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GeoVenturing-LNT
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Understanding INTERdependence using Failure Mode and Effects Analysis (FMEA):

The effects of these pollutants may be immediate or delayed. Primary effects of pollution occur immediately after contamination occurs, such as the death of marine plants and wildlife after an oil spill at sea.

- ***Secondary effects may be delayed or may persist in the environment into the future, perhaps going unnoticed for many years. DDT, a nondegradable compound, seldom poisons birds immediately, but gradually accumulates in their bodies. Birds with high concentrations of this pesticide lay thin-shelled eggs that fail to hatch or produce deformed offspring.***
- ***These secondary effects, publicized by Rachel Carson in her 1962 book, Silent Spring, threatened the survival of species such as the bald eagle and peregrine falcon, and aroused public concern over the hidden effects of nondegradable chemical compounds.***

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TYPES OF POLLUTION

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Air Pollution

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Web Links

EPA: US Environmental Protection Agency
The Environmental Protection Agency home page contains its rules and regulations, recent press releases, and information about its testing methods and programs.
http://www.epa.gov/

Noise Pollution Clearinghouse
The Noise Pollution Clearinghouse, a national nonprofit organization, offers news and information about noise control.
http://www.nonoise.org/

Chemical Scorecard
The Environmental Defense Fund provides searchable chemical pollutants information, including a tool that locates community polluters by zip code.
http://www.scorecard.org/

Further Reading

For younger readers

Air pollution

Water pollution

Primary Sources

Historic Headlines

Contributed By:
Paul Engelking

The collapse of the Interstate 35W bridge in downtown Minneapolis, Minnesota, in 2007 was the most recent major bridge disaster. The Minneapolis bridge collapse raised renewed concerns about bridge safety in the United States.

- **It followed a report issued in 2006 by the Federal Highway Administration ranking 13 percent of U.S. bridges as "structurally deficient" and almost 14 percent as "functionally obsolete."**

Schultz, B. Cameron, and Grivas, Dimitri A. "Bridge (structure)."

Bridge (structure)

I INTRODUCTION

Collapse of the Tacoma Narrows Bridge

The original Tacoma Narrows Bridge stretched 1,810 m (5,940 ft) across a narrow channel of Puget Sound near Tacoma, Washington. After two years of construction, the bridge opened to traffic on July 1, 1940. Four months later the bridge collapsed during a windstorm with gusts that reached 68 km/h (42 mph). The catastrophe was attributed to faulty design. Instead of allowing the wind to pass through, the suspended girders caught the wind, causing the bridge to buck and roll. The bucking motion earned the bridge the nickname Galloping Gertie. The stronger the wind blew, the more violently the structure oscillated, until it finally broke apart and crashed into the water. In 1992 the bridge's sunken remains were placed on the United States National Register of Historic Places.
Archive Photos

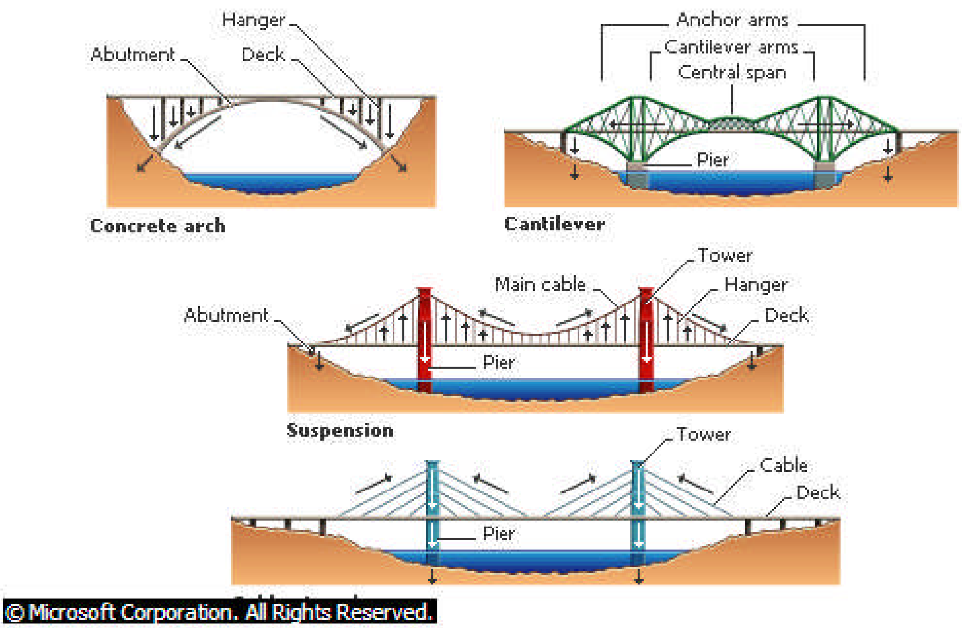
Bridge (structure), structure designed to provide continuous passage over an obstacle. Bridges commonly carry highways, railroad lines, and pathways over obstacles such as waterways, deep valleys, and other transportation routes. Bridges may also carry water, support power cables, or house telecommunications lines.

Akashi Kaikyo Bridge, Japan

The Akashi Kaikyo Bridge in Japan is the longest suspension bridge in the world. Completed in 1998, it measures 1.99 km (1.24 mi) between its two supporting towers. The bridge connects the city of Kōbe with Awaji Island and carries both road and rail traffic. Built to withstand earthquakes, the bridge survived a 1995 tremor measuring 7.2 on the Richter scale.

Kaku Kurita/Liaison Agency

Some special types of bridges are defined according to function. An overpass allows one transportation route, such as a highway or railroad line, to cross over another without traffic interference between the two routes. The overpass elevates one route to provide clearance to traffic on the lower level. An aqueduct transports water. Aqueducts have historically been used to supply drinking water to densely populated areas. A viaduct carries a railroad or highway over a land obstruction, such as a valley.



Principles of Bridge Construction

A bridge must be strong enough to support its own weight as well as the weight of the vehicles and people that use it. It must also be able to resist varying environmental conditions. Different designs serve different purposes and lengths of spans. Load is transferred by hangers (arch bridges) or cables (suspension and cable-stayed bridges) to towers or abutments at the ends of the bridge, and these in turn transfer the force into the ground. Cantilever bridges have two independent cantilever arms projecting toward each other and joined by a central span.

The earliest bridges were simple structures created by spanning a gap with timber or rope. Designs became more complex as builders developed new construction methods and discovered better materials. The stone arch was the first major advance in bridge design. It was used by the ancient Greeks, Etruscans, and Chinese (*see* Arch and Vault). The Romans perfected arch design, using arches to build massive stone bridges throughout the Roman Empire. Stone arch construction remained the premier bridge design until the introduction of the steam locomotive in the early 19th century.

Golden Gate Bridge, San Francisco
The Golden Gate Bridge links the city of San Francisco with Marin County to the north. The suspension bridge was opened in 1937 and since then has been one of the principal landmarks of both San Francisco and California.
Michael J. Howell/ProFiles West

Between 1830 and 1880, as railroad building expanded throughout the world, bridge design and construction also evolved to carry these heavy vehicles over new obstacles. Designers experimented with a wide variety of bridge types and materials to meet the demand for greater heights, spans, and strength. Locomotives were heavier and moved faster than anything before, requiring stronger bridges. The basic beam bridge, a simple beam over a span, was strengthened by adding support piers underneath and by reinforcing the structure with elaborate scaffolding called a truss. During the period of railroad expansion, iron trusses replaced stone arches as the preferred design for large bridges.

Verrazano-Narrows Bridge

An overview of the Verrazano-Narrows steel suspension bridge reveals the structure and cable system that allows it to support weight over an extended span. The bridge links Brooklyn and Staten Island at the entrance of New York Harbor, crossing 1,298 m (4,260 ft) of water. Cable systems often rise hundreds of meters above the roadway; at the peak of its towers the Verrazano-Narrows is 210 m (690 ft) tall. More than 135,000 metric tons (150,000 U.S. tons) of steel were used in the bridge, which cost $325 million to build.

Frederica Georgia/Photo Researchers, Inc.

In 1855 British inventor Sir Henry Bessemer developed a practical process for converting cast iron into steel (*see* Iron and Steel Manufacture). This process increased the availability of steel and lowered production costs considerably. The strength and lightness of steel revolutionized bridge building. In the late 19th century and the first half of the 20th century, many large-scale steel suspension bridges were constructed over major waterways. Also in the late 19th century, engineers began to experiment with concrete reinforced with steel bars for added strength. More recently, reinforced concrete has been combined with steel girders, which are solid beams that extend across a span. When the Interstate Highway System in the United States and similar road systems in other countries were constructed in the mid- to late 20th century, the steel-and-concrete girder bridge was one of the most commonly used bridge designs. The last three decades of the 20th century saw a period of large-scale bridge building in Europe and Asia. Current research focuses on using computers, instrumentation, automation, and new materials to improve bridge design, construction, and maintenance.

II TYPES OF BRIDGES

Bridge designs differ in the way they support loads. These loads include the weight of the bridges themselves, the weight of the material used to build the bridges, and the weight and stresses of the vehicles crossing them. There are basically eight common bridge designs: beam, cantilever, arch, truss, suspension, cable-stayed, movable, and floating bridges. Combination bridges may incorporate two or more of the above designs into a bridge. Each design differs in appearance, construction methods and materials used, and overall expense. Some designs are better for long spans. Beam bridges typically span the shortest distances, while suspension and cable-stayed bridges span the greatest distances.

A Beam Bridges

Beam bridges represent the simplest of all bridge designs. A beam bridge consists of a rigid horizontal member called a beam that is supported at both ends, either by a natural land structure, such as the banks of a river, or by vertical posts called piers. Beam bridges are the most commonly used bridges in highway construction. Single-piece, rolled-steel beams can support spans of 15 to 30 m (50 to 100 ft). Heavier, reinforced beams and girders are used for longer spans.

B Cantilever Bridges

Forth Bridge, Scotland

The Forth Bridge, a steel railway bridge across the Firth of Forth near Edinburgh, Scotland, was built between 1882 and 1890. It is one of the longest cantilever bridges in the world.

Tony Waltham/Robert Harding Picture Library

Cantilever bridges are a more complex version of the beam-bridge design. In a cantilever design, a tower is built on each side of the obstacle to be crossed, and the bridge is built outward, or cantilevered, from each tower. The towers support the entire load of the cantilevered arms. The arms are spaced so that a small suspended span can be inserted between them. The cantilevered arms support the suspended span, and the downward force of the span is absorbed by the towers.

Cantilever bridges are self-supporting during construction. They are often used in situations in which the use of scaffolding or other temporary supports would be difficult. The Forth Bridge, a railway bridge across the Firth of Forth in Queensferry, Scotland, has two main spans of 521 m (1,710 ft) each. The Hāora (Howrah) Bridge in Calcutta (now Kolkata), India, was opened in 1943, with a main span of 457 m (1,500 ft). The Québec Bridge across the St. Lawrence River in Canada has a span of 549 m (1,800 ft).

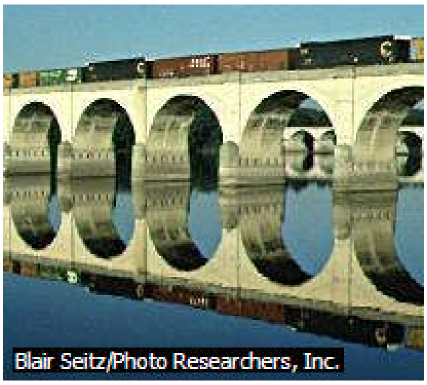
C Arch Bridges

Iron Rail Bridge

An early iron arch bridge supporting a railway spans the Adda River in northern Italy. The arch makes use of truss framework to help support the bridge.

Danilo Donadoni/Bruce Coleman, Inc.

Arch bridges are characterized by their stability. In an arch, the force of the load is carried outward from the top to the ends of the arch, where abutments keep the arch ends from spreading apart. Arch bridges have been constructed of stone, brick, timber, cast iron, steel, and reinforced concrete.



Masonry Arch Bridge

This railroad bridge near Harrisburg, Pennsylvania, has cut stones arranged in a semicircular arch construction. Masonry arch bridges have largely been replaced by steel and concrete arch bridges because masonry bridges are more expensive to build.

Blair Seitz/Photo Researchers, Inc.

Steel and concrete arches are particularly well suited for bridging ravines or chasms with steep, solid walls. The New River Gorge Bridge in West Virginia is the longest arch bridge, spanning a gap of 518 m (1,700 ft). Other long arch bridges include the Bayonne Bridge between New York and New Jersey, and the Sydney Harbour Bridge in Australia, with main spans of 504 m (1,652 ft) and 503 m (1,650 ft), respectively.

D Truss Bridges

Astoria Bridge

Constructed of continuous trusses, this interstate bridge over the meandering Columbia River connects Astoria, Oregon, to Megler, Washington. The bridge was named for Fort Astor, a fur-trading post established in 1811 by John Jacob Astor's Pacific Fur Company.

Jim Corwin

Truss bridges utilize strong, rigid frameworks that support these bridges over a span. Trusses are created by fastening beams together in a triangular configuration. The truss framework distributes the load of the bridge so that each beam shares a portion of the load. Beam, cantilever, and arch bridges may be constructed of trusses. Truss bridges can carry heavy loads and are relatively lightweight. They are also inexpensive to build. The Astoria Bridge over the Columbia River in Oregon has a span of 376 m (1,232 ft).

E Suspension Bridges

Bob-RJ Burkhart :: LCDR, USNR-Ret.

Clifton Bridge

Suspension bridges, like the Clifton Suspension Bridge in Bristol, England, are commonly used in areas where building a bridge with mid-span supports would be either extremely difficult or overly expensive. The span hangs from two enormous main cables, eliminating the need to bolster the span from underneath. In turn, the main cables place their load on the towers at each end of the bridge, and on the points where the cables are attached to the ground beyond each of the towers.

Sarah Ellis/Hutchison Library

Suspension bridges consist of two large, or main, cables that are hung (suspended) from towers. The main cables of a suspension bridge drape over two towers, with the cable ends buried in enormous concrete blocks known as anchorages. The roadway is suspended from smaller vertical cables that hang down from the main cables. In some cases, diagonal cables run from the towers to the roadway and add rigidity to the structure. The main cables support the weight of the bridge and transfer the load to the anchorages and the towers.

Mackinac Bridge

The Mackinac Bridge in northern Michigan is one of the longest suspension bridges in the world, with a total span of more than 2.5 km (more than 1.5 mi). It connects Michigan's Upper Peninsula (between Lake Superior and Lake Michigan) and Lower Peninsula (between Lake Michigan and Lake Huron).

Kit Kittle/Corbis

Suspension bridges are used for the longest spans. The Brooklyn Bridge, which was the world's longest suspension bridge at the time of its completion in 1883, crosses the East River in New York City and has a main span of 486 m 31 cm (1,595 ft 6 in). The Akashi Kaikyo Bridge between Honshū and Awaji Island in Japan was completed in 1998, with a span of 1,991 m (6,532 ft). While suspension bridges can span long distances, this design has a serious drawback: It is very flexible, and traffic loading may cause large deflections, or bending, in the bridge roadway. Suspension design is rarely used for railroad bridges, because trains are heavier and can travel faster than highway traffic.

F Cable-Stayed Bridges

Normandy Bridge
Normandy Bridge near Le Havre, France, is one of the world's longest cable-stayed suspension bridges, with a main span of 856 m (2808 ft). The bridge opened to traffic in January 1995. Unlike conventional suspension bridges, which use two massive cables, cable-stayed bridges employ numerous smaller cables attached to two large towers or pylons.
REUTERS/THE BETTMANN ARCHIVE

Cable-stayed bridges represent a variation of the suspension bridge. Cable-stayed bridges have tall towers like suspension bridges, but in a cable-stayed bridge, the roadway is attached directly to the towers by a series of diagonal cables. A cable-stayed bridge is constructed in much the same way as a suspension bridge is, but without the main cables.

Millau Viaduct

The spectacular Millau Viaduct soars above the valley of the Tarn River near Millau in southwestern France. The 2.5 km- (1.5 mi-) long cable-stayed structure is the highest vehicular bridge in the world, with the road surface reaching a maximum height of 270 m (885 ft) above the valley floor. The viaduct's tallest pier rises to a height of more than 340 m (1,115 ft). The viaduct opened to traffic in December 2004.
Chris Hellier/Corbis

Cable-stayed designs are used for intermediate-length spans. Advantages a cable-stayed bridge has over a standard suspension bridge include speed of construction and lower cost, since anchorages are not necessary. There are no massive cables, as with suspension bridges, making cable repair or replacement simpler. The Pont de Normandie (Normandy Bridge) over the Seine River near Le Havre in France opened in 1995, with a span length of 856 m (2,808 ft).

G Movable Bridges

London Tower Bridge
The 244-m (800-ft) London Tower Bridge spans the Thames River in London. It was the only movable bridge crossing the Thames when it was completed in 1894. Sir Horace Jones designed the bridge, and Sir John Wolfe Barry built it.
SIME/Ripani Massimo /4Corners Images

Movable bridges make up a class of bridge in which a portion of the bridge moves up or swings out to provide additional clearance beneath the bridge. Movable bridges are usually found over heavily traveled waterways. The three most common types of movable bridge are the bascule (drawbridge), vertical-lift, and swing bridges. Modern bascule bridges usually have two movable spans that rise upward, opening in the middle. A vertical-lift bridge consists of a rigid deck frame held between two tall towers. The bridge opens by hoisting the entire bridge roadway upward between the towers in an elevator-like fashion. Swing bridges are mounted on a central pier and open by swinging to one side, allowing ships to pass.

Bascule Bridge

A bascule bridge on the Miami River in Florida is open to let a ship pass. Bascule bridges are useful for spanning short distances over busy waterways, and they allow ships of any height to pass underneath.
Morton Beebe-S.F./Corbis

Movable bridges are generally constructed over waterways where it is either impractical or too costly to build bridges with high enough clearances for water traffic to pass underneath. Bascule bridges are used for short spans. A bascule bridge over the Black River in Lorain, Ohio, has a length of 102 m (333 ft). Vertical-lift bridges are useful for longer spans, but they must be built so they can be lifted high enough for tall ships to pass underneath. The vertical-lift bridge over Arthur Kill between Staten Island in New York City and New Jersey has a span of 170 m (558 ft) and can be raised 41 m (135 ft) above the water. Swing bridges have the advantage of not limiting the height of passing vessels, but they do restrict the horizontal clearance, or width, of passing ships. The longest swing-bridge span is that of a railroad and highway bridge crossing the Mississippi River at Fort Madison, Iowa. This bridge has a span of 166 m (545 ft).

H Floating Bridges

Floating Bridge

The simple pontoon floating bridge over the Kābul River, Pakistan, is supported by flat-bottomed boats rather than fixed piers. Pontoon bridges may also be supported by other types of floats or metal cylinders.

Robert Harding Picture Library

Floating bridges are formed by fastening together sealed, floating containers called pontoons and placing a roadbed on top of them. A pontoon typically contains many compartments so that if a leak occurs in one compartment, the pontoon will not sink. Some floating bridges are constructed using boats or other floating devices rather than pontoons.

Floating bridges were originally developed and are most widely used as temporary structures for military operations. For everyday use, floating bridges are popular when deep water, bad riverbed conditions, or other conditions make it difficult to construct traditional bridge piers and foundations. A concrete-pontoon bridge carries a highway across Lake Washington, near Seattle, Washington. It consists of 25 floating sections bolted together and anchored in place and a span that can be opened to permit the passage of large ships. The floating section of the bridge is 2.3 km (1.4 mi) long.

I Combination Bridges

Chesapeake Bay Bridge-Tunnel

Chesapeake Bay features a piece of construction that may startle unprepared travelers. The 28.2 km (17.5 mi) crossing between Norfolk and Cape Charles, Virginia, begins as a bridge, but disappears into the water midway. A combination structure, the Chesapeake Bay Bridge-Tunnel combines two bridges with two tunnels that pass under major shipping channels.

Chesapeake Bay Bridge and Tunnel District

Combination bridges include crossings consisting of several types of bridges or both bridges and tunnels. For example, the Chesapeake Bay Bridge-Tunnel in Virginia includes two tunnels that are each 1.6 km (1.0 mi) long along its 28 km (17 mi) length from shore to shore. The Triborough Bridge in New York City is actually a network of bridges connecting the boroughs of Queens, Manhattan, and the Bronx. These bridges meet over Randall’s Island. Seven truss spans stretch over Bronx Kills, and three truss spans and a vertical lift extend over the Harlem River. A viaduct and a suspension bridge also make up part of the Triborough Bridge.

III BRIDGE PLANNING AND CONSTRUCTION

Concrete Bridge

Modern bridge construction for the Gateway Bridge over the Brisbane River in Australia uses lightweight and durable concrete reinforced with steel bars or mesh. Concrete is made from three components: an aggregate material such as sand or gravel, water, and the binding agent, portland cement.

Joyce Photographics/Photo Researchers, Inc.

New bridges are built either to replace old structures that no longer meet the demands of modern traffic or to cross obstacles on a new transportation route. Old bridges are replaced when repairs cannot be made economically or when traffic becomes too heavy for the old bridge. New transportation routes are built when traffic levels have outgrown the capacity of existing routes or simply to make it faster to get from one busy place to another. Often, new transportation routes are part of government programs to promote regional economic development.

In the United States, state and local transportation agencies determine where new bridges are needed and pay a small portion of the cost. The federal government usually pays for most of the construction expense, using money generated from taxes. Bridges funded by tax dollars are used free of charge. The few bridges for which a toll is charged to drivers for use are funded through the sale of bonds to raise money for construction. The money collected from the toll is used to pay back the bonds. The use of tolls and borrowing to finance bridge construction was more widespread in the past than it is today.

A Design Selection

Engineers must consider several factors when designing a bridge. They consider the distance to be crossed and the feature, such as a river, bay, or canyon, to be crossed. Engineers must anticipate the type of traffic and the amount of load the bridge will have to carry and the minimum span and height required for traffic traveling across and under the bridge. Temperature, environmental conditions, and the physical nature of the building site (such as the geometry of the approaches, the strength of the ground, and the depth to firm bedrock) also determine the best bridge design for a particular situation.

Once engineers have the data they need in order to design a bridge, they create a work plan for constructing it. Factors to be considered include availability of materials, equipment, and trained labor; availability of workshop facilities; and local transportation to the site. These factors, in combination with the funding and time available for bridge design and construction, are the major requirements and constraints on design decisions for a particular site.

B Design Decisions

There are four basic categories of design decisions: the type of bridge, the materials of which it will be made, the type of foundations that will support the structure, and the construction method to be used. Typically, several feasible choices exist in each category, and each option is evaluated in terms of convenience, appearance, endurance, and cost. Bridges must be convenient to build, use, and maintain. Appearance is important in gaining public approval, which is particularly critical for taxpayer-funded projects. Bridges must be designed to endure, as most structures can be expected to provide service for at least 50 to 100 years. Durability of materials and maintenance requirements are important considerations, as the true cost of a bridge is not simply the initial construction expense but the total cost of constructing and maintaining the structure throughout its service life. Good designs minimize total cost.

B1 Bridge Type

The bridge type (such as beam, arch, truss, and others) depends largely on the required dimensions for the bridge and the type of traffic to be carried. The required length and clearances needed by traffic are major considerations in bridge design. Many bridges are long enough to require several intermediate supports, or piers. The location of piers is usually a crucial factor, whether in water or on land.

B2 Materials

Materials historically used for bridge building include rope and other fibers, wood, stone and masonry, iron, steel, and concrete. Fiber, timber, stone, and masonry are still used occasionally, but steel and concrete are the materials used for most modern bridge building. Fiber rope is occasionally used for short pedestrian bridges. Timber is perceived as a rustic material and is sometimes used in public parks, on private property, or in other situations in which a natural or historic appearance is desirable. The strength and durability of timber are quite limited compared to those of steel and concrete. Therefore, timber is suitable only for short spans that carry minimal traffic loads. Stone and masonry are sometimes used as facing materials on concrete and steel bridges, if appearance is important enough to justify the additional expense.

When deciding between steel and concrete, designers evaluate the tradeoffs among weight, strength, and expense to determine which material is best for a particular bridge. Concrete is heavier than steel, but steel is much stronger. The major advantages of concrete are that it is considerably cheaper than steel and can be formed into a greater variety of shapes. For short bridges, the weight of material is not an important concern, and so concrete is an economical choice. However, as span increases, the weight of the structure grows substantially, and greater strength is needed to support the overall structure. Steel tends to be preferred for large bridges because less material has to be handled and supported during the construction process.

The distinction between steel and concrete is not absolute, as most steel bridges have concrete decks, and all concrete is reinforced with steel to provide greater tensile strength (resistance to pulling). Reinforced concrete is made by pouring concrete mix over steel bars or mesh. The concrete and metal bond as the mix hardens, producing a material in which the high tensile strength of steel is combined with the great compressive strength (ability to resist pushing or squeezing) of concrete. An alternative method of reinforcing concrete is prestressing. Prestressed concrete is made by pouring concrete over stretched and anchored steel strands. After the concrete has set, the anchors are released. As the steel tries to return to its original length, it compresses the concrete, resulting in a relatively lightweight, extremely strong material.

B3 Foundations

All bridge piers rest on foundations that transfer loads from the bridge structure into the ground. The foundations support the bridge, and their design is critical. Difficult conditions, such as deep water or soft ground, can make foundation construction complicated and expensive. In such circumstances designers may choose to decrease the number of piers by increasing span length. Of course, greater span lengths often require a more expensive bridge type, and therefore the tradeoffs must be evaluated carefully.

If the ground is very strong at a bridge site, a foundation is formed by pouring a simple concrete mat beneath each of the piers. If the soil is weak, it may be excavated down to bedrock, and the piers can then be built directly on the solid rock. Alternatively, a group of vertical posts, or piles, can be driven through the soil to bedrock, and piers can be built on top of the piles.

B4 Construction Methods

Storebælt Bridge

After many delays and redesigns, the bridge over the Storebælt (Great Belt), a channel linking the North and Baltic seas, opened to traffic in 1998. The bridge connects the Danish islands of Fyn and Sjælland. With a main span of 1,624 m (5,328 ft), it is the second longest suspension bridge in the world. Its twin concrete piers stand 254 m (833 ft) high. This photograph shows the bridge under construction.

Rossi Xavier/Liaison Agency

Bridges are erected using a variety of construction methods. Some techniques are associated with a particular bridge type, and care must be taken not to select a design that requires construction methods unsuitable for the site. Concrete and steel bridges are generally built using similar techniques, although concrete bridges are built in shorter sections than are steel bridges because of the greater weight of the material.

One of the simplest construction methods for bridges is to assemble a span away from the bridge site and then transport it to the site. The span can then be lifted into position as one piece. This method is most often suitable for small truss bridges or for the suspended span of a cantilever truss. Another approach is to use falsework, or temporary scaffolding, to support the incomplete parts of a bridge before they are joined and able to support themselves.

The use of falsework is not always possible, owing to strong river currents, interference with river traffic, or great distances to the ground. If falsework is impractical, bridges can be constructed by the cantilever method. With this technique, a bridge is built piece by piece, with the entire structure supported from the section previously completed. Thus, the structure is self-supported throughout the entire construction process. The use of cantilever construction methods saves material and therefore expense, but it is very complex, as great care must be taken not to unbalance the structure during construction. Most arch bridges, and of course cantilever bridges, are built using cantilever methods.

The large towers and cable anchorages of suspension bridges are built without the use of falsework, and then the suspension cables are spun. Many individual wires are draped over the towers and are then squeezed together into a circular shape and clamped at intervals to create a main cable. Suspension wires are dropped from the cables to support the roadway, and the roadway is completed.

For all bridge types, underwater foundations require unique construction methods. Builders use cofferdams and caissons to obtain access to ground that is normally under water. A cofferdam is a temporary watertight enclosure constructed on the spot where a pier is to be built. A cofferdam usually consists of sheets of steel driven into the ground to create a walled chamber. The cofferdam is then pumped dry to expose the riverbed. Soil can be excavated to bedrock, or piles can be driven to create the pier foundation. The cofferdam is removed after the foundation and pier are constructed. A caisson is a large cylinder or box chamber that is sunk into the riverbed. The excavation and foundation work takes place within the submerged caisson. Some caissons are removed after construction, while others are left in place, filled with concrete, and used as part of a permanent foundation.

C Safety

In bridge design, engineers strive to plan an economical structure that will safely transmit loads to the ground without collapsing or deforming excessively. Since it is difficult to predict the exact loading and circumstances that a bridge must withstand, all bridge designs include a substantial margin of safety. Design standards vary throughout the world, but all aim at ensuring that new bridges will provide many years of service and will maintain an adequate margin of safety against failure. Of course, the safety of a structure when it is first erected does not ensure that it will remain safe for all time. All structures require both periodic inspection and proper maintenance to keep them safe.

Notable bridge failures include the collapse of the Firth of Tay Bridge in Scotland in 1879, the collapse of the Québec Bridge in Canada while under construction in 1907, and the collapse of the Tacoma Narrows Bridge, nicknamed Galloping Gertie, in Washington State in 1940. Other recent disasters in which bridges collapsed due to structural or engineering failures rather than collisions or flooding include the Mianus River Bridge in Greenwich, Connecticut, in 1982, the Seongsu Bridge collapse in Seoul, South Korea, in 1994, and the collapse of a bridge in Lisbon, Portugal, in 2001. In 2002 there were two major bridge collapses in China, and in 2006 a bridge collapsed in Laval, Canada.

- *The collapse of the Interstate 35W bridge in downtown Minneapolis, Minnesota, in 2007 was the most recent major bridge disaster. The Minneapolis bridge collapse raised renewed concerns about bridge safety in the United States. It followed a report issued in 2006 by the Federal Highway Administration ranking 13 percent of U.S. bridges as "structurally deficient" and almost 14 percent as "functionally obsolete."*

The National Transportation Safety Board (NTSB) concluded in 2008 that the Minneapolis bridge collapse was due to a design flaw. The NTSB investigation found that a critical metal plate linking the bridge's girders was too thin to support weight added to the bridge over years of upgrades and repairs. Known as a gusset plate, its use in the design of this and other bridges was in part due to its lower cost.

- *The NTSB urged bridge inspectors to examine bridges for this design flaw, which it characterized as a "fracture critical" flaw because there were no backup structures to prevent a collapse if the gusset plate failed. In the case of the Minneapolis bridge, extra weight on the bridge from a construction repair project at the time of the collapse added to the strain on the gusset plate.*

IV HISTORY

The different sizes and shapes of bridges encountered today reflect thousands of years of progress in engineering, technology, and building materials.

A Early and Medieval Bridges

Ponte Vecchio, Florence, Italy

Many of the older bridges in Florence were destroyed during World War II; however, the Ponte Vecchio (Old Bridge), built in 1345 and shown here, survived. Goldsmith and jewelry shops line the bridge.

Walter Rawlings/Robert Harding Picture Library

In ancient times, builders would throw a log across a stream or use two vines or ropes (the upper for a handhold and the lower for a foothold) to create a crossing. The earliest rudimentary arches (built from 4000 to 2000 BC) consisted of stones balanced on top of one another. The ancient Romans perfected stone arch design and were the first to build large-scale bridges, many of which still stand today. The largest remaining ancient Roman aqueduct, the Pont du Gard in southern France, is 270 m (886 ft) long and consists of three tiers of semicircular stone arches. The Romans built the Pont du Gard in the late 1st century BC or the early 1st century AD. The aqueduct stands approximately 47 m (155 ft) tall, and the longest arch spans 24 m (80 ft).

The ancient Chinese also built many notable bridges. In the 7th century AD, bridge designer Li Chun built the Anji Bridge south of Beijing using a stone arch built of massive limestone wedges reinforced with iron. The innovative main arch of the Anji curves in a shallow arc or segment of a circle, rather than the half circle preferred by Roman engineers at the time. The Anji Bridge, which spans 37 m (121 ft), predates any comparable development in Europe by several hundred years.

From ancient times through the 16th century, designers made few engineering advances. Masonry arch construction remained the premier choice for bridge design. In the Middle Ages in Europe, religious orders administered bridge construction. Considered pious works, bridges often had chapels and were decorated with effigies of saints. Inhabited bridges were developed during the Renaissance. These bridges were exemplified by the Ponte Vecchio, 100 m (330 ft) long, in Florence, Italy, designed by Taddeo Gaddi in 1345; and by the Rialto Bridge, 27 m (89 ft) long, in Venice, Italy, designed by Antonio da Ponte in 1591. Shops were built directly on the roadway of these bridges, and rents were used to finance new public works.

B Iron and Steel Bridges

Ironbridge, Telford, England

Ironbridge, which crosses the River Severn in Telford, Shropshire, in western England, was completed in 1779. The first large-scale structure made of cast iron, the bridge was considered a remarkable feat of engineering at the time of its construction.

Robert Harding Picture Library

The widespread use of iron in the 18th century and the introduction of the steam locomotive in the 19th century encouraged rapid innovation in bridge design. Engineers made more advances in the first half of the 19th century than they had in the previous 1,800 years. As the railroad industry developed, bridges rapidly increased in height, span, strength, and numbers. Iron was plentiful, cheap, much stronger than wood, and more flexible than stone. The Ironbridge at Coalbrookdale in Shropshire, England, completed in 1779, was the first major structure to be constructed entirely of iron. Designed by Abraham Darby III and Thomas Pritchard, the arched structure spans about 30 m (about 100 ft).

Scottish engineer Thomas Telford used wrought iron and limestone to design the Menai Suspension Bridge in Wales in 1826. This bridge was the world's first major suspension bridge. It spanned 176 m (579 ft). During the first half of the 19th century, iron became the premier building material. In addition, truss designs were developed to provide the additional strength needed to bear the massive weight of railroad trains.

The major disadvantage of iron, namely, low tensile strength, was overcome in the mid-1850s, when the Bessemer process of making steel (an alloy of iron and carbon) was developed. The first major structure built entirely of steel was the cantilevered Forth Bridge in Scotland, completed in 1890. Its two record-setting spans of 521 m (1,710 ft) were the longest in existence until 1917. The arched Eads Bridge over the Mississippi River at St. Louis, Missouri, designed by James Eads and completed in 1874, was the first steel bridge in the United States. The Eads Bridge has three main spans. The center span is 160 m (520 ft) long, and the spans on either side are each 153 m (502 ft) in length. At the time the Eads Bridge was built, it was the longest structure in the United States. By 1890 the strength and lightness of steel had made it the material of choice for bridge building.

C **Suspension Bridges**

The Roebling family pioneered the use of steel in suspension bridges. John Augustus Roebling, a German-born engineer who emigrated to the United States in 1831, is considered the father of modern suspension-bridge design. His major contribution was the development of construction techniques to spin wire cables. He was the first to use cables and stiffening trusses in suspension bridges. Roebling designed the Cincinnati Bridge, over the Ohio River at Cincinnati, Ohio. It was built by his son Washington Roebling in 1866. The Cincinnati Bridge has a span of 322 m (1,057 ft).

John and Washington Roebling also designed and built the Brooklyn Bridge, which was the world's longest suspension bridge at the time of its completion in 1883, having a main span of 486 m 31 cm (1,595 ft 6 in). The completion of the Brooklyn Bridge marked the beginning of an 80-year period of large-scale suspension-bridge design in the United States. That period ended in 1964 with the completion of the Verrazano-Narrows Bridge in New York. With a main span 1298 m (4260 ft) long, the Verrazano-Narrows is still the longest suspension bridge in the United States. The Golden Gate Bridge in San Francisco, California, is perhaps the best-known landmark of this remarkable era in bridge building (*see* Golden Gate). Completed in 1937, the Golden Gate Bridge has a main span of 1,280 m (4,200 ft).

D **Introduction of Concrete**

Paul Sauer Bridge, South Africa

The concrete arch of the Paul Sauer Bridge spans the Storms River in South Africa, on the road between Cape Town and Port Elizabeth. An arch bridge transfers the weight of the bridge down along the arch to the abutments where, in this example, the arch meets the canyon walls.

K.M. Westermann/Corbis

The introduction of concrete as a building material represented a major chapter in the history of bridge building. Although the ancient Romans had used concrete, the knowledge of this material virtually disappeared during the Middle Ages and was not rediscovered until the late 18th century. The first modern concrete bridge was a solid concrete bridge, 12 m (39 ft) long, built over the Garonne Canal at Grisoles, France, in 1840.

All early concrete bridges used arched designs by necessity because concrete has great compressive strength but is very weak in tension. Until the invention of metal reinforcement, which adds strength in tension, the arch was the only feasible shape for structures made entirely of concrete. Reinforced concrete emerged simultaneously in Germany, the United States, England, and France between 1870 and 1900. Swiss engineer Robert Maillart became a celebrated designer of reinforced-concrete bridges in the first half of the 20th century, producing extremely innovative designs based on the unique engineering properties of reinforced concrete. The last half of the 20th century saw the construction of major reinforced-concrete structures, such as the Lake Maracaibo Bridge in Venezuela, designed by Italian engineer Riccardo Morandi. This prestressed-concrete cable-stayed bridge is 8 km (5 mi) long.

E Recent Designs

Alamillo Bridge

The city of Seville, Spain, built six new bridges in preparation for Expo '92. Spanish architect and engineer Santiago Calatrava designed the Alamillo Bridge (1992), shown here. Lightweight and sculptural in appearance it calls to mind a harp or bird, according to Calatrava. The bridge is 200 m (656 ft) long and the single pylon that supports the roadway rises 140 m (459 ft) above road level.

Fernando Alda/Corbis

The first modern cable-stayed bridge featured a span of 183 m (600 ft). German engineers constructed this bridge in Sweden in 1956. Thereafter, Germany led the field in developing this type of bridge. Cable-stayed bridges can be constructed in an infinite variety of shapes and are one of the most popular long-span bridge designs. Notable examples include the Severn II Bridge in Bristol, England, completed in 1996 with a span of 456 m (1,496 ft), and the Sunshine Skyway Bridge in Tampa, Florida, completed in 1987 with a span of 366 m (1,200 ft).

At the end of the 20th century, construction was under way on a number of monumental bridges, most notably in Northern Europe and in Asia. Engineers are combining aspects of both suspension and cable-stayed bridges into new bridge designs that will someday span once-impossible distances of more than 3,000 m (10,000 ft). At the same time, researchers are investigating new methods of preserving and renewing bridges, so that existing structures will last longer and provide greater service and fewer new structures will have to be built in the future.

Contributed By:

B. Cameron Schultz

Dimitri A. Grivas