RICHARD M. BARKER AND JAY A. PUCKETT

DESIGN OF HIGHWAY BRIDGES

AN LRFD APPROACH

FOURTH EDITION

WILEY

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Fourth Edition

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PART III CONCRETE BRIDGES

PART I

General Aspects of Bridge Design

CHAPTER 1

Introduction to Bridge Engineering

Bridges are important to everyone. But they are not seen or understood in the same way, which is what makes their study so fascinating. A single bridge over a small river will be viewed differently because the eyes each one sees it with are unique to that individual. Someone traveling over the bridge everyday may only realize a bridge is there because the roadway now has a railing on either side. Others may remember a time before the bridge was built and how far they had to travel to visit friends or to get the children to school. Civic leaders see the bridge as a link between neighborhoods, a way to provide fire and police protection and access to hospitals. In the business community, the bridge is seen as opening up new markets and expanding commerce. An artist may consider the bridge and its setting as a possible subject for a future painting. A theologian may see the bridge as symbolic of making a connection with God, while a boater on the river, looking up when passing underneath the bridge, will have a completely different perspective. Everyone is looking at the same bridge, but it produces different emotions and visual images in each.

Bridges affect people. People use them, and engineers design them and later build and maintain them. Bridges do not just happen. They must be planned and engineered before they can be constructed. In this book, the emphasis is on the engineering aspects of this process: selection of bridge type, analysis of load effects, resistance of cross sections, and conformance with bridge specifications. Although very important, factors of technical significance should not overshadow the *people* factor.

1.1 A BRIDGE IS THE KEY ELEMENT IN A TRANSPORTATION SYSTEM

A bridge is a key element in a transportation system for three reasons:

It likely controls the capacity.

It is the highest cost per mile.

If the bridge fails, a link in the system fails.

If the width of a bridge is insufficient to carry the number of lanes required to handle the traffic volume, the bridge will be a constriction to the traffic flow. If the strength of a bridge is deficient and unable to carry heavy trucks, load limits will be posted and truck traffic will be rerouted. The bridge controls both the volume and weight of the traffic carried.

Bridges are expensive. The typical cost per mile of a bridge is many times that of the approach roadways. This is a major investment and must be carefully planned for best use of the limited funds available for a transportation system.

When a bridge is removed from service and not replaced, the transportation system may be restricted in its function. Traffic may be detoured over routes not designed to handle the increase in volume. Users of the system experience increased travel times and fuel expenses. Normalcy does not return until the bridge is repaired or replaced.

Because a bridge is a key element in a transportation system, balance must be achieved between handling future traffic volume and loads and the cost of a heavier and wider bridge structure. Strength is always a foremost consideration but so should measures to prevent deterioration. The designer of new bridges has control over these parameters and must make wise decisions so that capacity and cost are in balance and safety is not compromised.

1.2 BRIDGE ENGINEERING IN THE UNITED STATES

Usually a discourse on the history of bridges begins with a log across a small stream or vines suspended above a deep chasm. This preamble is followed by the development of the stone arch by the Roman engineers of the second and first centuries BCE and the building of beautiful bridges across Europe during the Renaissance period of the fourteenth through seventeenth centuries. Next is the Industrial Revolution, which began in the last half of the eighteenth century and saw the emergence of cast iron, wrought iron, and finally steel for bridges. Such discourses are found in the books by Brown (1993), Gies (1963), and Kirby et al. (1956) and are not repeated here. An online search for "bridge engineering history" leads to a host of other references on this topic. Instead a few of the bridges that are typical of those found in the United States are highlighted.

1.2.1 Stone Arch Bridges

The Roman bridge builders first come to mind when discussing stone arch bridges. They utilized the semicircular arch and built elegant and handsome aqueducts and bridges, many of which are still standing today. The oldest remaining Roman stone arch structure is from the seventh century BCE and is a vaulted tunnel near the Tiber River. However, the oldest surviving stone arch bridge dates from the ninth century BCE and is in Smyrna, Turkey, over the Meles River.

In excavations of tombs and underground temples, archaeologists found arched vaults dating to the fourth millennium BCE at Ur in one of the earliest Tigris–Euphrates civilizations (Gies, 1963). The stone arch has been around a long time, and how its form was first discovered is unknown. But credit is due to the Roman engineers because they are the ones who saw the potential in the stone arch, developed construction techniques, built foundations in moving rivers, and left us a heritage of engineering works at which we marvel today such as Pont du Gard (Exhibit 1 in the color insert).

Compared to these early beginnings, the stone arch bridges in the United States are relative newcomers. One of the earliest stone arch bridges is the Frankford Avenue Bridge over Pennypack Creek built in 1697 on the road between Philadelphia and New York. It is a three-span bridge, 73 ft (23 m) long and is the oldest bridge in the United States that continues to serve as part of a highway system (Jackson, 1988).

Stone arch bridges were usually small scale and built by local masons. These bridges were never as popular in the United States as they were in Europe. Part of the reason for lack of popularity is that stone arch bridges are labor intensive and expensive to build. However, with the development of the railroads in the mid- to late nineteenth century, the stone arch bridge provided the necessary strength and stiffness for carrying heavy loads, and a number of impressive spans were built. One was the Starrucca Viaduct, Lanesboro, Pennsylvania, which was completed in 1848, and another was the James J. Hill Stone Arch Bridge, Minneapolis, Minnesota, completed in 1883.

The Starrucca Viaduct (Exhibit 2 in the color insert) is 1040 ft (317 m) in overall length and is composed of 17 arches, each with a span of 50 ft (15 m). The viaduct is located on what was known as the New York and Erie Railroad over Starrucca Creek near its junction with the Susquehanna River. Except for the interior spandrel walls being of brick masonry, the structure was of stone masonry quarried locally. The maximum height of the roadbed above the creek is 112 ft (34 m) (Jackson, 1988) and it still carries heavy railroad traffic.

The James J. Hill Stone Arch Bridge (Fig. 1.1) is 2490 ft (760 m) long and incorporated 23 arches in its original design (later, 2 arches were replaced with steel trusses to provide navigational clearance). The structure carried Hill's Great Northern Railroad (now merged into the Burlington Northern Santa Fe Railway) across the Mississippi River just below St. Anthony Falls. It played a key role in the development of the Northwest. The bridge was retired in 1982, just short of its 100th birthday, but it still stands today as a reminder of an era gone by and bridges that were built to last (Jackson, 1988).

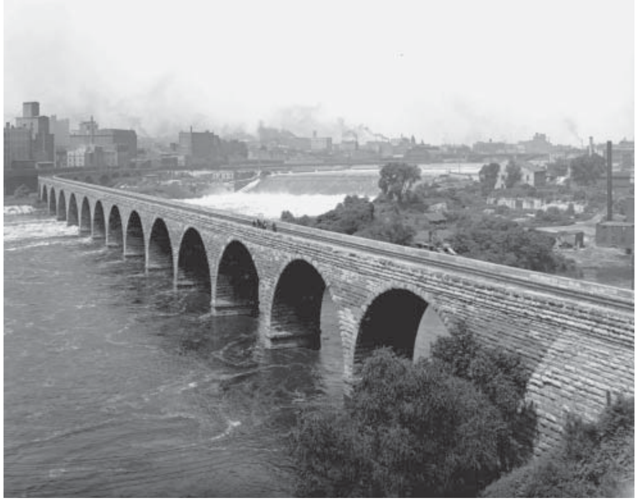

Fig. 1.1 James J. Hill Stone Arch Bridge, Minneapolis, Minnesota. (Hibbard Photo, Minnesota Historical Society, July 1905.)

1.2.2 Wooden Bridges

Early bridge builders in the United States (Timothy Palmer, Lewis Wernwag, Theodore Burr, and Ithiel Town) began their careers as millwrights or carpenter–mechanics. They had no clear conception of truss action, and their bridges were highly indeterminate combinations of arches and trusses (Kirby and Laurson, 1932). They learned from building large mills how to increase clear spans by using the king-post system or trussed beam. They also appreciated the arch form and its ability to carry loads in compression to the abutments. This compressive action was important because wood joints can transfer compression more efficiently than tension.

The long-span wooden bridges built in the late eighteenth and early nineteenth centuries incorporated both the truss and the arch. Palmer and Wernwag constructed trussed arch bridges in which arches were reinforced by trusses (Fig. 1.2). Palmer built a 244 ft (74 m) trussed arch bridge over the Piscataqua in New Hampshire in the 1790s. Wernwag built his "Colossus" in 1812 with a span of 340 ft (104 m) over the Schuylkill at Fairmount, Pennsylvania (Gies, 1963).

In contrast to the trussed arch of Palmer and Wernwag, Burr utilized an arched truss in which a truss is reinforced by an arch (Fig. 1.3) and patented his design in 1817. An example of one that has survived until today is the Philippi Covered Bridge (Fig. 1.4) across the Tygant's Valley River, West Virginia. Lemuel Chenoweth completed it in 1852 as a two-span Burr arched truss with a total length of 577 ft (176 m) long. In later years, two reinforced concrete piers were added under each span to strengthen the bridge (Exhibit 3 in the color insert). As a result, it is able to carry traffic loads and is the nation's only covered bridge serving a federal highway.

One of the reasons many covered bridges have survived for well over 100 years is that the wooden arches and trusses have been protected from the weather. Palmer put a roof and siding on his "permanent bridge" (called permanent because it replaced a pontoon bridge) over the Schuylkill at Philadelphia in 1806, and the bridge lasted nearly 70 years before it was destroyed by fire in 1875.

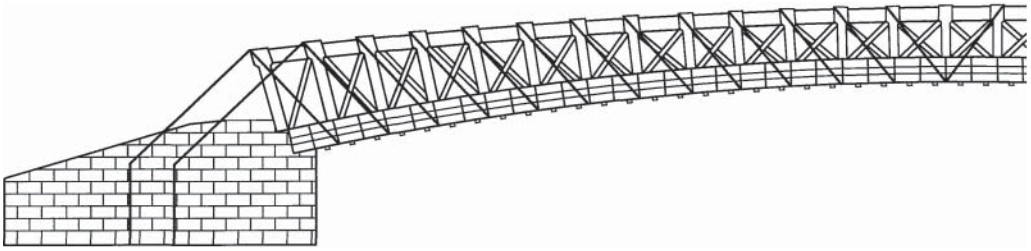

Fig. 1.2 Trussed arch—designed by Lewis Wernwag, patented 1812.

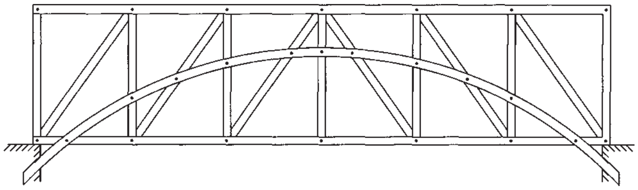

Fig. 1.3 Arched truss—designed by Theodore Burr, patented 1817. (From *Bridges and Men* by Joseph Gies. Copyright © 1963 by Joseph Gies. Used by permission of Doubleday, a division of Bantam Doubleday Dell Publishing Group, Inc.)

Besides protecting the wood from alternating cycles of wet and dry that cause rot, other advantages of the covered bridge occurred. During winter blizzards, snow did not accumulate on the bridge. However, this presented another problem: bare wooden decks had to be paved with snow because everybody used sleighs. Another advantage was that horses were not frightened by the prospect of crossing a rapidly moving stream over an open bridge because the covered bridge had a comforting barnlike appearance (so says the oral tradition). American folklore also says the covered bridges became favorite parking spots for couples in their rigs, out of sight except for the eyes of curious children who had climbed up and hid in the rafters (Gies, 1963). However, the primary purpose of covering the bridge was to prevent deterioration of the wood structure.

Another successful wooden bridge form first built in 1813 was the lattice truss, which Ithiel Town patented in 1820 (Edwards, 1959). This bridge consisted of strong top and bottom chords, sturdy end posts, and a web of lattice work (Fig. 1.5). This truss type was popular with builders because all of the web members were of the same length and could be prefabricated and sent to the job site for assembly. Another advantage is that it had sufficient stiffness by itself and did not require an arch to reduce deflections. This inherent stiffness meant that horizontal thrusts did not have to be resisted by abutments, and a true truss, with only vertical reactions, had really arrived.

The next step toward simplicity in wooden bridge truss types in the United States is credited to an army engineer named Colonel Stephen H. Long who had been assigned by the War Department to the Baltimore and Ohio Railroad (Edwards, 1959). In 1829, Colonel Long built the first

Fig. 1.4 Philippi covered bridge. (Photo by Larry Belcher, courtesy of West Virginia Department of Transportation.)

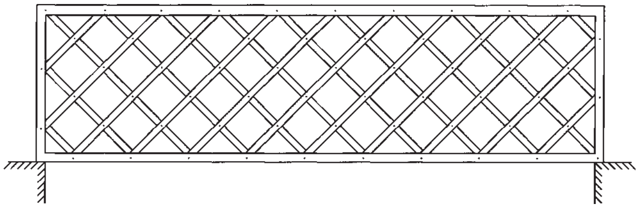

Fig. 1.5 Lattice truss—designed by Ithiel Town, patented 1820. (From *Bridges and Men* by Joseph Gies. Copyright © 1963 by Joseph Gies. Used by permission of Doubleday, a division of Bantam Doubleday Dell Publishing Group, Inc.)

American highway–railroad grade separation project. The trusses in the superstructure had parallel chords that were subdivided into panels with counterbraced web members (Fig. 1.6). The counterbraces provided the necessary stiffness for the panels as the loading changed in the diagonal web members from tension to compression as the railroad cars moved across the bridge.

The development of the paneled bridge truss in wooden bridges enabled long-span trusses to be built with other materials. In addition, the concept of web panels is important because it is the basis for determining the shear resistance of girder bridges. These concepts are called the modified compression field theory in Chapter 14 and tension field action in Chapter 19.

1.2.3 Metal Truss Bridges

Wooden bridges were serving the public well when the loads being carried were horse-drawn wagons and carriages. Then along came the railroads with their heavy loads, and the wooden bridges could not provide the necessary strength and stiffness for longer spans. As a result, wrought-iron rods replaced wooden tension members, and a hybrid truss composed of a combination of wood and metal members was developed. As bridge builders' understanding of which members were carrying tension and which were carrying compression increased, cast iron replaced wooden compression members, thus completing the transition to an all-metal truss form. (Web search for *wrought iron*, *cast iron*, *mild steel* for background on chemistry and properties. Also see Chapter 17 on making steel.)

In 1841, William Howe, uncle of Elias Howe, the inventor of the sewing machine, received a patent on a truss arrangement in which he took Long's panel system and replaced the wooden vertical members with wrought-iron rods (Gies, 1963). The metal rods ran through the top and bottom chords and could be tightened by turnbuckles to hold the wooden diagonal web members in compression against cast-iron angle blocks (Fig. 1.7). Occasionally, Howe truss bridges were built entirely of metal, but in general they were composed of both wood and metal components. These bridges have the advantages of the panel system as well as those offered by counterbracing.

Thomas and Caleb Pratt (Caleb was the father of Thomas) patented a second variation on Long's panel system in 1844 with wooden vertical members to resist compression and metal diagonal members, which resist only tension (Jackson, 1988). Most of the Pratt trusses built in the United States were entirely of metal, and they became more commonly used than any other type. Simplicity, stiffness, constructability, and economy earned this recognition (Edwards, 1959). The distinctive feature of the Pratt truss (Fig. 1.8), and related designs, is that the main diagonal members are in tension.

In 1841, Squire Whipple patented a cast-iron arch truss bridge (Fig. 1.9), which he used to span the Erie Canal at Utica, New York. (Note: Whipple was not a country gentleman; his first name just happened to be Squire.) Whipple utilized wrought iron for the tension members and cast iron for the compression members. This bridge form became known as a bowstring arch truss, although some engineers considered the design to be more a tied arch than a truss (Jackson, 1988). The double-intersection Pratt truss of Figure 1.10, in which the diagonal tension members extended over two panels, was also credited to Whipple because he was the first to use the design when he built railroad bridges near Troy, New York.

To implement his designs, it is implied that Squire Whipple could analyze his trusses and knew the magnitudes of the

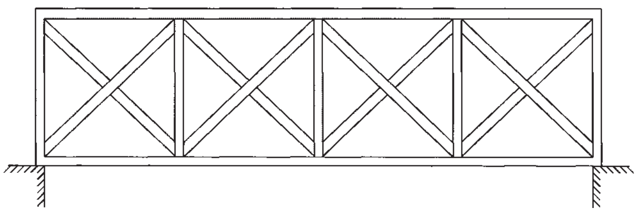

Fig. 1.6 Multiple king-post truss—designed by Colonel Stephen H. Long in 1829. (From *Bridges and Men* by Joseph Gies. Copyright © 1963 by Joseph Gies. Used by permission of Doubleday, a division of Bantam Doubleday Dell Publishing Group, Inc.)

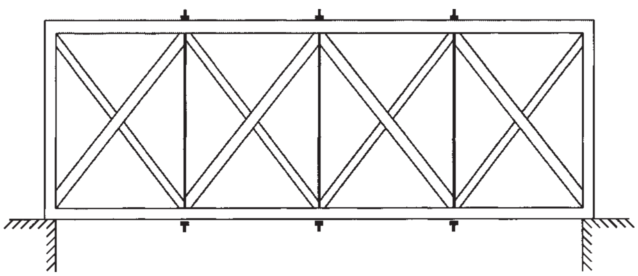

Fig. 1.7 Howe truss—designed by William Howe, patented in 1841. (From *Bridges and Men* by Joseph Gies. Copyright © 1963 by Joseph Gies. Used by permission of Doubleday, a division of Bantam Doubleday Dell Publishing Group, Inc.)

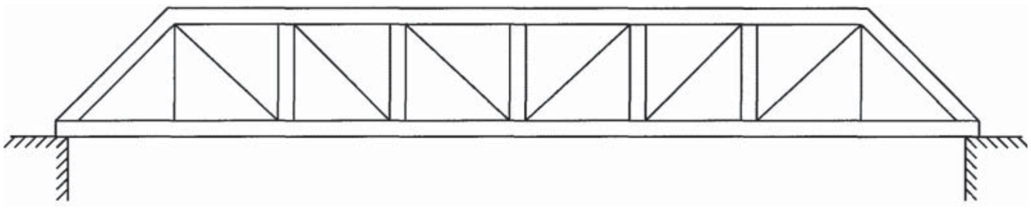

Fig. 1.8 Pratt truss—designed by Thomas and Caleb Pratt, patented in 1844. (From *Bridges and Men* by Joseph Gies. Copyright © 1963 by Joseph Gies. Used by permission of Doubleday, a division of Bantam Doubleday Dell Publishing Group, Inc.)

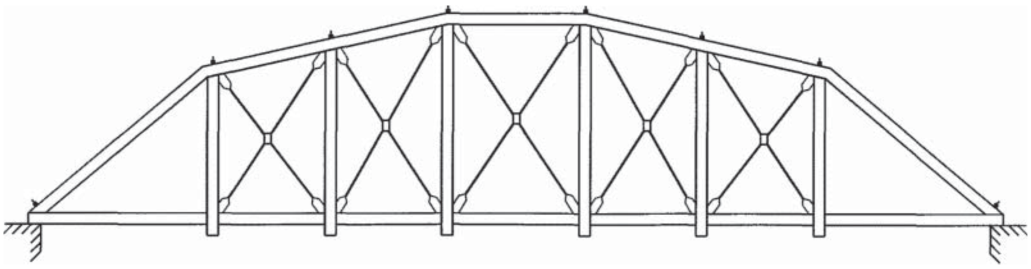

Fig. 1.9 Bowstring arch—designed by Squire Whipple, patented in 1841.

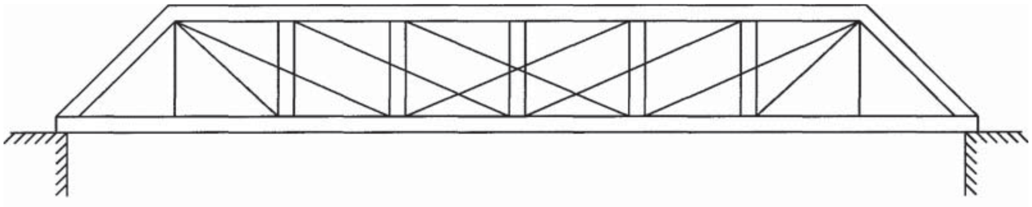

Fig. 1.10 Double-intersection Pratt—credited to Squire Whipple.

tensile and compressive forces in the various members. He was a graduate of Union College, class of 1830, and in 1847 he published the first American treatise on determining the stresses produced by bridge loads and proportioning bridge members. It was titled *A Work on Bridge Building; Consisting of Two Essays, the One Elementary and General, the Other Giving Original Plans, and Practical Details for Iron and Wooden Bridges* (Edwards, 1959). In it he showed how one could compute the tensile or compressive stress in each member of a truss that was to carry a specific load (Kirby et al., 1956).

In 1851, Herman Haupt, a graduate of the U.S. Military Academy at West Point, class of 1835, authored a book titled *General Theory of Bridge Construction*, which was published by D. Appleton and Company (Edwards, 1959). This book and the one by Squire Whipple were widely used by engineers and provided the theoretical basis for selecting cross sections to resist bridge dead loads and live loads.

One other development that was critical to the bridge design profession was the ability to verify the theoretical predictions with experimental testing. The tensile and compressive strengths of cast iron, wrought iron, and steel had to be determined and evaluated. Column load curves had to be developed by testing cross sections of various lengths. This experimental work requires large-capacity testing machines.

The first testing machine to be made in America was built in 1832 to test a wrought-iron plate for boilers by the Franklin Institute of Philadelphia (Edwards, 1959). Its capacity was about 10 tons (90 kN), not enough to test bridge components. About 1862, William Sallers and Company of Philadelphia built a testing machine that had a rated capacity of 500 tons (4500 kN) and was specially designed for the testing of full-size columns.

Two testing machines were built by the Keystone Bridge Works, Pittsburgh, Pennsylvania, in 1869–1870 for the St. Louis Bridge Company to evaluate materials for the Eads Bridge over the Mississippi River. One had a capacity of 100 tons (900 kN) and the other a capacity of 800 tons (7200 kN). At the time it was built, the capacity of the larger testing machine was greater than any other in existence (Edwards, 1959).

During the last half of the nineteenth century, the capacity of the testing machines continued to increase until in 1904 the American Bridge Company built a machine having a tension capacity of 2000 tons (18,000 kN) (Edwards, 1959) at its Ambridge, Pennsylvania, plant. These testing machines were engineering works in themselves, but they were essential to verify the strength of the materials and the resistance of components in bridges of ever increasing proportions.

1.2.4 Suspension Bridges

Suspension bridges capture the imagination of people everywhere. With their tall towers, slender cables, and tremendous spans, they appear as ethereal giants stretching out to join together opposite shores. Sometimes they are short and stocky and seem to be guardians and protectors of their domain. Other times, they are so long and slender that they seem to be fragile and easily moved. Whatever their visual image, people react to them and remember how they felt when they first saw them.

Imagine the impression on a young child on a family outing in a state park and seeing for the first time the infamous "swinging bridge" across the raging torrent of a rock-strewn river (well, it seemed like a raging torrent). And then the child hears the jeers and challenge of the older children, daring him to cross the river as they moved side to side and purposely got the swinging bridge to swing. Well, it did not happen that first day; it felt more comfortable to stay with mother and the picnic lunch. But it did happen on the next visit, a year or two later. It was like a rite of passage. A child no longer, he was able to cross over the rock-strewn stream on the swinging bridge, not fighting it but moving with it and feeling the exhilaration of being one with forces stronger than he was.

Suspension bridges also make strong impressions on adults, and having an engineering education is not a prerequisite. People in the United States have enjoyed these structures on both coasts, where they cross bays and mouths of rivers. The most memorable are the Brooklyn Bridge (Exhibit 4 in the color insert) in the east and the Golden Gate Bridge (Exhibit 5 in the color insert) in the west. They are also in the interior of the country, where they cross the great rivers, gorges, and straits. Most people understand that the cables are the tendons from which the bridge deck is hung, but they marvel at their strength and the ingenuity it took to get them in place. When people see photographs of workers on the towers of suspension bridges, they catch their breath and then wonder at how small the workers are compared with the towers they have built. Suspension bridges bring out the emotions—wonder, awe, fear, pleasure—but mostly they are enjoyed for their beauty and grandeur.

In 1801, James Finley erected a suspension bridge with wrought-iron chains of 70 ft (21 m) span over Jacob's Creek near Uniontown, Pennsylvania. He is credited as the inventor of the modern suspension bridge with its stiff level floors and secured a patent in 1808 (Kirby and Laurson, 1932). In previous suspension bridges, the roadway was flexible and followed the curve of the ropes or chains. By stiffening the roadway and making it level, Finley developed a suspension bridge that was suitable not only for footpaths and trails but also for roads with carriages and heavy wagons.

Most engineers are familiar with the suspension bridges of John A. Roebling: the Niagara River Bridge, completed in 1855 with a clear span of 825 ft (250 m); the Cincinnati Suspension Bridge, completed in 1867 with a clear span of 1057 ft (322 m); and the Brooklyn Bridge, completed in 1883 with a clear span of 1595 ft (486 m). Of these three wire cable suspension bridges from the nineteenth century, the last two are still in service and are carrying highway traffic. However, there is one other long-span wire cable suspension bridge from this era that is noteworthy and still carrying traffic: the Wheeling Suspension Bridge completed in 1849 with a clear span of 1010 ft (308 m) (Fig. 1.11).

The Wheeling Suspension Bridge over the easterly channel of the Ohio River was designed and built by Charles Ellet

Fig. 1.11 Wheeling Suspension Bridge. (Photo by John Brunell, courtesy of West Virginia Department of Transportation.)

who won a competition with John Roebling; that is, he was the low bidder. This result of a competition was also true of the Niagara River Bridge, except that Ellet walked away from it after the cables had been strung, saying that the $190,000 he bid was not enough to complete it. Roebling was then hired and he completed the project for about $400,000 (Gies, 1963).

The original Wheeling Suspension Bridge did not have the stiffening truss shown in Figure 1.11. This truss was added after a windstorm in 1854 caused the bridge to swing back and forth with increased momentum, the deck to twist and undulate in waves nearly as high as the towers, until it all came crashing down into the river (very similar to the Tacoma Narrows Bridge failure some 80 years later). A Web search for "Tacoma Narrows Movie" will provide several opportunities to view movies that illustrate the failure.

The Wheeling Bridge had the strength to resist gravity loads, but it was aerodynamically unstable. Why this lesson was lost to the profession is unknown, but if it had received the attention it deserved, it would have saved a lot of trouble in the years ahead.

What happened to the Wheeling Suspension Bridge was not lost on John Roebling. He was in the midst of the Niagara River project when he heard of the failure and immediately ordered more cable to be used as stays for the double-decked bridge. An early painting of the Niagara River Bridge shows the stays running from the bottom of the deck to the shore to provide added stability.

In 1859 William McComas, a former associate of Charles Ellet, rebuilt the Wheeling Suspension Bridge. In 1872 Wilhelm Hildenbrand, an engineer with Roebling's company, modified the deck and added diagonal stay wires between the towers and the deck to increase the resistance to wind (Jackson, 1988) and to give the bridge the appearance it has today.

The completion of the Brooklyn Bridge in 1883 brought to maturity the building of suspension bridges and set the stage for the long-span suspension bridges of the twentieth century. Table 1.1 provides a summary of some of the notable long-span suspension bridges built in the United States and still standing.

Some comments are in order with regard to the suspension bridges in Table 1.1. The Williamsburg Bridge and the Brooklyn Bridge are of comparable span but with noticeable differences. The Williamsburg Bridge has steel rather than masonry towers. The deck truss is a 40 ft (12.5 m) deep lattice truss, compared with a 17 ft (5.2 m) deep stiffening truss of its predecessor. This truss gives the Williamsburg Bridge a bulky appearance, but it is very stable under traffic and wind loadings. Another big difference is that the wire in the steel cables of the Brooklyn Bridge was galvanized to protect it from corrosion in the briny atmosphere of the East River (Gies, 1963), while the wire in its successor was not. As a result, the cables of the Williamsburg Bridge have had to be rehabilitated with a new protective system that cost $73 million (Bruschi and Koglin, 1996). A Web search

Table 1.1 Long-Span Suspension Bridges in the United States (not inclusive)

Bridge	Site	Designer	Clear Span, ft (m)	Date
Wheeling	West Virginia	Charles Ellet	1010 (308)	1847
Cincinnati	Ohio	John Roebling	1057 (322)	1867
Brooklyn	New York	John Roebling Washington Roebling	1595 (486)	1883
Williamsburg	New York	Leffert Lefferts Buck	1600 (488)	1903
Bear Mountain	Hudson Valley	C. Howard Baird	1632 (497)	1924
Ben Franklin	Philadelphia	Ralph Modjeski Leon Moisseiff	1750 (533)	1926
Ambassador	Detroit	Jonathon Jones Leon Moisseiff	1850 (564)	1929
George Washington	New York	Othmar Ammann Leon Moisseiff	3500 (1067)	1931
Golden Gate	San Francisco	Joseph Strauss Charles Ellis Leon Moisseiff	4200 (1280)	1937
Verrazano-Narrows	New York	Ammann and Whitney	4260 (1298)	1964

for "Williamsburg Bridge image," or other bridge names listed in Table 1.1, provides a wealth of information and illustration.

Another observation of Table 1.1 is the tremendous increase in clear span attained by the George Washington Bridge over the Hudson River in New York. It nearly doubled the clear span of the longest suspension bridge in existence at the time it was built, a truly remarkable accomplishment.

One designer, Leon Moisseiff, is associated with most of the suspension bridges in Table 1.1 that were built in the twentieth century. He was the design engineer of the Manhattan and Ben Franklin bridges, participated in the design of the George Washington Bridge, and was a consulting engineer on the Ambassador, Golden Gate, and Oakland–Bay bridges (Gies, 1963). All of these bridges were triumphs and successes. He was a well-respected engineer who had pioneered the use of deflection theory, instead of the erroneous elastic theory, in the design of the Manhattan Bridge and those that followed. But Moisseiff will also be remembered as the designer of the Tacoma Narrows Bridge that self-destructed during a windstorm in 1940, not unlike that experienced by the Wheeling Suspension Bridge in 1854.

The use of a plate girder to stiffen the deck undoubtedly contributed to providing a surface on which the wind could act, but the overall slenderness of the bridge gave it an undulating behavior under traffic even when the wind was not blowing. Comparing the ratio of depth of truss or girder to the span length for the Williamsburg, Golden Gate, and Tacoma Narrows bridges, we have 1:40, 1:164, and 1:350, respectively (Gies, 1963). The design had gone one step too far in making a lighter and more economical structure. The tragedy for bridge design professionals of the Tacoma Narrows failure was a tough lesson, but one that will not be forgotten.

1.2.5 Metal Arch Bridges

Arch bridges are aesthetically pleasing and can be economically competitive with other bridge types. Sometimes the arch can be above the deck, as in a tied-arch design, or as in the bowstring arch of Whipple (Fig. 1.9). Other times, when the foundation materials can resist the thrusts, the arch is below the deck. Restraint conditions at the supports of an arch can be fixed or hinged. And if a designer chooses, a third hinge can be placed at the crown to make the arch statically determinate or nonredundant.

The first iron arch bridge in the United States was built in 1839 across Dunlap's Creek at Brownsville in southwestern Pennsylvania on the National Road (Jackson, 1988). The arch consists of five tubular cast-iron ribs that span 80 ft (24 m) between fixed supports. It was designed by Captain Richard Delafield and built by the U.S. Army Corps of Engineers (Jackson, 1988). It is still in service today.

The second cast-iron arch bridge in this country was completed in 1860 across Rock Creek between Georgetown and Washington, D.C. It was built by the Army Corps of Engineers under the direction of Captain Montgomery Meigs as part of an 18.6 mile (30 km) aqueduct, which brings water from above the Great Falls on the Potomac to Washington, D.C. The two arch ribs of the bridge are 4 ft (1.2 m) diameter cast-iron pipes that span 200 ft (61 m) with a rise of 20 ft (6.1 m) and carry water within its 1.5 inch (38 mm) thick walls. The arch supports a level roadway on open-spandrel posts that carried Washington's first horse-drawn street railway line (Edwards, 1959). The superstructure was removed in 1916 and replaced by a concrete arch bridge. However, the pipe arches remain in place between the concrete arches and continue to carry water to the city today.

Two examples of steel deck arch bridges from the nineteenth century that still carry highway traffic are the Washington Bridge across the Harlem River in New York and the Panther Hollow Bridge in Schenely Park, Pittsburgh (Jackson, 1988). The two-hinged arches of the Washington Bridge, completed in 1889, are riveted plate girders with a main span of 508 ft (155 m). This bridge is the first American metal arch bridge in which the arch ribs are plate girders (Edwards, 1959). The three-hinged arch of the Panther Hollow Bridge, completed in 1896, has a span of 360 ft (110 m). Due to space limitations, not all bridges noted here can be illustrated in this book; however, Web searches for the bridge name and location easily takes the reader to a host of images and other resources.

One of the most significant bridges built in the United States is the steel deck arch bridge designed by James B. Eads (Exhibit 6 in the color insert) across the Mississippi River at St. Louis. It took 7 years to construct and was completed in 1874. The three-arch superstructure consisted of two 502 ft (153 m) side arches and one 520 ft (159 m) center arch that carried two decks of railroad and highway traffic (Fig. 1.12). The Eads Bridge is significant because of the very deep pneumatic caissons for the foundations, the early use of steel in the design, and the graceful beauty of its huge arches as they span across the wide river (Jackson, 1988).

Because of his previous experience as a salvage diver, Eads realized that the foundations of his bridge could not be placed on the shifting sands of the riverbed but must be set on bedrock. The west abutment was built first with the aid of a cofferdam and founded on bedrock at a depth of 47 ft (14 m). Site data indicated that bedrock sloped downward from west to east, with an unknown depth of over 100 ft (30 m) at the east abutment, presenting a real problem for cofferdams. While recuperating from an illness in France, Eads learned that European engineers had used compressed air to keep water out of closed caissons (Gies, 1963). He adapted the technique of using caissons, or wooden boxes; added a few innovations of his own, such as a sand pump; and completed the west and east piers in the river. The west pier is at a depth of 86 ft (26 m) and the east pier at a depth of 94 ft (29 m).

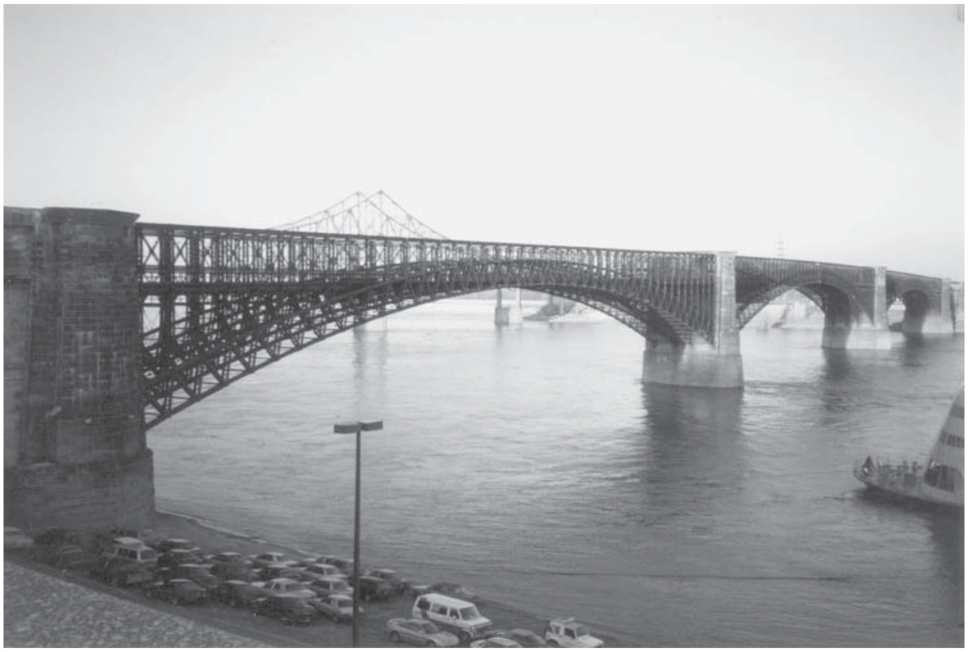

Fig. 1.12 Eads Bridge, St. Louis, Missouri. (Photo courtesy of Kathryn Kontrim, 1996.)

However, the construction of these piers was not without cost. Twelve workmen died in the east pier and one in the west pier from caisson's disease, or the bends. These deaths caused Eads and his physician, Dr. Jaminet, much anxiety because the east abutment had to go even deeper. Based on his own experience in going in and out of the caissons, Dr. Jaminet prescribed slow decompression and shorter working time as the depth increased. At a depth of 100 ft (30 m), a day's labor consisted of two working periods of 45 min each, separated by a rest period. As a result of the strict rules, only one death occurred in the placement of the east abutment on bedrock at a depth of 136 ft (42 m). Today's scuba diving tables suggest a 30 min stay at 100 ft (30 m) for comparison.

It is ironic that the lessons learned by Eads and Dr. Jaminet were not passed on to Washington Roebling and his physician, Dr. Andrew H. Smith, in the parallel construction of the Brooklyn Bridge. The speculation is that Eads and Roebling had a falling-out because of Eads' perception that Roebling had copied a number of caisson ideas from him. Had they remained on better terms, Roebling may not have been stricken by the bends and partially paralyzed for life (Gies, 1963).

Another significant engineering achievement of the Eads Bridge was in the use of chrome steel in the tubular arches that had to meet, for that time, stringent material specifications. Eads insisted on an elastic limit of 50 ksi (345 MPa) and an ultimate strength of 120 ksi (827 MPa) for his steel at a time when the steel producers (one of which was Andrew Carnegie) questioned the importance of an elastic limit (Kirby et al., 1956). The testing machines mentioned in Section 1.2.3 had to be built, and it took some effort before steel could be produced that would pass the tests. The material specification of Eads was unprecedented in both its scale and quality of workmanship demanded, setting a benchmark for future standards (Brown, 1993).

The cantilever construction of the arches for the Eads Bridge was also a significant engineering milestone. Falsework in the river was not possible, so Eads built falsework on top of the piers and cantilevered the arches, segment by segment in a balanced manner, until the arch halves met at midspan (Kirby et al., 1956). On May 24, 1874, the highway deck was opened for pedestrians; on June 3 it was opened for vehicles; and on July 2 some 14 locomotives, 7 on each track, crossed side by side (Gies, 1963). The biggest bridge of any type ever built anywhere up to that time had been completed. The Eads Bridge remains in service today and at the time of this writing is being rehabilitated to repair the track, ties, and rails, the deck and floor system, masonry, and other structural improvements.

Since the Eads Bridge, steel arch bridges longer than its 520 ft (159 m) center span have been constructed. These include the 977 ft (298 m) clear span Hell Gate Bridge over the East River in New York, completed in 1917; the 1675 ft (508 m) clear span Bayonne Arch Bridge over the Kill van Kull between Staten Island and New Jersey, completed in 1931; and the United States' longest 1700 ft (518 m) clear span New River Gorge Bridge near Fayetteville, West Virginia, completed in 1978 and designed by Michael Baker, Jr., Inc. (Fig. 1.13). Annually the locals celebrate "New River Bridge Day" noted as the state's biggest party of the year. A Web search provides a lot of detail, movies on base jumping, and so forth. This is yet another example of the importance

Fig. 1.13 New River Gorge Bridge. (Photo by Terry Clark Photography, courtesy of West Virginia Department of Transportation.)

of our bridges for social affairs perhaps not even expected by the owner or designers.

1.2.6 Reinforced Concrete Bridges

In contrast to wood and metal, reinforced concrete has a relatively short history. It was in 1824 that Joseph Aspdin of England was recognized for producing Portland cement by heating ground limestone and clay in a kiln. This cement was used to line tunnels under the Thames River because it was water resistant. In the United States, D. O. Taylor produced Portland cement in Pennsylvania in 1871, and T. Millen produced it about the same time in South Bend, Indiana. It was not until the early 1880s that significant amounts were produced in the United States (MacGregor and Wight, 2008).

In 1867, a French nursery gardener, Joseph Monier, received a patent for concrete tubs reinforced with iron. In the United States, Ernest Ransome of California was experimenting with reinforced concrete, and in 1884 he received a patent for a twisted steel reinforcing bar. The first steel bar reinforced concrete bridge in the United States was built by Ransome in 1889: the Alvord Lake Bridge (Exhibit 7 in the color insert) in Golden Gate Park, San Francisco. This bridge has a modest span of 29 ft (9 m), is 64 ft (19.5 m) wide, and is still in service (Jackson, 1988).

After the success of the Alvord Lake Bridge, reinforced concrete arch bridges were built in other parks because their classic stone arch appearance fit the surroundings. One of these that remains to this day is the 137 ft (42 m) span Eden Park Bridge in Cincinnati, Ohio, built by Fritz von Emperger in 1895. This bridge is not a typical reinforced concrete arch but has a series of curved steel I-sections placed in the bottom of the arch and covered with concrete. Joseph Melan of Austria developed this design and, though it was used only for a few years, it played an important role in establishing the viability of reinforced concrete bridge construction (Jackson, 1988).

Begun in 1897, but not completed until 1907, was the high-level Taft Bridge carrying Connecticut Avenue over Rock Creek in Washington, D.C. This bridge consists of five open-spandrel unreinforced concrete arches supporting a reinforced concrete deck. George Morison designed it and Edward Casey supervised its construction (Jackson, 1988). This bridge has recently been renovated and is prepared to give many more years of service. A Web search for “Rock Creek Bridge DC” provides nice pictures that illustrate the rich aesthetics of this structure in an important urban and picturesque setting.

Two reinforced concrete arch bridges in Washington, D.C., over the Potomac River are also significant. One is the Key Bridge (named after Francis Scott Key who lived near the Georgetown end of the bridge), completed in 1923, which connects Georgetown with Rosslyn, Virginia. It has seven open-spandrel three-ribbed arches designed by Nathan C. Wyeth and the bridge has recently been refurbished. The other is the Arlington Memorial Bridge, completed in 1932, which connects the Lincoln Memorial and Arlington National Cemetery. It has nine arches; eight are closed-spandrel reinforced concrete arches, and the center arch, with a span of 216 ft (66 m), is a double-leaf steel bascule bridge that has not been opened for several years. It was designed by the architectural firm of McKim, Mead, and White (Jackson, 1988).

Other notable reinforced concrete deck arch bridges still in service include the 9-span, open-spandrel Colorado Street Bridge in Pasadena, California, near the Rose Bowl, designed by Waddell and Harrington, and completed in 1913; the 100 ft (30 m) single-span, open-spandrel Shepperd’s Dell Bridge across the Young Creek near Latourell, Oregon, designed by K. R. Billner and S. C. Lancaster, and completed in 1914; the 140 ft (43 m) single-span, closed-spandrel Canyon Padre Bridge on old Route 66 near Flagstaff, Arizona, designed by Daniel Luten and completed in 1914; the 10-span, open-spandrel Tunkhannock Creek Viaduct (Exhibit 8 in the color insert) near Nicholson, Pennsylvania, designed by A. Burton Cohen and completed in 1915 (considered to be volumetrically the largest structure of its type in the world); the 13-span, open-spandrel Mendota Bridge across the Minnesota River at Mendota, Minnesota, designed by C. A. P. Turner and Walter Wheeler and completed in 1926; the

7-span, open-spandrel Rouge River Bridge on the Oregon Coast Highway near Gold Beach, Oregon, designed by Conde B. McCullough and completed in 1932; the 5-span, open-spandrel George Westinghouse Memorial Bridge across Turtle Creek at North Versailles, Pennsylvania, designed by Vernon R. Covell and completed in 1931; and the 360 ft (100 m) single-span, open-spandrel Bixby Creek Bridge south of Carmel, California, on State Route 1 amid the rugged terrain of the Big Sur (Fig. 1.14), designed by F. W. Panhorst and C. H. Purcell and completed in 1933 (Jackson, 1988).

Reinforced concrete through-arch bridges were also constructed. James B. Marsh received a patent in 1912 for the Marsh rainbow arch bridge. This bridge resembles a bowstring arch truss but uses reinforced concrete for its main members. Three examples of Marsh rainbow arch bridges still in service are the 90 ft (27 m) single-span Spring Street Bridge across Duncan Creek in Chippewa Falls, Wisconsin, completed in 1916; the eleven 90 ft (27 m) arch spans of the Fort Morgan Bridge across the South Platte River near Fort Morgan, Colorado, completed in 1923; and the 82 ft (25 m) single-span Cedar Creek Bridge near Elgin, Kansas, completed in 1927 (Jackson, 1988).

One interesting feature of the 1932 Rogue River Bridge (Exhibit 9 in the color insert), which is a precursor of things to come, is that the arches were built using the prestressing construction techniques first developed by the French engineer Ernest Freyssinet in the 1920s (Jackson, 1988). In the United States, the first prestressed concrete girder bridge was the Walnut Lane Bridge in Philadelphia, which was completed in 1950. After the success of the Walnut Lane Bridge, prestressed concrete construction of highway bridges gained in popularity and is now used throughout the United States.

1.2.7 Girder Bridges

Girder bridges are the most numerous of all highway bridges in the United States. Their contribution to the transportation system often goes unrecognized because the great suspension, steel arch, and concrete arch bridges are the ones people remember. The spans of girder bridges seldom exceed 500 ft (150 m), with a majority of them less than 170 ft (50 m), so they do not get as much attention as they perhaps should. Girder bridges are important structures because they are used so frequently.

With respect to the overall material usage, girders are not as efficient as trusses in resisting loads over long spans. However, for short and medium spans the difference in material weight is small and girder bridges are competitive. In addition, the girder bridges have greater stiffness and are less subject to vibrations. This characteristic was important to the railroads and resulted in the early application of plate girders in their bridges.

A plate girder is an I-section assembled out of flange and web plates. The earliest ones were fabricated in England with rivets connecting double angles from the flanges to the web. In the United States, a locomotive builder, the Portland Company of Portland, Maine, fabricated a number of railroad bridges around 1850 (Edwards, 1959). In early plate girders, the webs were often deeper than the maximum width of plate produced by rolling mills. As a result, the plate girders were assembled with the lengthwise dimension of the web plate in the transverse direction of the section from flange to flange. An example is a wrought-iron plate

Fig. 1.14 Bixby Creek Bridge, south of Carmel, California. [From Roberts (1990). Used with permission of American Concrete Institute.]

girder span of 115 ft (35 m) built by the Elmira Bridge Company, Elmira, New York, in 1890 for the New York Central Railroad with a web depth of 9 ft (2.7 m) fabricated from plates 6 ft (1.8 m) wide (Edwards, 1959).

Steel plate girders eventually replaced wrought iron in the railroad bridge. An early example is the 1500 ft (457 m) long Fort Sumner Railroad Bridge on concrete piers across the Pecos River, Fort Sumner, New Mexico, completed in 1906 (Jackson, 1988). This bridge is still in service.

Other examples of steel plate girder bridges are the 5935 ft (2074 m) long Knight's Key Bridge and the 6803 ft (1809 m) long Pigeon Key Bridge, both part of the Seven Mile Bridge across the Gulf of Mexico from the mainland to Key West, Florida (Jackson, 1988). Construction on these bridges began in 1908 and was completed in 1912. Originally they carried railroad traffic but were converted to highway use in 1938.

Following the success of the Walnut Lane Bridge (Exhibit 10 in color insert) in Philadelphia in 1950, prestressed concrete girders became popular as a bridge type for highway interchanges and grade separations. In building the interstate highway system, innumerable prestressed concrete girder bridges, some with single and multiple box sections have been and continue to be built.

Some of the early girder bridges, with their multiple short spans and deep girders, were not very attractive. However, with the advent of prestressed concrete and the development of segmental construction, the spans of girder bridges have become longer and the girders more slender. The result is that the concrete girder bridge is not only functional but can also be designed to be aesthetically pleasing (Fig. 1.15).

1.2.8 Closing Remarks

Bridge engineering in the United States has come a long way since those early stone arch and wooden truss bridges. It is a rich heritage, and much can be learned from the early builders in overcoming what appeared to be insurmountable difficulties. These builders had a vision of what needed to be done and, sometimes, by the sheer power of their will, completed projects that we view with awe today.

A brief excerpt from a book on the building of the Golden Gate by Kevin Starr (2010) reinforces this thought:

> *But before the bridge could be built it had to be envisioned. Imagining the bridge began as early as the 1850's and reached a crisis point by the 1920's. In this pre-design and pre-construction drama of vision, planning, and public and private organization, four figures played important roles. A Marin county businessman …, the San Francisco city engineer …, an engineering entrepreneur …, and a banker in Sonoma County …, played a crucial role in persuading the counties north of San Francisco that a bridge across the Golden Gate was in their best interest. Dreamers and doers, each of these men helped initiate a process that would after a decade of negotiations enlist hundreds of engineers, politicians, bankers, steelmakers, and, of equal importance to all of them, construction workers, in a successful effort to span the strait with a gently rising arc of suspended steel.*

Fig. 1.15 Napa River Bridge. (Photo courtesy of California Department of Transportation.)

The challenge for today's bridge engineer is to follow in the footsteps of these early designers and create and build bridges that other engineers will write about 100 and 200 years from now.

1.3 BRIDGE ENGINEER—PLANNER, ARCHITECT, DESIGNER, CONSTRUCTOR, AND FACILITY MANAGER

The bridge engineer is often involved with several or all aspects of bridge planning, design, and management. This situation is not typical in the building design profession where the architect usually heads a team of diverse design professionals consisting of architects and civil, structural, mechanical, and electrical engineers. In the bridge engineering profession, the bridge engineer works closely with other civil engineers who are in charge of the roadway alignment and design. After the alignment is determined, the engineer often controls the bridge type, aesthetics, and technical details. As part of the design process, the bridge engineer is often charged with reviewing shop drawing and other construction details.

Many aspects of the design affect the long-term performance of the system, which is of paramount concern to the bridge owner. The owner, who is often a department of transportation or other public agency, is charged with the management of the bridge, which includes periodic inspections, rehabilitation, and retrofits as necessary and continual prediction of the life-cycle performance or deterioration modeling. Such bridge management systems (BMS) are beginning to play an integral role in suggesting the allocation of resources to best maintain an inventory of bridges. A typical BMS is designed to predict the long-term costs associated with the deterioration of the inventory and recommend maintenance items to minimize total costs for a system of bridges. Because the bridge engineer is charged with maintaining the system of bridges, or inventory, their role differs significantly from the building engineer where the owner is often a real estate professional controlling only one, or a few, buildings, and then perhaps for a short time.

In summary, the bridge engineer has significant control over the design, construction, and maintenance processes. With this control comes significant responsibility for public safety and resources. The decisions the engineer makes in design will affect the long-term site aesthetics, serviceability, maintainability, and ability to retrofit for changing demands. In short, the engineer is (or interfaces closely with) the planner, architect, designer, constructor, and facility manager.

Many aspects of these functions are discussed in the following chapters where we illustrate both a broad-based approach to aid in understanding the general aspects of design, and also include many technical and detailed articles to facilitate the computation and validation of design. Often engineers become specialists in one or two of the areas mentioned in this discussion and interface with others who are expert in other areas. The entire field is so involved that near-complete understanding can only be gained after years of professional practice, and then, few individual engineers will have the opportunity for such diverse experiences.

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PROBLEMS

1.1 Explain why the *people* factor is important in bridge engineering.

1.2 In what way does a bridge control the capacity of a transportation system?

1.3 Discuss the necessity of considering life-cycle costs in the design of bridges.

1.4 How were the early U.S. wooden bridge builders able to conceive and build the long-span wooden arch and truss bridges (e.g., Wernwag's Colossus) without theoretical knowledge to analyze and proportion their structures?

1.5 What is the main reason wooden bridges were covered?

1.6 How is the bridge designer Col. Stephen H. Long linked to Long's Peak in Colorado?

1.7 Whipple in 1847 and Haupt in 1851 authored books on the analysis and design of bridge trusses. Discuss the difficulty steel truss bridge designers prior to these dates had in providing adequate safety.

1.8 Both cast-iron and wrought-iron components were used in early metal truss and arch bridges. How do they differ in manufacture? What makes the manufacture of steel different from both of them?

1.9 Explain why the development of large-capacity testing machines was important to the progress of steel bridges.

1.10 Who secured a patent, and when, for the modern suspension bridge with a stiff level floor?

1.11 The Wheeling Suspension Bridge that still carries traffic today is not the same bridge built in 1849. Explain what happened to the original.

1.12 Who was Charles Ellis, and what was his contribution to the building of the Golden Gate Bridge?

1.13 List four significant engineering achievements of the Eads Bridge over the Mississippi at St. Louis.

1.14 Use the Historic American Engineering Record (HAER) digitized collection of historic bridges and obtain additional information on one of the reinforced concrete bridges mentioned in Section 1.2.6.

1.15 Explain why girder bridges are not as efficient as trusses in resisting loads (with respect to material quantities).

1.16 Comment on the significance of the Walnut Lane Bridge in Philadelphia.

CHAPTER 2

Specifications and Bridge Failures

2.1 BRIDGE SPECIFICATIONS

For most bridge engineers, it seems that bridge specifications were always there. But that is not the case. The early bridges were built under a design–build type of contract. A bridge company would agree, for some lump-sum price, to construct a bridge connecting one location to another. There were no standard bridge specifications and the contract went to the low bidder. The bridge company basically wrote its own specifications when describing the bridge it was proposing to build. As a result, depending on the integrity, education, and experience of the builder, some very good bridges were constructed and at the same time some very poor bridges were built.

Of the highway and railroad bridges built in the 1870s, one out of every four failed, a rate of 40 bridges per year (Gies, 1963). The public was losing confidence and did not feel safe when traveling across any bridge. Something had to be done to improve the standards by which bridges were designed and built.

An event took place on the night of December 29, 1876, that attracted the attention of not only the public but also the engineering profession. In a blinding snowstorm, an 11-car train with a double-header locomotive started across the Ashtabula Creek at Ashtabula, Ohio, on a 175 ft (48 m) long iron bridge, when the first tender derailed, plowed up the ties, and caused the second locomotive to smash into the abutment (Gies, 1963). The coupling broke between the lead tender and the second locomotive, and the first locomotive and tender went racing across the bridge. The bridge collapsed behind them. The second locomotive, tender, and 11 cars plunged some 70 ft (20 m) into the creek. The wooden cars burst into flames when their pot-bellied stoves were upset, and a total of 80 passengers and crew died.

In the investigation that followed, a number of shortcomings in the way bridges were designed, approved, and built were apparent. An executive of the railroad who had limited bridge design experience designed the bridge. The acceptance of the bridge was by test loading with six locomotives, which only proved that the factor of safety was at least 1.0 for that particular loading. The bridge was a Howe truss with cast-iron blocks for seating the diagonal compression members. These blocks were suspected of contributing to the failure. It is ironic that at a meeting of the American Society of Civil Engineers (ASCE), a statement was made that "the construction of the truss violated every canon of our standard practice" at a time when there were no standards of practice (Gies, 1963).

The American practice of using concentrated axle loads instead of uniformly distributed loads was introduced in 1862 by Charles Hilton of the New York Central Railroad (Edwards, 1959). It was not until 1894 that Theodore Cooper proposed his original concept of train loadings with concentrated axle loadings for the locomotives and tender followed by a uniformly distributed load representing the train. The Cooper series loading became the standard in 1903 when adopted by the American Railroad Engineering Association (AREA) and remains in use to the present day.

On December 12, 1914, the American Association of State Highway Officials (AASHO) was formed, and in 1921 its Committee on Bridges and Allied Structures was organized. The charge to this committee was the development of standard specifications for the design, materials, and construction of highway bridges. During the period of development, mimeographed copies of the different sections were circulated to state agencies for their use. The first edition of the *Standard Specifications for Highway Bridges and Incidental Structures* was published in 1931 by AASHO.

The truck train load in the standard specifications is an adaptation of the Cooper loading concept applied to highway bridges (Edwards, 1959). The "H" series loading of AASHO was designed to adjust to different weights of trucks without changing the spacing between axles and wheels. These specifications have been reissued periodically to reflect the ongoing research and development in concrete, steel, and wood structures with the final seventeenth edition of the *Standard Specifications for Highway Bridges* appearing in 2002 (AASHTO, 2002). In 1963, the AASHO became the American Association of State Highway and Transportation Officials (AASHTO). The insertion of the word *Transportation* was to recognize the officials' responsibility for all modes of transportation (air, water, light rail, subways, tunnels, and highways).

In the beginning, the design philosophy utilized in the standard specification was working stress design (also known as allowable stress design). In the 1970s, variations in the uncertainties of loads were considered and load factor design (LFD) was introduced as an alternative method. In 1986, the Subcommittee on Bridges and Structures initiated a study on incorporating the load and resistance factor design (LRFD) philosophy into the standard specification. This study recommended that LRFD be utilized in the design of highway bridges. The subcommittee authorized a comprehensive rewrite of the entire standard specification to accompany the conversion to LRFD. The result was the first edition of the AASHTO (1994) *LRFD Bridge Design Specifications*. Additional editions were published in 1998, 2004, 2007, 2010, 2014, and the eighth edition in 2017 (AASHTO, 2017). The eighth edition is used for this book.

2.2 IMPLICATION OF BRIDGE FAILURES ON PRACTICE

On the positive side of the bridge failure at Ashtabula Creek, Ohio, in 1876 was the realization by the engineering profession that standards of practice for bridge design and construction had to be codified. Good intentions and a firm handshake were not sufficient to ensure safety for the traveling public. Specifications, with legal ramifications if they were not followed, had to be developed and implemented. For railroad bridges, this task began in 1899 with the formation of the American Railway Engineering and Maintenance of Way Association and resulted in the adoption of Theodore Cooper's specification for loadings in 1903.

As automobile traffic expanded, highway bridges increased in number and size. Truck loadings were constantly increasing, and legal limits had to be established. The original effort for defining loads, materials, and design procedures was made by the U.S. Department of Agriculture, Office of Public Roads in 1913 with the publication of its Circular No. 100, "Typical Specifications for the Fabrication and Erection of Steel Highway Bridges" (Edwards, 1959). In 1919, the Office of Public Roads became the Bureau of Public Roads (now the Federal Highway Administration [FHWA]), and a revised specification was prepared and issued.

The Committee on Bridges and Allied Structures of the AASHO issued the first edition of *Standard Specifications for Highway Bridges* in 1931. It is interesting to note in the preface of the seventeenth edition of this publication the listing of the years when the standard specifications were revised: 1935, 1941, 1944, 1949, 1953, 1957, 1961, 1965, 1969, 1973, 1977, 1983, 1989, 1992, 1996, and 2002. It is obvious that this document is constantly changing and adapting to new developments in the practice of bridge engineering.

In some cases, new information on the performance of bridges was generated by a bridge failure. A number of lessons have been learned from bridge failures that have resulted in revisions to the standard specifications. For example, changes were made to the seismic provisions after the 1971 San Fernando earthquake. Other bridge failure incidents that influence the practice of bridge engineering are given in the sections that follow.

2.2.1 Silver Bridge, Point Pleasant, West Virginia, December 15, 1967

The collapse of the Silver Bridge over the Ohio River between Point Pleasant, West Virginia, and Kanauga, Ohio, on December 15, 1967, resulted in 46 deaths, 9 injuries, and 31 of the 37 vehicles on the bridge fell with the bridge (NTSB, 1970).

Description The Point Pleasant Bridge was a suspension bridge with a main span of 700 ft (213 m) and two equal side spans of 380 ft (116 m). The original design was a parallel wire cable suspension bridge but had provisions for a heat-treated steel eyebar suspension design (Fig. 2.1) that could be substituted if the bidders furnished stress sheets and specifications of the proposed materials. The eyebar suspension bridge design was accepted and built in 1927 and 1928.

Two other features of the design were also unique (Dicker, 1971): The eyebar chains were the top chord of the stiffening truss over a portion of all three spans, and the base of each tower rested on rocker bearings (Fig. 2.2). As a result, redundant load paths did not exist, and the failure of a link in the eyebar chain would initiate rapid progressive failure of the entire bridge.

Cause of Collapse The National Transportation Safety Board (NTSB) found that the cause of the bridge collapse was a cleavage fracture in the eye of an eyebar of the north suspension chain in the Ohio side span (NTSB, 1970). The fracture was caused by development of a flaw due to stress corrosion and corrosion fatigue over the 40-year life of the bridge as the pin-connected joint adjusted its position with each passing vehicle.

Effect on Bridge Practice The investigation following the collapse of the Silver Bridge disclosed the lack of regular inspections to determine the condition of existing bridges. Consequently, the National Bridge Inspection Standards (NBIS) were established under the 1968 Federal Aid Highway Act. This act requires that all bridges built with federal

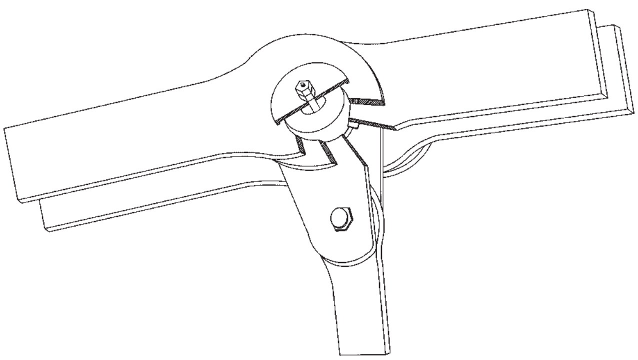

Fig. 2.1 Typical detail of eyebar chain and hanger connection (NTSB, 1970).

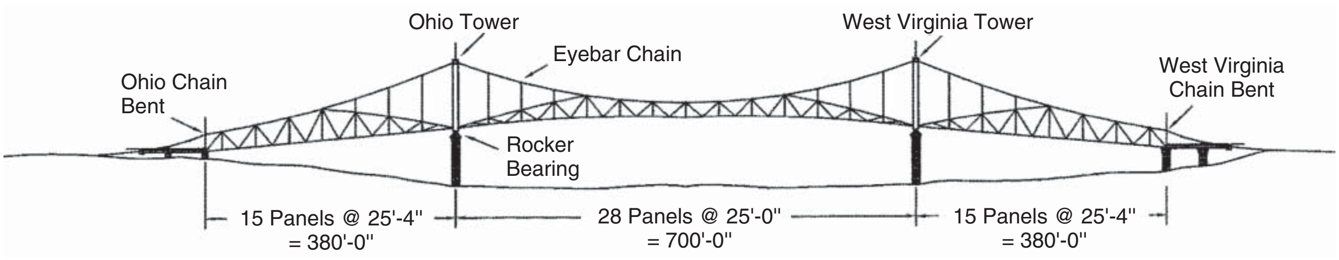

Fig. 2.2 Elevation of Silver Bridge over Ohio River, Point Pleasant, West Virginia (NTSB, 1970).

monies be inspected at regular intervals not to exceed 2 years. As a result, the state bridge agencies were required to catalog all their bridges in a National Bridge Inventory (NBI). There are over 600,000 bridges (100,000 are culverts) with spans greater than 20 ft (6 m) in the inventory.

It is ironic that even if the stricter inspection requirements had been in place, the collapse of the Silver Bridge probably could not have been prevented because the flaw could not have been detected without disassembly of the eyebar joint. A visual inspection of the pin connections with binoculars from the bridge deck would not have been sufficient. The problem lies with using materials that are susceptible to stress corrosion and corrosion fatigue and in designing structures without redundancy.

2.2.2 I-5 and I-210 Interchange, San Fernando, California, February 9, 1971

At 6:00 a.m. (Pacific Standard Time), on February 9, 1971, an earthquake with a Richter magnitude of 6.6 occurred in the north San Fernando Valley area of Los Angeles. The earthquake damaged approximately 60 bridges. Of this total, approximately 10% collapsed or were so badly damaged that they had to be removed and replaced (Lew et al., 1971). Four of the collapsed and badly damaged bridges were at the interchange of the Golden State Freeway (I-5) and Foothill Freeway (I-210). At this interchange, two men in a pickup truck lost their lives when the South Connector Overcrossing structure collapsed as they were passing underneath. These were the only fatalities associated with the collapse of bridges in the earthquake.

Description Bridge types in this interchange included composite steel girders, precast prestressed I-beam girders, and prestressed and nonprestressed cast-in-place reinforced concrete box girder bridges. The South Connector Overcrossing structure (bridge 2, Fig. 2.3) was a seven-span, curved, nonprestressed reinforced concrete box girder, carried on single-column bents, with a maximum span of 129 ft (39 m). The North Connector Overcrossing structure (bridge 3, Fig. 2.3) was a skewed four-span, curved, nonprestressed reinforced concrete box girder, carried on multiple-column bents, with a maximum span of 180 ft (55 m). A group of parallel composite steel girder bridges (bridge group 4,

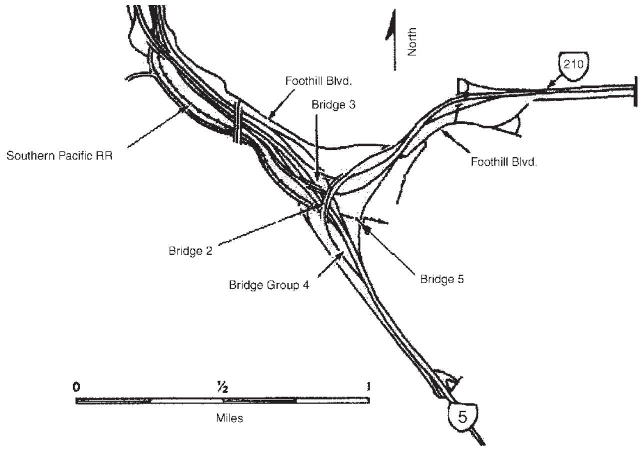

Fig. 2.3 Layout of the I-5 and I-210 Interchange (Lew et al., 1971).

Fig. 2.3) carried I-5 North and I-5 South over the Southern Pacific railroad tracks and San Fernando Road. Immediately to the east of this group, over the same tracks and road, was a two-span cast-in-place prestressed concrete box girder (bridge 5, Fig. 2.3) that was carried on a single bent, with a maximum span of 122 ft (37 m).

When the earthquake struck, the South Connector structure (Fig. 2.4, center) collapsed on to the North Connector and I-5, killing the two men in the pickup truck. The North Connector superstructure (Fig. 2.4, top) held together, but the columns were bent double and burst their spiral reinforcement (Fig. 2.5). One of the group of parallel bridges on I-5 was also struck by the falling South Connector structure, and two others fell off their bearings (Fig. 2.4, bottom). The bridge immediately to the east suffered major column damage and was removed.

Cause of Collapse More than one cause contributed to the collapse of the bridges at the I-5 and I-210 interchange. The bridges were designed for lateral seismic forces of about 4% of the dead load, which is equivalent to an acceleration of 0.04 g, and vertical seismic forces were not considered. From field measurements made during the earthquake, the estimated ground accelerations at the interchange were from 0.33 g to 0.50 g laterally and from 0.17 g to 0.25 g vertically. The seismic forces were larger than what the structures

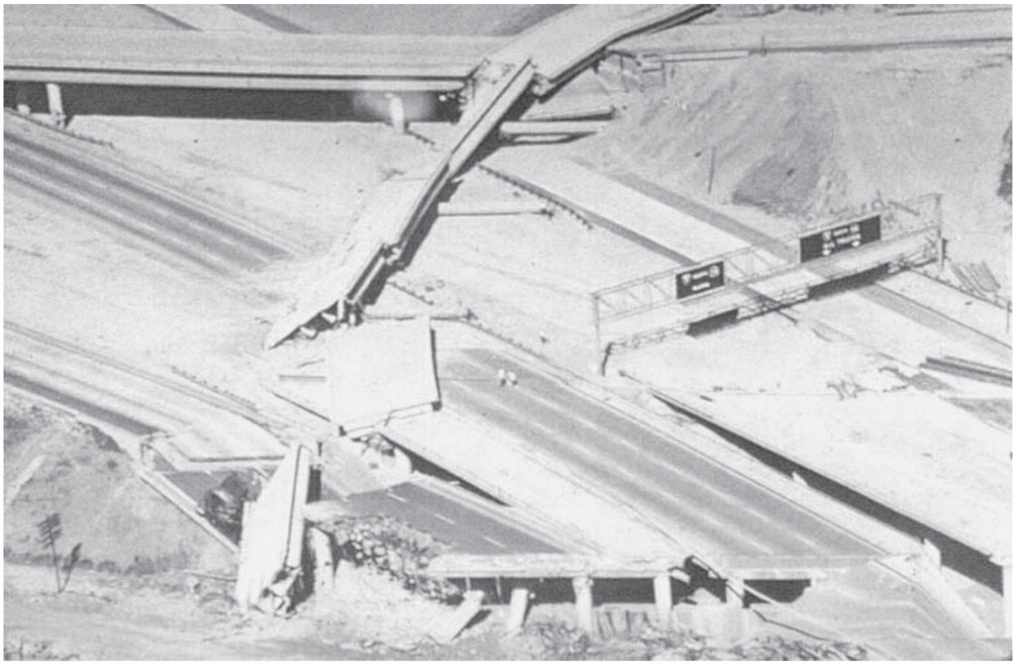

Fig. 2.4 View looking north at the I-5 and I-210 interchange after the quake showing the collapsed South Connector Overcrossing structure (bridge 2) in the center, the North Connector Overcrossing structure (bridge 3) at the top, and bridge group 4 at the bottom. (Photo courtesy E. V. Leyendecker, U.S. Geological Survey.)

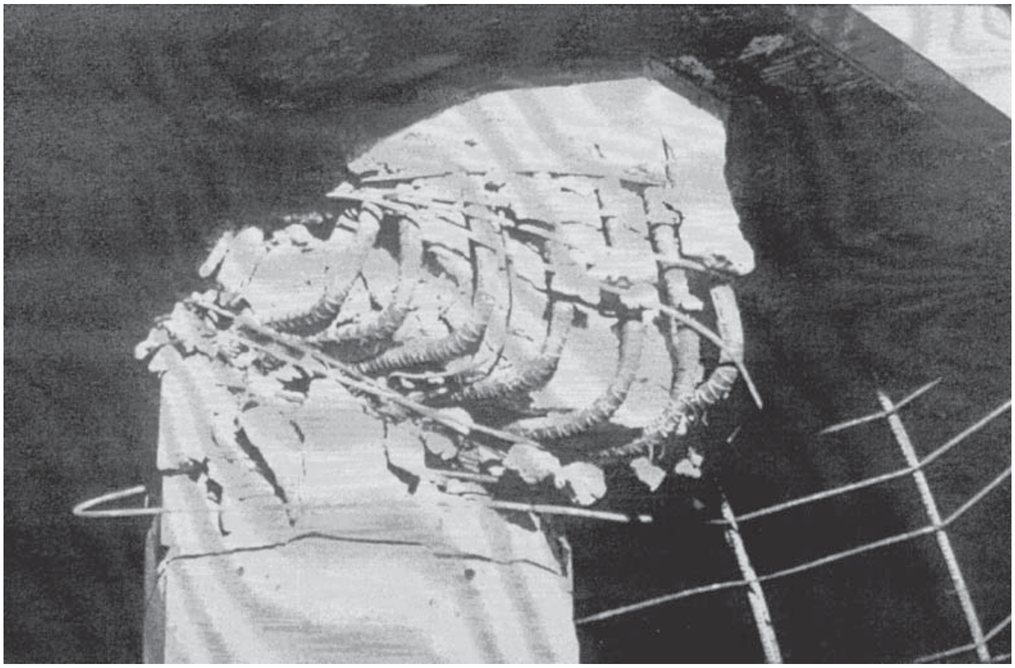

Fig. 2.5 Close-up of exterior spiral column in bent 2 of bridge 3. (Photo courtesy E. V. Leyendecker, U.S. Geological Survey.)

were designed for and placed an energy demand on the structures that could not be dissipated in the column–girder and column–footing connections. The connections failed, resulting in displacements that produced large secondary effects, which led to progressive collapse. Girders fell off their supports because the seat dimensions were smaller than the earthquake displacements. These displacement effects were amplified in the bridges that were curved or skewed and were greater in spread footings than in pile-supported foundations.

Effect on Bridge Practice The collapse of bridges during the 1971 San Fernando earthquake pointed out the inadequacies of the lateral force and seismic design provisions of the specifications. Modifications were made and new articles were written to cover the observed deficiencies in design and construction procedures. The issues addressed in the revisions included the following: (1) seismic design forces include a factor that expresses the probability of occurrence of a high-intensity earthquake for a particular geographic region, a factor that represents the soil conditions, a factor that reflects the importance of the structure, and a factor that considers the amount of ductility available in the design; (2) methods of analysis capable of representing horizontal curvature, skewness of span, variation of mass, and foundation conditions; (3) provision of alternative load paths through structural redundancy or seismic restrainers; (4) increased widths on abutment pads and hinge supports; and (5) dissipation of seismic energy by development of increased ductility through closely spaced hoops or spirals, increased anchorage and lap splice requirements, and restrictions on use of large-diameter reinforcing bars. Research is continuing in all of these areas, and the specifications are constantly being revised as new information on seismic safety becomes available.

2.2.3 Sunshine Skyway, Tampa Bay, Florida, May 9, 1980

The ramming of the Sunshine Skyway Bridge by the Liberian bulk carrier *Summit Venture* in Tampa Bay, Florida, on May 9, 1980, destroyed a support pier and about 1297 ft (395 m) of the superstructure fell into the bay. A Greyhound bus, a small pickup truck, and six automobiles fell 150 ft (45 m) into the bay. Thirty-five people died, and one was seriously injured (NTSB, 1981).

Description The Sunshine Skyway was composed of two parallel bridges across Lower Tampa Bay from Maximo Point on the south side of St. Petersburg to Manatee County slightly north of Palmetto, Florida. The twin bridge structures are 4.24 miles (6.82 km) long and consist of posttensioned concrete girder trestles, steel girder spans, steel deck trusses, and a steel cantilever through truss. The eastern structure was completed in 1954 and was one of the first bridges in the United States to use prestressed concrete. The western structure, which was struck by the bulk carrier, was completed in 1971. No requirements were made for structural pier protection.

The main shipping channel was spanned by the steel cantilever through truss (Fig. 2.6) with a center span of 864 ft (263 m) and two equal anchor spans of 360 ft (110 m). The through truss was flanked on either end by two steel deck trusses with spans of 289 ft (88 m). The bulk carrier rammed the second pier south of the main channel that supported the anchor span of the through truss and the first deck span. The collision demolished the reinforced concrete pier and brought down the anchor span and suspended span of the through truss and one deck truss span.

Cause of Collapse The NTSB determined that the probable cause of the accident was the failure of the pilot of the *Summit Venture* to abort the passage under the bridge when the navigational references for the channel and bridge were lost in the heavy rain and high winds of an intense thunderstorm (NTSB, 1981). The lack of a structural pier protection system, which could have redirected the vessel and reduced the amount of damage, contributed to the loss of life. The collapse of the cantilever through truss and deck truss spans of the Sunshine Skyway Bridge was due to the loss of support of the pier rammed by the *Summit*

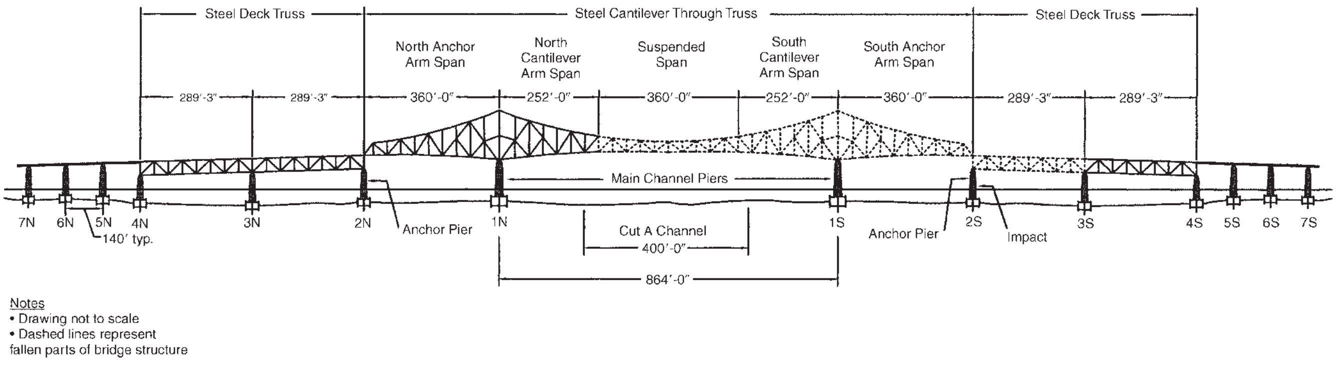

Fig. 2.6 Diagram of the damaged Sunshine Skyway Bridge (looking eastward). (NTSB, 1981).

Venture and the progressive instability and twisting failure that followed.

Effect on Bridge Practice A result of the collapse of the Sunshine Skyway Bridge was the development of standards for the design, performance, and location of structural bridge pier protection systems. Provisions for determining vessel collision forces on piers and bridges are now incorporated in the AASHTO LRFD Bridge Specifications.

2.2.4 Mianus River Bridge, Greenwich, Connecticut, June 28, 1983

A 100 ft (30 m) suspended span of the eastbound traffic lanes of Interstate Route 95 over the Mianus River in Greenwich, Connecticut, collapsed and fell into the river on June 28, 1983. Two tractor-semitrailers and two automobiles drove off the edge of the bridge and fell 70 ft (21 m) into the river. Three people died, and three received serious injuries (NTSB, 1984).

Description The Mianus River Bridge is a steel deck bridge of welded construction that has 24 spans, 19 of which are approach spans, and is 2656 ft (810 m) long. The five spans over water have a symmetric arrangement about a 205 ft (62.5 m) main span, flanked by a 100 ft (30 m) suspended span and a 120 ft (36.6 m) anchor span on each side (Fig. 2.7). The main span and the anchor span each cantilever 45 ft (13.7 m) beyond their piers to a pin-and-hanger assembly, which connects to the suspended span (Fig. 2.8). The highway is six lanes wide across the bridge, but a lengthwise expansion joint on the centerline of the bridge separates the structure into two parallel bridges that act independently of each other. The bridge piers in the water are skewed 53.7° to conform to the channel of the Mianus River.

The deck structure over the river consists of two parallel haunched steel girders with floor beams that frame into the girders. The continuous five-span girder has four internal hinges at the connections to the suspended spans and is, therefore, statically determinate. The inclusion of hinges raises the question of redundancy and existence of alternative load paths. During the hearing after the collapse, some engineers argued that because there were two girders, if one pin-and-hanger assembly failed, the second assembly could provide an alternative load path.

The drainage system on the bridge had been altered by covering the curb drains with steel plates when the roadway was resurfaced in 1973 with bituminous concrete. With the curb drains sealed off, rainwater on the bridge ran down the bridge deck to the transverse expansion joints between the suspended span and the cantilever arm of each anchor span. During heavy rainfall, considerable water leaked through the expansion joint where the pin-and-hanger assemblies were located.

After the 1967 collapse of the Silver Bridge, the National Bridge Inspection Standards were established, which required regular inspections of bridges at intervals not exceeding 2 years. ConnDOT's Bridge Safety and Inspection Section had inspected the Mianus River Bridge 12 times since 1967 with the last inspection in 1982. The pin-and-hanger assemblies of the inside girders were observed from a catwalk between the separated roadways, but the pin-and-hanger assemblies connecting the outside

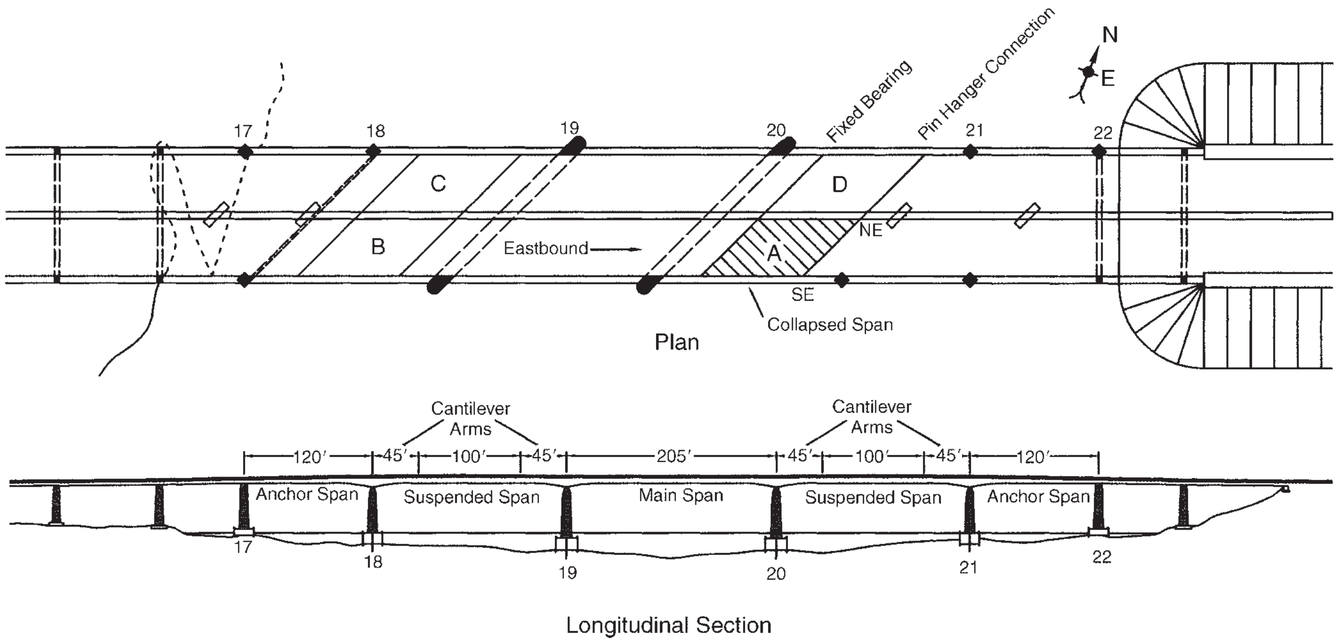

Fig. 2.7 Plan view (top) and longitudinal view (bottom) of the Mianus River Bridge. (Note that the skew of piers 17 through 22 is not depicted in the longitudinal view). (NTSB, 1984).

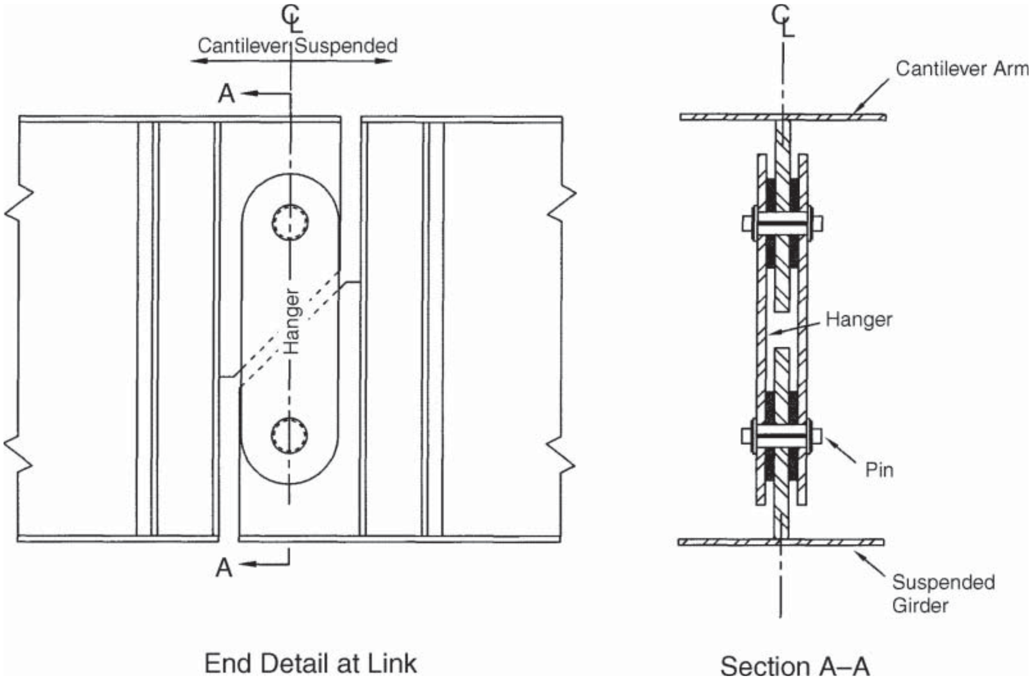

Fig. 2.8 Schematic of pin-and-hanger assembly of the Mianus River Bridge. (NTSB, 1984).

girders were visually checked from the ground using binoculars. The inspectors noted there was heavy rust on the top pins from water leaking through the expansion joints.

Cause of Collapse The eastbound suspended span that collapsed was attached to the cantilever arms of the anchor spans at each of its four corners (Fig. 2.7). Pin-and-hanger assemblies were used to support the northeast (inside girder) and southeast (outside girder) corners of the eastern edge of the suspended span. The western edge was attached to the cantilever arms by a pin assembly without hangers. The pin-and-hanger assemblies consist of an upper pin in the cantilever arm and a lower pin in the suspended span connected by two hangers, one on either side of the web (Fig. 2.8).

Sometime before the collapse of the suspended span, the inside hanger at the southeast corner came off the lower pin, which shifted all the weight on this corner to the outside hanger. With time, the outside hanger moved laterally outward on the upper pin. Eventually, a fatigue crack developed in the end of the upper pin, its shoulder fractured, the outside hanger slipped off, and the suspended span fell into the river.

The NTSB concluded that the probable cause of the collapse of the Mianus River Bridge suspended span was the undetected lateral displacement of the hangers in the southeast corner suspension assembly by corrosion-induced forces due to deficiencies in the State of Connecticut's bridge safety inspection and bridge maintenance program (NTSB, 1984).

Effect on Bridge Practice A result of the collapse of the Mianus River Bridge was the development and enforcement of detailed and comprehensive bridge inspection procedures. The Mianus River Bridge was being inspected on a regular basis, but the inspectors had no specific directions as to what the critical elements were that could result in a catastrophic failure.

Another effect of this collapse was the flurry of activity in all the states to inspect all of their bridges with pin-and-hanger assemblies. In many cases, they found similar deterioration and were able to prevent accidents by repair or replacement of the assemblies. In designs of new bridges, pin-and-hanger assemblies have found disfavor and will probably not be used unless special provisions are made for inspectability and maintainability.

The investigation of the collapse also pointed out the importance of an adequate surface drainage system for the roadway on the bridge. Drains, scuppers, and downspouts must be designed to be self-cleaning and placed so that they discharge rainwater and melting snow with de-icing salts away from the bridge structure in a controlled manner.

Perhaps the most important result of the recommendations of the NTSB was the development of the FHWA's fracture-critical bridge inspection program. As was mentioned previously in the Silver Bridge collapse, when the eyebar failed, the whole bridge failed because there was no alternative path for the loads to be carried. In the case of the Mianus River Bridge, when the pin assembly failed, it led to the collapse of the suspended span because the structural system was *non-load-path-redundant*. Both the eyebar and the pin assembly are fracture-critical elements because their failure leads to partial or total failure of the bridge. A bridge that is non-load-path-redundant is not inherently unsafe, but it does lack redundancy in the design of its support structure.

Such bridges are sometimes referred to as fracture critical and they require special attention when being inspected. According to FHWA 2007 data, of the 600,000 bridges in the National Bridge Inventory, 19,273 are considered non-load-path-redundant.

2.2.5 Schoharie Creek Bridge, Amsterdam, New York, April 5, 1987

Three spans of the Schoharie Creek Bridge on I-90 near Amsterdam, New York, fell 80 ft (24 m) into a rain-swollen creek on April 5, 1987, when two of its piers collapsed. Four automobiles and one tractor-semitrailer plunged into the creek. Ten people died (NTSB, 1988).

Description The Schoharie Creek Bridge consisted of five simply supported spans of lengths 100, 110, 120, 110, and 100 ft (30.5, 33.5, 36.6, 33.5, and 30.5 m). The roadway width was 112.5 ft (34.3 m) and carried four lanes of highway traffic (Fig. 2.9). The superstructure was composed of two main steel girders 12 ft (3.66 m) deep with transverse floor beams that spanned the 57 ft (17.4 m) between girders and cantilevered 27.75 ft (8.45 m) on either side. Stringers ran longitudinally between the floor beams and supported a noncomposite concrete deck. Members were connected with rivets.

The substructure consisted of four piers and two abutments. The reinforced concrete piers had two columns directly under the two girders and a tie beam near the top (Fig. 2.10). A spread footing on dense glacial deposits supported each pier. Piers 2 and 3 were located in the main channel of Schoharie Creek and were to be protected by riprap. Only the abutments were supported on piles. Unfortunately, in the early 1950s when this bridge was being designed, no reliable method was available to predict scour depth.

The bridge was opened to traffic on October 26, 1954, and on October 16, 1955, the Schoharie Creek experienced its flood of record (1900–1987) of 76,500 cfs (2170 m^3/s). The estimated discharge on April 5, 1987, when the bridge collapsed was 64,900 cfs (1840 m^3/s). The 1955 flood caused slight damage to the riprap, and in 1977 a consulting engineering firm recommended replacing missing riprap. This replacement was never done.

Records show that the Schoharie Creek Bridge had been inspected annually or biennially as required by the National Bridge Inspection Standards of the 1968 Federal Aid Highway Act. These inspections of the bridge were only of the above-water elements and were usually conducted by maintenance personnel, not by engineers. At no time since its completion had the bridge received an underwater inspection of its foundation.

Cause of Collapse The severe flooding of Schoharie Creek caused local scour to erode the soil beneath pier 3, which then dropped into the scour hole, and resulted in the collapse of spans 3 and 4. The bridge wreckage in the creek redirected the water flow so that the soil beneath pier 2 was eroded, and some 90 min later it fell into the scour hole and caused the collapse of span 2. Without piles, the Schoharie Creek Bridge was completely dependent on riprap to protect its foundation against scour and it was not there.

The NTSB determined that the probable cause of the collapse of the Schoharie Creek Bridge was the failure of the New York State Thruway Authority to maintain adequate riprap around the bridge piers, which led to the severe erosion of soil beneath the spread footings (NTSB, 1988). Contributing to the severity of the accident was the lack of structural redundancy in the bridge.

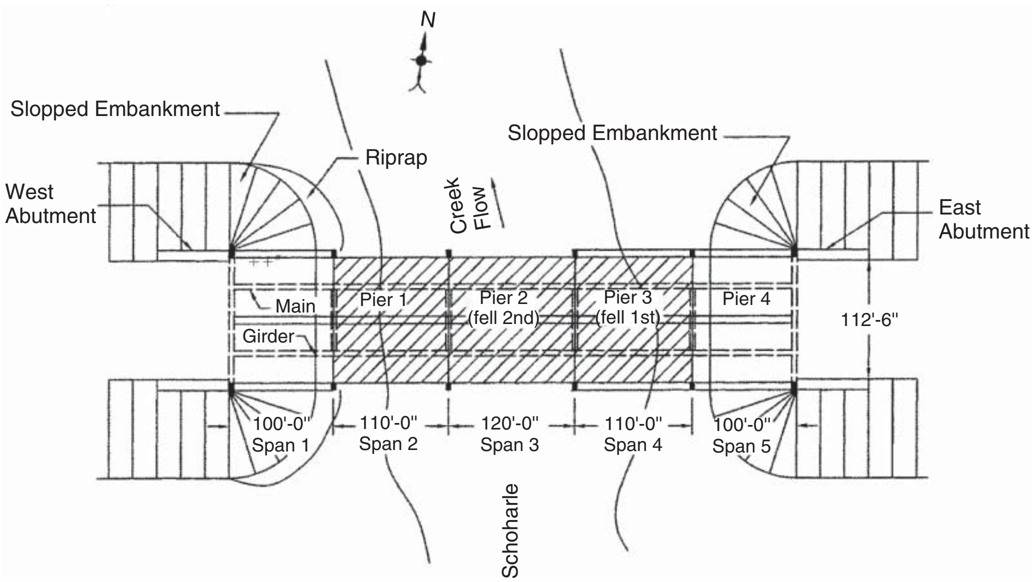

Fig. 2.9 Schematic plan of Schoharie Creek Bridge. (NTSB, 1988).

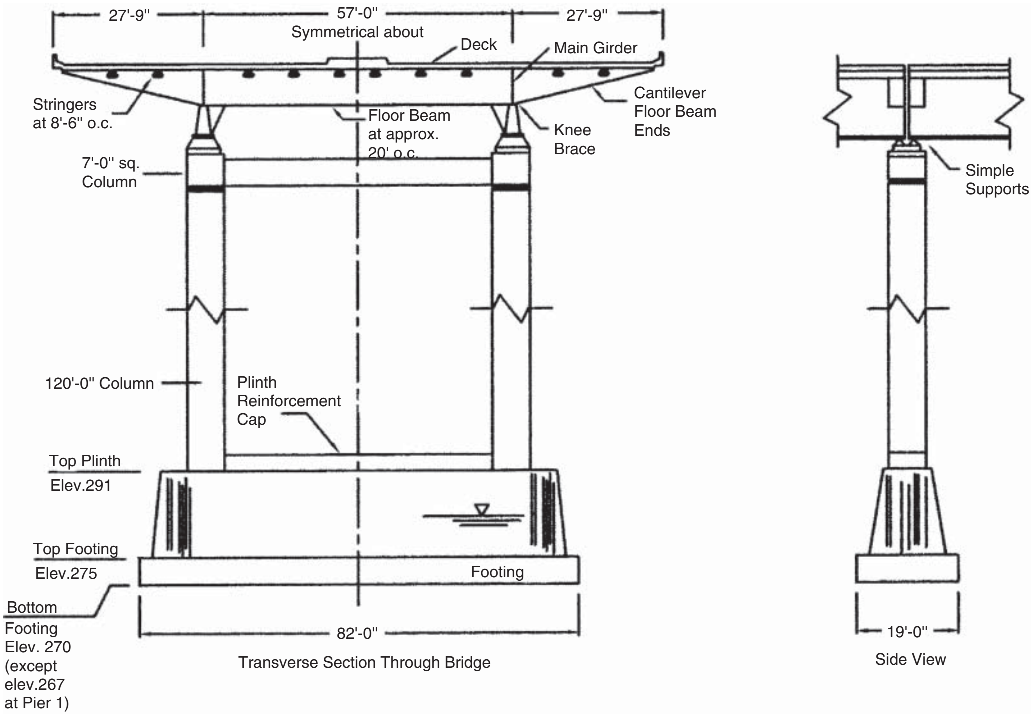

Fig. 2.10 Sections showing the Schoharie Creek Bridge pier supported on a spread footing. (NTSB, 1988).

Effect on Bridge Practice The collapse of the Schoharie Creek Bridge resulted in an increased research effort to develop methods for estimating depth of scour in a streambed around bridge piers and for estimating size of riprap to resist a given discharge rate or velocity. Methods for predicting depth of scour are now available.

An ongoing problem that needs to be corrected is the lack of qualified bridge inspection personnel. This problem is especially true for underwater inspections of bridge foundations because there are approximately 300,000 bridges over water and 100,000 have unknown foundation conditions.

Once again the NTSB recommends that bridge structures should be redundant and have alternative load paths. Engineers should finally be getting the message and realize that continuity is one key to a successful bridge project.

2.2.6 Cypress Viaduct, Loma Prieta Earthquake, October 17, 1989

The California Department of Transportation (Caltrans) has been and is a leader in the area of seismic design and protection of bridges. Over the course of many years and numerous earthquakes, Caltrans continues to assess seismic risk, update design procedures, and evaluate existing bridges for catastrophic potential. One of the difficulties, however, is gaining the funding necessary to improve the critical design features and weakness of existing bridges within the inventory.

Description The 1989 Loma Prieta earthquake that occurred on October 17 resulted in over $8 billion in damage and loss of 62 lives. Figure 2.11 illustrates the Cypress Viaduct in Oakland. This bridge was perhaps one of the most reported-on structures by the national media as this double-deck bridge failed in shear within the columns and pancaked the bridge on traffic below.

Cause of Collapse Caltrans was aware of the critical design features that were necessary to provide the ductility and energy absorption required to prevent catastrophic failure. Unfortunately, similar details were common in other bridge substructures designed by the best practices at the time. Caltrans was working on correcting these defects, but with over 13,000 bridges in its inventory and limited resources, engineers had not been able to retrofit the Cypress Viaduct before the earthquake.

Effect on Bridge Practice With Loma Prieta the political will was generated to significantly increase the funding necessary to retrofit hundreds of bridges within the Caltrans inventory. In addition, Caltrans substantially increased its research efforts that has resulted in many of the design specification and construction details used today. From a Caltrans press release (Caltrans, 2003):

> *The Department's current Seismic Safety Retrofit Program was established following the 1989 Loma Prieta earthquake to identify and strengthen bridges that needed to be brought up to seismic safety standards.*

This reference outlines the funding and phases that California has and will use to improve thousands of bridges statewide. As illustrated in several examples in this section,

Fig. 2.11 Cypress Viaduct. (Photo courtesy H. G. Wilshire, U.S. Geological Survey.)

sometime failures are required to provide the catalyst necessary for change either from a technical or political perspective.

2.2.7 I-35W Bridge, Minneapolis, Minnesota, August 1, 2007

About 6:05 p.m. central daylight time on Wednesday, August 1, 2007, the eight-lane, 1907 ft (581 m) long I-35W Highway Bridge over the Mississippi River in Minneapolis, Minnesota, experienced a catastrophic failure in the main truss span of the deck truss. As a result, 1000 ft (305 m) of the deck truss collapsed, with about 456 ft (140 m) of the main span falling 108 ft (33 m) into the 15 ft (4.6 m) deep river (Fig. 2.12). A total of 111 vehicles were on the portion of the bridge that collapsed. As a result of the bridge collapse, 13 people died, and 145 were injured (NTSB, 2008).

Fig. 2.12 Aerial view of I-35W Bridge after collapse. (NTSB, 2008).

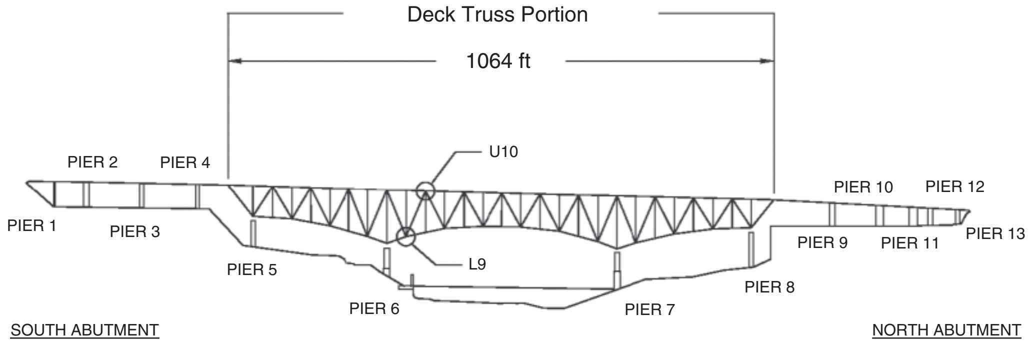

Fig. 2.13 East elevation of I-35W bridge. The deck truss portion of the bridge extends from just south of pier 5 to just north of pier 8. (NTSB, 2008).

Fig. 2.14 Center span of I-35W bridge looking northeast. The center span is supported by pier 6 on the near (south) riverbank and pier 7 on the far (north) riverbank. (NTSB, 2008).

Description The bridge elevation is shown in Figures 2.13 and 2.14. A total of 11 of the 14 spans were approach spans to the deck truss portion that failed. The original bridge design accounted for thermal expansion using a combination of fixed and expansion bearings for the bridge–pier interfaces. For the deck truss portion, a fixed bearing assembly was located at pier 7. Expansion roller bearings were used at piers 5, 6, and 8.

When opened for traffic in 1967, the cast-in-place concrete deck slab had a minimum thickness of 6.5 in. Bridge renovation projects eventually increased the average thickness by about 2 in.

The deck truss portion of the bridge was comprised of two parallel main Warren-type trusses spaced 72 ft 4 in apart. The upper and lower chords of the main trusses were connected by straight vertical and diagonal members that made up the truss structure. The upper and lower chords were welded box members. The vertical and diagonal members were H members consisting of flanges welded to a web plate.

Riveted steel gusset plates at each of the 112 nodes (connecting points) of the two main trusses tied the ends of the truss members to one another and to the rest of the structure. The gusset plates were riveted to the side plates of the box members and to the flanges of the H members. A typical I-35W main truss node with gusset plates is shown in Figure 2.15.

Cause of Collapse On the day of the collapse, roadway work was underway on the I-35W Bridge. Four of the eight travel lanes were closed to traffic. Construction equipment and piles of sand and gravel were positioned in the deck truss portion of the bridge. The construction loads were in place by about 2:30 p.m. in preparation for a concrete pour that was to begin about 7:00 p.m.

Fig. 2.15 Typical five-member node (two upper chord members, one vertical member, and two diagonal members) on I-35W Bridge. (NTSB, 2008).

About 6:05 p.m., a motion-activated surveillance video camera at the Lower St. Anthony Falls Lock and Dam, just southwest of the bridge center span, recorded a portion of the collapse sequence. The video showed the bridge center span separating from the rest of the bridge with the south end dropping before the north end and falling into the river (Fig. 2.16). The center section remained relatively level east to west as it fell. Many of the vehicles remained in their lanes as the collapse occurred, indicating that the east and west main trusses at the south end fractured at about the same time (e.g., Web search “Minnesota dot I-35 bridge failure video”).

What elements in the bridge could have fractured simultaneously in both main trusses near the south support to cause the center span to drop to the river in a flat even manner? There was no eyebar chain and hanger connection as in the Silver Bridge, nor was there a pin-and-hanger assembly as in the Mianus River Bridge.

The NTSB searched the bridge inspection reports dating from 1971 to 2006 looking for signs of a possible weak link. One detail that caught their attention was provided by a series of photographs taken in 2003 that showed visible bowing in the gusset plates at several upper truss nodes (Fig. 2.13). At both U10 nodes, the unsupported edges of the gusset plates between the upper chords and the diagonals were bowed. At the two U10 nodes located on each side, the plate edges between the upper chords and the diagonals were bowed. The U10 gusset plates were the only plates that showed obvious evidence of bowing.

In an interview, the bridge safety inspection engineer stated that he had observed the bowing during his inspections. He said he consulted with another inspector about the bowing and concluded (NTSB, 2008, p. 63):

Our inspections are to find deterioration or findings of deterioration on maintenance. We do not note or describe construction or design problems.

As previously noted, at or near the beginning of the collapse sequence, most of the bridge center span fractured and broke away from the rest of the deck truss structure. Video and physical evidence indicated that the breaks in the span occurred just north of pier 6 and just south of pier 7. Fractures in the south and north fracture areas were at or adjacent to the U10 nodes (NTSB, 2008).

Because much of the bridge center span collapsed, its structural components did not receive detailed inspection until after their removal. The recovered truss portions were laid out relative to their original positions at a nearby park. A gusset plate fracture pattern reconstructed from the pieces at node U10W (west side) is shown in Fig. 2.17. The curved line indicates the fracture, which was similar for both trusses. The diagonal and chords were separated from the remaining

Fig. 2.16 Collapsed bridge center section, looking southeast. (NTSB, 2008).

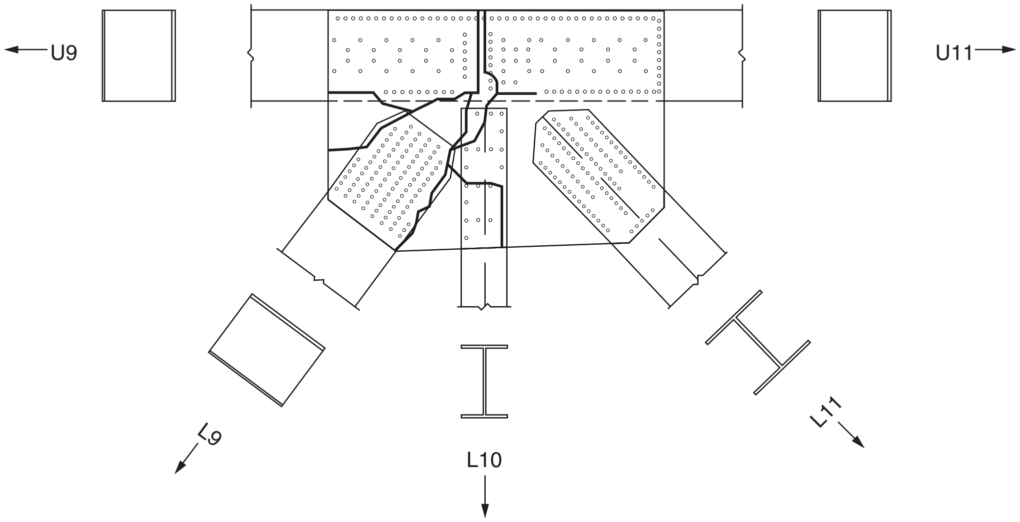

Fig. 2.17 Fracture pattern of outside (west) gusset plate at U10W. (NTSB, 2008).

members in the node. The remaining portion of the gusset plates kept the vertical and other diagonal connected.

During the investigation a finite-element model of the bridge deck portion with all its components was constructed. The model was able to simulate the behavior of the gusset plates when subjected to different loading conditions. This analysis showed that areas of the U10 gusset plates at the ends of the L9/U10 (Fig. 2.17) diagonals were beyond their yield stress under the dead load of the initial bridge design. As loads on the bridge increased as a result of the added deck thickness (1977) and barriers (1998), the area of the gusset plates beyond the yield stress expanded, but large deflections were prevented by the surrounding elastic material.

With the added construction and traffic loads on the day of the accident, the areas of yielding increased further, and the finite-element analysis predicted that the failure mode under these conditions would be the unstable lateral shifting of the U10 end of the L9/U10 diagonal. The load-carrying capacity of the gusset plates would be reduced as the bending deformations and yielding increase, resulting in the tensile fracture pattern observed and the tearing away of the L9/U10 diagonal.

The finite-element analysis predicted that the lateral shifting instability of the L9/U10 diagonal would occur first at the U10W node because it was more highly stressed than the U10E node due to the placement of the construction materials. As the load-carrying capacity was reduced at the U10W node, the load would be shed to the U10E node triggering a similar fracture pattern. The failure likely proceeded rapidly, and almost simultaneously, through both the U10W and U10E nodes.

The NTSB therefore concluded that the initiating event was a lateral shifting instability of the upper end of the L9/U10W diagonal member and the subsequent failure of the U10 node gusset plates on the center portion of the deck truss.

The deck truss structure of the I-35W Bridge was non-load-path-redundant, which means that it would lose its entire load-carrying capacity if a single primary load member failed. The failure of the U10 gusset plates led to the sequential separation of the structural members connected to the plates, which placed unsupportable loads on the remainder of the structure. The total collapse followed immediately.

The NTSB determined that the probable cause of the collapse of the I-35W Bridge was due to a design error by the original design firm that resulted in an inadequate load capacity of the gusset plates at the U10 nodes. These plates failed under a combination of substantial increases in the bridge weight from previous modifications and the traffic–construction loads on the bridge on the day of the collapse (NTSB, 2008).

Effect on Bridge Practice A major effect of the collapse of the I-35W Bridge was to direct attention on the importance of proper design, quality control, and inspection of gusset plates. A number of recommendations were given by the NTSB to the FHWA and the AASHTO for implementation.

The recommendations to the FHWA included procedures to detect and correct bridge design errors before the design plans are made final, use of nondestructive evaluation technologies to assess gusset plate condition, and update of the training courses to address inspection techniques and conditions specific to gusset plates.

The recommendations to AASHTO, besides working with the FHWA on quality control, are to modify the *Manual for Bridge Evaluation* (AASHTO, 2008) to include the capacity of gusset plates as part of the load-rating calculations, develop guidelines to ensure that construction loads and stockpiled materials do not overload the structure, develop guidance for responding to potentially damaging conditions in gusset plates, such as corrosion and distortion, and revise the *AASHTO Guide for Commonly Recognized (CoRe) Structural Elements* (AASHTO, 1998) to incorporate this new information.

In addition, the NTSB issued the following safety recommendation to the FHWA on January 15, 2008: For all non-load-path-redundant steel truss bridges within the

National Bridge Inventory, require that bridge owners conduct load capacity calculations to verify that the stress levels in all structural elements, including gusset plates, remain within applicable requirements whenever planned modifications or operational changes may significantly increase stresses (NTSB, 2008).

2.2.8 Failures during Construction

Most of the memorable bridge failures and the ones that most affect bridge engineering practice have occurred in structures that were in service for many years. However, in-service bridges are not the source of the most common occurrence of failures. Most failures occur during construction and are likely the most preventable kind of failure. This topic is simply too voluminous to address in this book; however, it certainly warrants discussion. Several books and many references are available; for example, in his landmark book, Feld (1996) outlines many kinds of construction failures including technical details, case studies, and litigation issues.

Discussion of one girder failure that occurred near Golden, Colorado, illustrates the importance of considering the construction process during design and construction (9News.com, 2004). An overpass bridge was being widened with the placement of a steel plate girder along the edge of the existing structure. Construction had terminated for the weekend and the girder was left with some attachments to provide lateral stability. The girder became unstable, fell, and killed three people. An aerial view is illustrated in Figure 2.18. The Web reference provided and the associated video linked on this page illustrate many aspects of this failure from a first-day perspective. Stability is the likely cause of failure and is commonly the cause—either stability of the girders supporting the deck with wet concrete or the stability of temporary formwork and shoring required to support the structure. In later chapters, construction staging is discussed related to the design. Again, see 9News.com to review what can happen when mistakes occur. This particular incident could have killed many more—the failure occurred on a Sunday morning when traffic volume was relatively light.

2.2.9 Failures Continue and Current Data

Since the turn of the century until January 2019, 96 bridges have failed worldwide, and 25 have failed in the United States. Although all failures are important, only those deemed relevant to U.S. bridge practice are described herein. Table 2.1 illustrates failure in the U.S. during this period. Note that many failures are now due to scour cause by extreme flooding events, extreme wind events, ship and truck collisions, and fires. As our climate and weather patterns change, this will unfortunately continue. (Web search for bridge failures can provide the current status.)

Table 2.1 Bridge Failure 2000 to Early 2019 https://en.wikipedia.org/wiki/List_of_bridge_failures

Fig. 2.18 Bridge failure near Golden, Colorado. (Photo from Golden Fire Department Annual Report 2004, Golden, Colorado. http://ci.golden.co.us/files/2004fdreport.pdf.)

Table 2.1 **Bridge Failure 2000 to Early 2019**

Bridge	Location	Country	Date	Construction type, use of bridge	Reason	Casualties	Damage	Comments
Hoan Bridge	Milwaukee, Wisconsin	United States	13-Dec-00	Concrete and steel bridge	Northbound right lane began to buckle during the morning rush hour and sagged a few feet below normal. Damage was a result of a violent failure of cross bracing members caused by extremely high stress concentrations in triaxial welds.	0 killed, 0 injured	Partial collapse	Damaged section removed by controlled demolition and rebuilt. Remainder of bridge extensively repaired and retrofitted. Triaxial welds were drilled and most cross bracing members were removed. Many other similar bridges around the world were also modified in this way as a result of this failure.
Hintze Ribeiro disaster	Entre-os-Rios, Castelo de Paiva	Portugal	4-Mar-01	Masonry and steel bridge built in 1887	Pillar foundation became compromised due to years of illegal, but permitted sand extraction and the central span collapsed.	59 killed	Collapse of central sections	Hintze Ribeiro Bridge after the collapse
I-285 bridge over GA-400	Atlanta, Georgia	United States	9-Jun-01	Concrete and steel bridge	A fuel tanker overturned underneath the bridge, engulfing the bridge in fire	0 killed, 1 injured	Structural damage required closure of the bridge	Reopened after four week repair [31][32]
Kadalundi River rail bridge	Kadalundi	India	21-Jul-01	140-year-old rail bridge collapsed		57 killed (all drowned)		
Queen Isabella Causeway	Port Isabel, Texas and South Padre Island, Texas	United States	15-Sep-01	Concrete bridge for vehicle traffic over Laguna Madre	4 loaded barges veered 175 feet (53 m) west of the navigation channel and struck one of the bridge supports, causing a partial collapse of 3 sections measuring approximately 80 feet (24 m) each.	8 killed, 13 survivors	Partial collapse	The damaged section of the Queen Isabella Causeway

(*Continues*)

Table 2.1 (***Continued***)

Bridge	Location	Country	Date	Construction type, use of bridge	Reason	Casualties	Damage	Comments
I-40 bridge disaster	Webbers Falls, Oklahoma	United States	26-May-02	Concrete bridge for vehicle traffic over Arkansas River	Barge struck one pier of the bridge causing a partial collapse	14 killed	Partial collapse	I-40 Bridge, May 31, 2002
Rafiganj rail bridge	Rafiganj	India	10-Sep-02		Terrorists sabotaged rail bridge, causing crash	130 killed		
Chubut River Bridge disaster	Chubut River, Chubut Province	Argentina	19-Sep-02	Pedestrian suspension bridge	Excess weight due to passers-by	9 killed, + 5 injured	Total collapse	Collapse of the pedestrian suspension bridge when more than 50 students and teachers of a school who were running in the area crossed it when the capacity of the bridge support was maximum of three people.
Sgt. Aubrey Cosens VC Memorial Bridge,	Latchford, Ontario,	Canada	14-Jan-03		Partial failure under load of transport truck during severely cold temperatures. Fatigue fractures of three steel hanger rods cited to be primary reason for failure.	0 killed, 0 injured	Partial failure of bridge deck. Overhead superstructure undamaged.	Bridge reopened after complete reconstruction. Existing overhead arch remained, however new bridge deck was designed to be supported by sets of 4 hanger cables, where the existing deck was designed for single hanger cables.
Kinzua Bridge	Kinzua Bridge State Park, Pennsylvania	United States	21-Jul-03	Historic steel rail viaduct	Hit by tornado with 100 mph winds	0 killed	Partial collapse	Failed bridge
Interstate 95 Howard Avenue Overpass	Bridgeport, Connecticut	United States	26-Mar-04	Girder and floorbeam	Car struck a truck carrying 8,000 US gallons (30,000 litres; 6,700 imperial gallons) of heating oil, igniting a fire that melted the bridge superstructure, causing collapse of the southbound lanes	0 killed, 1 injured	Partial collapse	Northbound lanes shored up with falsework and reopened 3 days later; temporary bridge installed to carry southbound lanes. New permanent bridge completed in November 2004.

Big Nickel Road Bridge	Sudbury, Ontario	Canada	7-May-04			0 killed	Collapsed onto roadway below during construction	[33][34]
C-470 overpass over I-70	Golden, Colorado	United States	15-May-04		As part of a construction project, a girder twisted, sagged, and fell onto I-70. An SUV was driving eastbound and struck the fallen girder; the top of the vehicle was torn off and the three passengers died instantly. [35]	3 killed, 0 injured	Girder collapse	
Mungo Bridge [36]		Cameroon	1-Jul-04	Steel girder for road traffic			Partial collapse	Yet to be repaired [when?]
Loncomilla Bridge	near San Javier	Chile	18-Nov-04	Concrete bridge for vehicle traffic over Maule River	The structure was not built on rock, but rather on fluvial ground.	0 killed, 8 injured	Partial collapse	Bridge was later repaired
I-10 Twin Span Bridge	New Orleans and Slidell, Louisiana	United States	29-Aug-05	Two parallel trestle bridges crossing the eastern end of Lake Pontchartrain	After Hurricane Katrina on August 29, 2005, the old Twin Spans suffered extensive damage, as the rising storm surge had pulled or shifted bridge segments off their piers.	0 killed, 0 injured	The eastbound span was missing 38 segments with another 170 misaligned, while the westbound span was missing 26 segments with 265 misaligned.	Bridge was reconstructed but later replaced with two new spans due to vulnerability to storm surges.
Veligonda Railway Bridge		India	29-Oct-05	Railway bridge	flood washed rail bridge away	114 killed		
Almuñécar motorway bridge	Almuñécar, Province of Granada	Spain	7-Nov-05	Motorway bridge	Part collapsed during construction, reason unknown	6 killed, 3 injured	Partial collapse during construction; all the victims were workers.	A 60-metre (200 ft) long part fell 50 metres (160 ft)

(*Continues*)

Table 2.1 (***Continued***)

Bridge	Location	Country	Date	Construction type, use of bridge	Reason	Casualties	Damage	Comments
Caracas-La Guaira highway, Viaduct #1	Tacagua	Venezuela	19-Mar-06	Highway viaduct over a gorge	Landslides	0 killed, 0 injured	Total collapse	Demolished, it was rebuilt and reopened on 21 June 2007
E45 Bridge	Nørresundby	Denmark	25-Apr-06	Road bridge	Collapsed during reconstruction due to miscalculation	1 killed	Bridge total damage	[37]
Interstate 88 Bridge	Unadilla, New York	United States	28-Jun-06	Road bridge	Collapsed during Mid-Atlantic United States flood of 2006	2 killed [38]	Bridge total damage	NYSDOT started construction to replace the section of highway almost immediately, and it was re-opened August 31. [39]
Yekaterinburg bridge collapse	Yekaterinburg	Russia	6-Sep-06		Collapse during construction	0 killed, 0 injured		
Highway 19 overpass at Laval (De la Concorde Overpass collapse)	Laval, Quebec	Canada	30-Sep-06	Highway overpass	Shear failure due to incorrectly placed rebar, low-quality concrete	5 killed, 6 injured	20-metre (66 ft) section gave way	Demolished; was rebuilt, reopened on 13 June 2007. [40]
Nimule	Nimule	Kenya/Sudan	Oct-06		Struck by truck overloaded with cement			
Pedestrian bridge	Bhagalpur	India	Dec-06		150-year-old pedestrian bridge (being dismantled) collapsed onto a railway train as it was passing underneath. [41]	More than 30 killed		
Railway bridge	Eziama, near Aba	Nigeria	Dec-06		Unknown	Unknown killed	Restored 2009 [42]	

Run Pathani Bridge Collapse	80 km (50 miles) east of Karachi,	Pakistan	2006		Collapsed during the 2006 monsoons			
	South eastern Guinea	Guinea	Mar-07		Bridge collapsed under the weight of a truck packed with passengers and merchandise. [43]	65 killed		
		South Korea	5-Apr-07		Parts of a bridge collapses during construction	5 killed, 7 injured		Bridge being built between the two Southern Islands. [44]
MacArthur Maze	Oakland, California	United States	29-Apr-07		Tanker truck crash and explosion, resulting fire softened steel sections of flyover causing them to collapse.	1 injured in crash, 0 from collapse		Span rebuilt in 26 days.
Highway 325 Bridge over the Xijiang River	Foshan, Guangdong	People's Republic of China	15-Jun-07	Motorway bridge	Struck by vessel	8 killed, unknown injured	Section collapsed	Unknown
Gosford Culvert washaway	Gosford, New South Wales	Australia	8-Jun-07		Culvert collapse [45]	5 killed (all drowned)		
Minneapolis I-35W bridge over the Mississippi River	Minneapolis, Minnesota	United States	1-Aug-07	Arch/truss bridge	The NTSB said that undersized gusset plates, increased concrete surfacing load, and weight of construction supplies/equipment caused this collapse.	13 killed, 145 injured	Total bridge failure	Security camera images show the collapse in animation, looking north.
Tuo River bridge	Fenghuang, Hunan	People's Republic of China	13-Aug-07	Unknown	Currently under investigation, [needs update] believed to be linked to the fact that local contractors often opt for shoddy materials to cut costs and use migrant laborers with little or no safety training	34 killed, 22 injured	Total collapse	Collapsed during construction as workers were removing scaffolding from its facade

(*Continues*)

Table 2.1 (***Continued***)

Bridge	Location	Country	Date	Construction type, use of bridge	Reason	Casualties	Damage	Comments
Harp Road bridge	Oakville, Washington	United States	15-Aug-07	Main thoroughfare into Oakville over Garrard Creek, Grays Harbor County	Collapsed under weight of a truck hauling an excavator [46][47][48]	0 killed, 0 injured	Majority to total collapse; temporary or permanent bridge is needed.	Approximate weight of load was 180,000 pounds (82,000 kg); bridge is rated at 35,000 pounds (16,000 kg). Residents must take a 23-mile (37 km) detour.
Water bridge	Taiyuan, Shanxi province	People's Republic of China	16-Aug-07		180t vehicle overloaded bridge designed for 20t [49]	unknown	Total collapse of 1 span of 2	
Shershah Bridge – Section of the Northern Bypass, Karachi	Karachi	Pakistan	1-Sep-07	Overpass bridge	Investigation underway	5 killed, 2 injured		Collapse may have been caused because of lack of material strength. The reconstruction is in progress. [when?]
Flyover bridge	Punjagutta, Hyderabad, Andhra Pradesh	India	9-Sep-07		During construction	15–30 killed		[50]
Cá;n Thó Bridge	Cán Thó	Vietnam	26-Sep-07		Collapse of a temporary pillar due to the sandy foundation it was set on. [51]	55 killed, hundreds injured	Section buckled while construction was underway	Pieces of Cán Thó Bridge remaining after its collapse on 4 October 2007, ten days after the accident.
Chhinchu suspension bridge	Nepalgunj, Birendranagar	Nepal	25-Dec-07		Overcrowded suspension bridge collapsed	19 killed, 15 missing		
Jintang Bridge	Ningbo, Zhejiang province	People's Republic of China	27-Mar-08		Ship hit lower support structure of bridge [49]	4 killed, 0 injured	60 m span of under-construction bridge collapsed	
The Cedar Rapids and Iowa City Railway (CRANDIC) bridge	Cedar Rapids, Iowa	United States	12-Jun-08	Railroad bridge	During June 2008 Midwest floods	0 killed, 0 injured	Three of the bridge's four steel spans were swept into the river along with 15 CRANDIC rail cars loaded with rock	The Cedar River was still swollen in this image taken 10 days after the bridge's collapse.

Road bridge	Studénka	Czech Republic	8-Aug-08		Train crashed into a road bridge over the railway under construction, which collapsed on the track immediately before the arrival of a train	8 killed, 70 injured		2008 Studénka train wreck
Somerton Bridge	Somerton, New South Wales	Australia	8-Dec-08	Timber road bridge	Heavy flooding	None	Collapse of northern span	Bridge collapsed during heavy flooding due to poor maintenance [52]
Devonshire Street pedestrian bridge	Maitland, New South Wales	Australia	5-Mar-09	Footbridge	Oversized truck clipping main span	0 killed, 4 injured (Car & Truck Drivers)	Main span falling on New England Highway, road closed for 4 days	Replaced by taller Footbridge 18 months later [53]
Bridge on SS9 over River Po	Piacenza	Italy	30-Apr-09	Road bridge	Collapsed due to flood of River Po	0 killed, 1 injured		Replaced by a temporary floating bridge 6 months later, then by a definitive new bridge that opened on 18 December 2010 [54]
Overpass on Hongqi Road	Zhuzhou City, Hunan Province	People's Republic of China	17-May-09	Road bridge	Collapsed during demolishing process [55]	9 killed, 16 injured, 24 vehicles damaged		
9 Mile Road Bridge at I-75	Hazel Park, Michigan	United States	15-Jul-09	Road bridge	Collapsed due to tanker accident [56]	0 killed, 1 injured		Rebuilt and reopened on 11 December of that year
Malahide Viaduct	Broadmeadow–13 km (8.1 miles) north of Dublin	Ireland	21-Aug-09	Railway bridge		0 killed, 0 injured	One span of viaduct collapsed after tidal scouring of foundations—first reported by local Sea-scouts.	[57]
Tarcoles Bridge	Orotina	Costa Rica	22-Oct-09	Suspension bridge built 1924, 270-foot (82 m) span.	Overload by heavy trucks and dead loads (water pipes). [58]	5 killed, 30 injured	Bridge total damage	

(*Continues*)

Table 2.1 (***Continued***)

Bridge	Location	Country	Date	Construction type, use of bridge	Reason	Casualties	Damage	Comments
San Francisco – Oakland Bay Bridge	Connects San Francisco and Oakland, California	United States	27-Oct-09	I-80	Two tension rods and a crossbeam from a recently installed repair collapsed during the evening commute, causing the bridge to be closed temporarily.	0 killed, 1 injury		During an extended closure as part of the eastern span replacement of the San Francisco Oakland Bay Bridge over the 2009 Labor Day holiday, a critical failure was discovered in an eyebar that would have been significant enough to cause a closure of the bridge. [59] Emergency repairs took 70 hours and were completed on 9 September 2009. This is the repair that failed.
Railway Bridge RDG1 48 over the River Crane near Feltham	Feltham	England	14-Nov-09	Brick arch railway bridge built 1848	Undermined by scour from river. [60]	No injuries	River span beyond repair.	Rebuilt as reinforced concrete.
Northside Bridge, Workington. Navvies Footbridge, Workington. Camerton Foot-bridge, Camerton. Memorial Gardens footbridge, Cockermouth. Low Lorton Bridge, Little Braithwaite Bridge.	Cumbria	England	21-Nov-09	Traditional sandstone bridges.	Very intense rainfall produced extreme river loads that overwhelmed all the bridges. [61]	1 policeman killed	All bridges destroyed or damaged beyond repair	See Barker Crossing.

Kota Chambal Bridge	Kota, Rajasthan	India	25-Dec-09	Under-Construction Bridge	Inexperience Official [62]	48 killed, several injured [63]	Total Collapse	
Myllysilta	Turku	Finland	6-Mar-10		Bridge bent 143 centimetres (56 in) due to structural failures of both piers	0 killed, 0 injured		Demolished June–July 2010
Gungahlin Drive Extension bridge	Canberra, Australian Capital Territory	Australia	14-Aug-10	Concrete road bridge	Under investigation	15 workers injured	Collapse of the half-built span	GDE Bridge after the collapse
Guaiba's Bridge (BR-290)	Porto Alegre, Rio Grande do Sul	Brazil	1-Oct-10	Concrete and steel bridge [66]	Braking system (electrical) failure stuck the main span 9 meters above the lane rendering the bridge useless by (at least) 3 hours. [67]	0 killed, 0 injured	Bridge fixed	Damaged probably due to a vessel which collided, bending the main span on April 30, 2008. [68]
Laajasalo pedestrian bridge	Helsinki	Finland	22-Nov-10	Steel reinforced concrete	Bridge collapsed on a van and a taxi in when a personnel lift truck with the lift by mistake elevated passed under the bridge. [69][70]	1 killed, 2 injured	Collapsed on the road beneath	Both other cars were driving in the opposite direction. The van driver died and taxi driver and passenger were injured. Bridge now rebuilt.
Overbridge over Chengdu-Kunming Freeway	Zigong	People's Republic of China	1-Jul-11		Truck crashed against concrete support pillar [49]		Overbridge destroyed, fell onto highway.	
Gongguan Bridge	Wuyishan, Fujian	People's Republic of China	14-Jul-11		Overloading [71]	1 killed, 22 injured	Entire bridge collapsed, tourist bus with 23 people on board crashed to ground	
No. 3 Qiantang River Bridge over Qiantang River	Hangzhou, Zhejiang province	People's Republic of China	15-Jul-11		Overloading [71]	0 killed, 1 injured	Partial collapse leaving a 20-meter-long, 1-meter-wide pit in one lane	Collapse due to two trucks each loaded with over 100 tonnes of goods crossing bridge [49]
Baihe Bridge in Huairou district	Beijing	People's Republic of China	19-Jul-11		Bridge designed for max. 46 tonne vehicles, truck overloaded with 160 tons of sand caused it to collapse. [71]	0 killed, 0 injured	Entire 230m bridge destroyed.	

(*Continues*)

Table 2.1 (*Continued*)

Bridge	Location	Country	Date	Construction type, use of bridge	Reason	Casualties	Damage	Comments
Kutai Kartanegara Bridge	Tenggarong, East Kalimantan	Indonesia	26-Nov-11	Suspension bridge	Human error. Bridge collapsed while workers repaired a cable. (Under investigation)	20 killed, 40 injured (33 missing)	Deck completely destroyed, 2 bridge pillars were standing at the time of the collapse.	Kutai Kartanegara Bridge
Eggner Ferry Bridge over the Tennessee River	Between Trigg County, Kentucky and Marshall County, Kentucky	United States	27-Jan-12	Truss bridge	The MV Delta Mariner struck the bottom portion of a span of the bridge when travelling in the incorrect channel of the river.	0 killed, 0 injured	Span over the recreational channel of the river collapsed.	Emergency repairs to bridge completed on May 25, 2012. There were preexisting plans before the collapse to replace the bridge with a 4-lane bridge over the river.
Jernbanebroen over Limfjorden	Aalborg	Denmark	28-Mar-12	steel beam, openable	Ship collision	none	Mechanical damage	All rail traffic cancelled for over a year, no alternative route
Jay Cooke State Park Swinging Bridge	Carlton, Minnesota	United States	20-Jun-12	Pedestrian swinging wooden plank and cable	Raging floodwaters	0 killed, 0 injured	Multiple wooden planks washed away. Cables stayed intact.	Closed for repairs. Reopened November 1, 2013.
Beaver River Trestle Bridge	Alberta	Canada	22-Jun-12	wood, concrete, metal trestle.	Three men set the bridge on fire. [72]	none	Bridge badly damaged and closed.	Bridge did not carry rail traffic anymore, and carried pedestrians, part of the Iron Horse Trail. Another small fire was set in 2015. Bridge is being rebuilt. [73]
Guangchang Hedong Bridge	Guangchang County, Fuzhou City, Jiangxi Province	People's Republic of China	8-Aug-12	steel, concrete		2 killed, 2 injured		
Yangmingtan Bridge over the Songhua River	Harbin	People's Republic of China	24-Aug-12	Suspension bridge	Overloading; usage of unsuitable building material (suspected) [74]	3 killed, 5 injured	100-metre section of a ramp of the eight-lane bridge dropped 100 feet to the ground.	Main bridge reopened on the same day, ramp still defunct.

Bridge under construction for road E6 at Lade/Leangen	Trondheim	Norway	8-May-13		Bridge collapsed under construction [75]	2 killed		
I-5 Skagit River Bridge collapse	Mount Vernon, Washington	United States	23-May-13	Polygonal Warren through truss bridge	Oversized semi-truck load carrying drilling equipment from Alberta clipped top steel girder causing bridge collapse.	0 killed, 3 injured	One 167 foot span collapsed.	Truss bridges like this one require both the top and the bottom to remain equal in strength and solidity. When the truck hit the top girder, or girders, this caused the pressure/squeeze system to fail, which made the bridge fold up. The design was outdated; more modern types of truss can better withstand such forces.
Scott City roadway bridge collapse	Scott City, Missouri	United States	25-May-13	Concrete road bridge	A Union Pacific train T-boned a Burlington Northern Santa Fe train outside of Scott City, Missouri, at approximately 2:30 am. The impact caused numerous rail cars to hit a support pillar of a highway overpass, collapsing two sections of the bridge onto the rail line. Two cars ended up driving onto the collapsed sections, injuring three people in one vehicle and two in the other. Two people on one of the trains were also injured. [76][77]	7 injured	Two roadway bridge sections collapsed onto the rail line below.	

(*Continues*)

Table 2.1 (***Continued***)

Bridge	Location	Country	Date	Construction type, use of bridge	Reason	Casualties	Damage	Comments
Wanup train bridge	Sudbury, Ontario	Canada	2-Jun-13	Steel bridge	Train trestle over the Wanapitei River near Sudbury, Ontario was struck by derailed railcar	0 killed, 0 injured	Total bridge collapse	CP trains temporarily diverted over CN track. Bridge reconstructed with new pier in 9 days.
CPR Bonnybrook Bridge	Calgary, Alberta	Canada	27-Jun-13	Steel railroad bridge	Partial pier collapse due to scouring from flood event of the Bow River	0 killed, 0 injured	Partial bridge collapse	[78]
Acaraguá bridge collapse	Oberá, Misiones	Argentina	12-Apr-14	Concrete road bridge	The total collapse of a road bridge over the Acaraguá river, when a passenger bus circulated, caused three dead and thirty wounded.	3 killed, 30 injured	Total bridge collapse	
Belo Horizonte overpass collapse	Belo Horizonte	Brazil	3-Jul-14	Steel and concrete bridge	Construction error	2 killed, 22 injured	Total bridge collapse	Bridge collapsed while under construction
Motorway bridge collapse during construction	Near Copenhagen, Denmark	Denmark	27-Sep-14	Steel and concrete bridge	Construction error	Workers received mild injuries	Partial bridge collapse	Bridge collapsed during concrete casting, with debris falling onto open motorway below and narrowly missing vehicles, closing major motorway E47 for several days. The remains of the bridge were subsequently demolished and a replacement built elsewhere. [79]
Hopple Street Overpass over I-75 Southbound	Cincinnati, Ohio	United States	19-Jan-15	Road bridge	Old Northbound Hopple Street offramp totally collapsed onto roadway below during demolition [80]	1 killed, 0 injured	Total bridge collapse	Bridge collapsed prematurely due to a faulty demolition process
Plaka Bridge	Plaka-Raftaneon, Epirus	Greece	1-Feb-15	Stone bridge	Flash flood ripped foundations from the riverbanks	0 killed, 0 injured	Central section of the bridge collapsed	