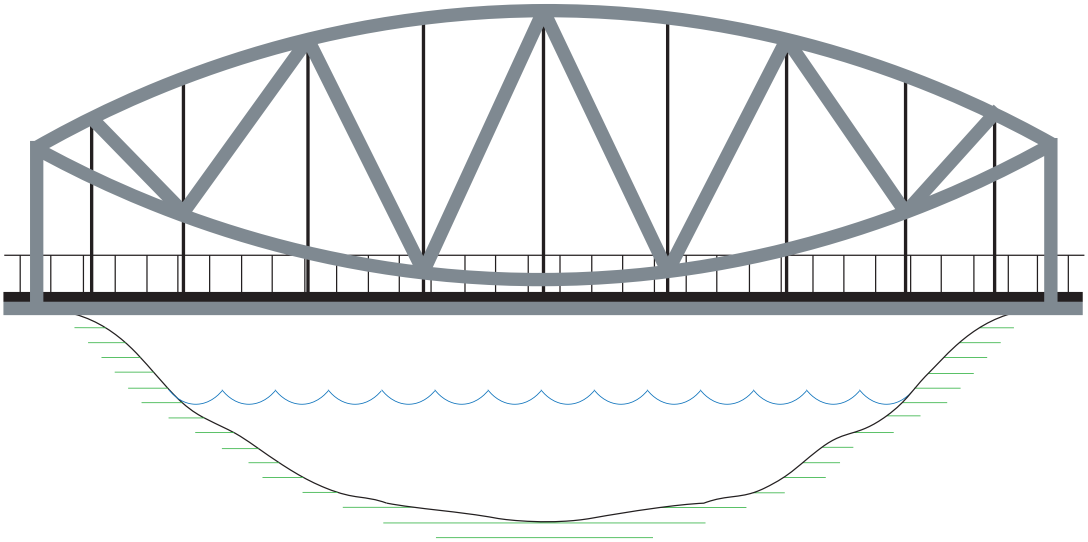
Other Classifications: Through Bridge



TYPE: Truss

Subtype: Lenticular

Other Classifications: Through Bridge



VII. CONCLUSIONS

Bridges are extremely important in modern civilization and yet many people continue to disregard their presence. Unlike a building, a bridge is a purely practical piece of structure that is designed to span an open space largely unsupported. If it is designed correctly then it provides a convenient link between landmasses, municipalities and people. In the world today, however, bridges have not garnered the attention of the architecture world. Compared to buildings, bridges are on such a large scale it becomes difficult to establish and appreciate a specific ornamental style. But they deserve a place in the architecture community and should be viewed as a new kind of language to be learned. Modern technology has brought bridge design past the point of challenging structural stability and into an era ready for unique creations.

The basic principle attributed to the beautiful bridges of the world is simple: if all of the structural elements are equally necessary and technically appropriate then the bridge will rise as a perfect form dedicated to balance and grace. An over-structured bridge will seem clunky and heavy while an under-structured bridge will feel unsafe for use. The engineering world has mastered the structural balance but creative designs are vital for the future of worldly iconic bridges.

This study presents the modern materials, the main types and a brief history of failures as a invitation to challenge what has already been created. Architects like Santiago Calatrava have already ventured into this field and the final products are clearly stamped with the influence of architecture. By fusing modern engineering, technology, materials and architecture they could enter a new phase of creation. The bridges of the world deserve appreciation by all for their technical beauty, it is time for a resurgence in the excitement that begun this great history of challenging the obstacles between nature and civilization.

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