Introduction to Cable Suspension Bridges

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in cooperation with

Transportation Cabinet
Commonwealth of Kentucky

and

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This report is an overview of suspension bridges. A historical perspective of bridge construction design and materials is included, focusing on bridges of interest to the Kentucky Transportation Cabinet. The report is intended to provide background information on suspension bridges to those not well acquainted with the structures.
INTRODUCTION

This is the first of a series of three reports concerning suspension bridges and wire corrosion. The second report addresses the sources and mechanistic features of suspension bridge wire corrosion. The third report discusses some technical aspects that should be addressed to preclude corrosion damage on suspension bridges.

In most jurisdictions, there is a dearth of suspension bridges compared to other bridge types. The purpose of this report is to acquaint those who are involved in bridge management with salient features of suspension bridges that often differ from those of other generic bridge types. A short history of suspension bridges which deals with the evolution of suspension bridge design also is included.

HISTORY OF SUSPENSION BRIDGES

Suspension bridges date back to antiquity. However, they were not products of western technology. Their origin appears to have been in China and the South Americas. Travelers and explorers from Europe saw those structures and their reports engendered interest in the suspension principle.

The earliest metal suspension bridges were built in China. Those bridges used iron chains suspended from ground level over gorges or rivers. The decks consisted of wooden planks placed directly on the chains. At least one of those bridges, built in the sixteenth century is still in service. The suspension bridges observed in the South Americas were nonmetallic, fibre structures used for pedestrians. Those structures were reported in the West in the mid-eighteenth century.

The suspension principle (Figure 1) was first applied in the west for temporary military bridges. The first European metal suspension bridge was a chain structure built near Glorywitz, Germany, in 1734. The Winch Bridge became the first British suspension structure, being built in 1741 (1).

The first American suspension bridge, also a chain structure, was built by James Finley in 1801. Finley patented the design and later built many small suspension bridges in Pennsylvania during the early 1800's. Among the many novel features of Finley's design were the use of a simple stiffening system for the deck and an intuitive, yet amazingly effective, method for determining the sag of the chains (2).

The first wire suspension bridge in the world (employing brass wire) was built over the Schuylkill River near Philadelphia by White and Hazzard in 1816. That structure might have been more notable, except for its failure under a load of ice and snow less than a year after erection.

The British were the first to use the advantages of the suspension principle in bridges of long, open spans. The first of those was Brown's Union Bridge, completed in 1823. Thomas Telford's Menai Strait Bridge, an eyebar chain structure, was the most important civil engineering feat of the first 50 years of the nineteenth century. The bridge, completed in 1826, had a 576-foot main span. That structure aroused worldwide interest that led to widespread employment of the suspension principle.
Figure 1. Conventional Suspension Bridge and Cable-Stayed Bridge.
In the early 1820's, the Frenchman, Navier, visited England to study suspension bridge construction. On returning to France, he published his famous *Memoire Sur Les Ponts Suspendus*. Thereafter, the French embarked on a widespread suspension-bridge construction program that would see them build over 500 suspension bridges in the next 50 years. Notable French suspension-bridge builders included the Vicat and Sequin brothers.

The largest suspension bridge built in nineteenth-century Europe was Chaley’s Fribourg (Switzerland) bridge completed in 1834 with a main span of 870 feet. Also of note was Clarke’s Budapest bridge (3). One possible reason for the lack of larger suspension bridges in Europe was the increased use of trains for transportation. Due to the lack of stiffness of early suspension bridges, civil engineers of the mid-nineteenth century considered the design to be unsuitable for rail traffic.

It is interesting to note that the British regarded eyebar-chain suspension bridges as being superior to those employing wire cables. The British felt that wire was too susceptible to corrosion damage. Also, their industry was better adapted to producing eyebars. The French felt corrosion was not serious (although at least one corrosion-induced failure occurred in the mid-nineteenth century). Also, the French were adept at drawing wrought-iron wire.

During most of the nineteenth century, navigation was the most important mode of transportion in the United States. Steamship owners pressed for the right of unhindered navigation on major waterways. As a result of their efforts, the only practical bridges that could be built spanning major rivers were suspension bridges.

Advantages of wire suspension bridges were quickly recognized by two designers, Charles Ellet and John A. Roebling. Ellet built a large, unstiffened, wire-cable suspension bridge over the Schuylkill River near Philadelphia in 1842. In 1848, Ellet spanned the Niagara River with a 770-foot span cable-suspension footbridge. His largest structure was the 1,010-foot span at Wheeling, West Virginia, built in 1849. In 1854, a storm demolished the bridge. However, it was subsequently rebuilt and still exists. This was the last bridge built by Ellet, who died during the Civil War.

John Augustus Roebling was the most noted suspension bridge builder in the United States. His first major work was a cable-suspended aqueduct built in Pittsburgh in 1845. Thereafter, he erected several small suspension bridges and aqueducts in Pennsylvania (4). Roebling completed his first landmark suspension bridge over the Niagara River in 1855. The 825-foot span had two decks; the lower deck carried highway traffic, and the upper one carried a railway. This was the first, or one of the first, large suspension bridges to employ a stiffening truss, which was made of wood. This bridge was dismantled in 1897.

The first suspension bridge built in Kentucky was a chain structure over the Kentucky River near Frankfort. It was completed in 1810. The first cable suspension bridge in Kentucky was also built in the same vicinity in 1850. That bridge was one of the first cable suspension bridges to feature a stiffening truss and was used to carry a railway. However, the design proved inadequate and the bridge was replaced in 1857. The next major cable suspension bridge in Kentucky, with a 323-foot span, was built over the Licking River at Falmouth in 1853. The bridge collapsed under a load of cattle shortly after completion.
In 1857, Roebling initiated construction on a large railway suspension bridge over the Kentucky River at Wilmore. After the towers were completed, work was discontinued due to failure of the railroad company. Roebling commenced work on the Ohio Bridge at Covington, Kentucky, in 1856. Owing to numerous delays, the bridge was not completed until 1867 (5). That bridge served as a prototype for modern suspension bridges. In 1869, Roebling started the Brooklyn Bridge over the East River between Brooklyn and New York City. However, he died in the same year and the bridge was actually built by his son, Washington Roebling.

The Brooklyn Bridge had great impact on suspension bridge construction, especially in the New York area. The 1,595-foot main span of the bridge was supported by four 15.75-inch diameter cables. The East River between Brooklyn and New York was successively spanned by two other large cable suspension bridges shortly after the turn of the century (6). The Williamsburg Bridge was completed in 1903 and has a main span of 1,600 feet. That bridge has four 18-inch diameter cables. The Manhattan Bridge was finished in 1909 and has a main span of 1,470 feet. That bridge has four 21.25-inch diameter cables.

Following completion of Roebling’s bridge over the Allegheny in 1871, no suspension bridges were built over the Ohio River or its tributaries for 25 years. A second period of Ohio River suspension construction was the work of Herman Laub and his followers between 1896 and 1905. Bridges built during that period included the first East Liverpool, Ohio, bridge (1896) and the second East Liverpool, Ohio bridge (1905). The main spans of those bridges were 510 and 800 feet, respectively (7).

In 1905, a suspension bridge failed at Charleston, West Virginia. Thereafter, no suspension bridge construction occurred in the Ohio Valley region until 1927. At that time, several chain- and cable-suspension bridges were built: the St. Marys, West Virginia, bridge (1929); the Point Pleasant, West Virginia, bridge (1928); the Portsmouth, Ohio, bridge (1927); the second Steubenville, Ohio, bridge (1928); and the Maysville, Kentucky, bridge (1930). Most of those bridges were designed by Robinson and Steinman, the J. E. Greiner Company, or Modjeski and Masters. The principal builders of those bridges were Dravo Contracting Company, John Roebling’s Sons Company, and the American Bridge Company.

In the US, there was a flurry of suspension-bridge construction between 1920 and 1940. However, after a series of problems, culminating with the spectacular Tacoma Narrows Bridge failure in 1940, American suspension-bridge construction ceased for a period of 10 years. Since the early 1950’s, some suspension bridges have been built in the west, north, and northeast portions of the US. However, those have usually been structures requiring long, open spans. The larger of those more recent bridges are the Mackinac Bridge, in Michigan (1955), designed by D. B. Steinmann, and the Verrazano Narrows Bridge, in New York (1964), designed by O. H. Ammann. The last major American suspension bridge was the William Preston Lane Jr. Memorial Bridge, built over the Chesapeake Bay in 1972.

Overseas construction of classic suspension bridges has centered in Great Britain with the Forth Road Bridge (1964), Severn Bridge (1966), and the Humber Bridge (1980). The Japanese erected a series of cable-
stayed and suspension bridges, including a 2,336-foot main-span suspension bridge between Honshu and Kyushu in 1973. A suspension bridge with a 4,635-foot main span is being planned for Hong Kong, though the construction has been temporarily deferred. The longest proposed suspension bridge will be the 10,827-foot main-span Messina Strait Bridge between Italy and Sicily (8).

On the European continent, the German revival of cable-stayed bridges has led to widespread employment of that type of bridge (Figure 1). The first cable-stayed vehicular bridge built in the US was erected in Sitka Harbor, Alaska, in 1972. A 1,222-foot main-span cable-stayed highway bridge is presently being built at Luling, Louisiana (9). That type of cable bridge has economic advantages over most other bridge types in spans ranging from 1,000 to 1,500 feet (10).

EVOLUTION OF THEORIES OF SUSPENSION BRIDGE DESIGN

Early nineteenth-century bridge designers were quick to exploit the advantages of suspension bridge design, especially after the commercial development of puddled wrought iron. Wrought iron presented an economical structural material that would reliably support high loads in tension. The suspension principle made the best use of that ability. Combined, those factors allowed designers to attempt long spans that were previously unattainable.

Telford’s Menai bridge was the first suspension bridge to benefit from theoretical analysis. Gilbert used Bernoulli’s theory of the catenary to study Telford’s original design and subsequently suggested changes for the towers and eyebar chains. In his classic Memoir Sur Les Ponts Suspendus, Navier determined the shape of the cables to be parabolic, when the load of the deck was uniform and much greater than the weight of the cables.

Unfortunately, many early suspension bridges suffered from several design deficiencies. Those bridges were flimsily stiffened and interconnected. Most early designers had not considered the effect of concentrated deck loads on the suspension systems. As a result, decks of the early bridges did not evenly distribute live loads to the cables or chains. Roebling’s early Monongahela Bridge would deflect as much as 2 feet on one end when loaded on the other by a heavy horse-drawn wagon. Also, due to the lack of stiffness and light construction, early suspension bridges were subject to extreme oscillation under severe wind loads. Those deficiencies led to many failures, including Ellet’s Wheeling Bridge, in Europe and the US.

Roebling approached those problems intuitively by adding a stiffening truss and stay cables to his bridge designs. Those components distributed live loads, stiffened the structure against wind-induced vibrations, and added mass to resist wind lift. In contrast to his earlier works, Roebling’s Niagara Bridge was quite rigid and would only deflect about four inches when loaded by a locomotive. The Niagara Bridge had a notable load-bearing redundancy. Not only was the truss held by the main cables via vertical suspenders, but also by inclined stay cables connecting the truss to the towers. The truss also was stabilized by guy wires attached to the ground in the gorge below the bridge.
After creation of the Niagara Bridge, Roebling gained assurance in the concept that inertia of a suspension bridge due to the cable, deck, and truss masses contributed significantly to suspension bridge stiffness. With further experience and confidence in that belief, the Roeblings designed the Brooklyn Bridge with a main truss only 1 foot deeper than the 16-foot depth of the Niagara Bridge. However, they continued in redundantly supporting the truss with both vertical suspenders and inclined stay cables.

The Roeblings also felt that large main cables made of many tightly clamped and wrapped parallel wires were superior to separate multiple strands. Failure of Ellet’s Wheeling Bridge, designed with separate strands, influenced that belief. When that bridge was rebuilt in 1862, it incorporated four consolidated cables along with inclined stay cables for added strength.

Roebling’s famous bridges were built using intuitive principles with simple bending and tension considerations. The first formal theory of truss-stiffened suspension bridges was derived by Rankine in 1858. Rankine’s basic assumptions, for a single span using a truss with pinned ends and inextensible cable, were:

1. Under total dead loading of the span, a main cable assumes a parabolic shape and the truss is unstressed.
2. Any live load applied to the truss is distributed by it to subject the cable to a uniformly distributed load across the entire span.
3. The suspenders connecting the cable to the truss exert a constant upward pull acting all along the truss of intensity \( q \) per unit length. The value of \( q \) is equal to the total live load divided by the effective span of the truss.

However, both Roebling’s and Rankine’s ideas were considered overly conservative and two further theories, the “elastic” theory and the “deflection” or “more exact” theory, were developed to provide economical designs (11).

In 1913, D. B. Steinman translated a paper, by J. Melan on “elastic” theory, that led to its use in the US. That theory differed from Rankine’s by considering the upward suspender pull \( q \) to depend upon the elastic stiffness of the main cables in tension and on the truss in bending. Elastic theory provided a less conservative stiffening truss, yielding a lower dead load than could be achieved by earlier theories. Calculation for that method are simple, and for that reason, it has been used for preliminary studies and for final designs of short-span bridges (12).

During the same period (from 1880 to 1906), the first nonlinear or "deflection" theory was expounded by Melan. That theory assumed a cable and truss deform in a mutually dependent manner and the loads applied to the system can be treated as concentrated loads. "Deflection" theory yielded a savings in truss weight up to 65 percent over the “elastic” theory and gave significant weight reductions to long-span bridges (13). The first application of that theory was by L. S. Moisseiff on the Manhattan Bridge, completed in 1909. The method was improved by Steinman and applied subsequently by most designers in the US. However, its use led to more ambitious slender structures, with resultant failure.
of Moisseiff's Tacoma Narrows Bridge in 1940 due to wind-induced vibrations (14).

No more suspension bridges were built in the US until the causes of the Tacoma Narrows failure were identified and widely accepted remedies adopted. In designing the 3,800-foot main-span Mackinac Bridge, Steinman combined a deep open truss with a partially perforated deck to overcome wind problems (15). The British used an aerodynamically stable, six-sided, welded box girder to overcome wind problems in design of the 3,240-foot main-span Severn Bridge, completed in 1966 (16). A similar approach was employed by the British in the longest span ever attempted, the 4,626-foot main span Humber Bridge completed in 1981 (17).

Additional suspension bridge designs have been developed in recent years. One of those uses integral equations in repetitive converging form to provide exact solutions for stresses and displacements (18). That method may be combined with computers to provide rapid, accurate analyses of a design.

In 1953, upon purchase of the Ohio Bridge at Covington by the Kentucky Department of Highways, a civil engineering consulting firm performed an interesting stress analysis of the four cables of the bridge. The backstay portions of the newer upper cables were unloaded. By measuring the sag of those cables, the horizontal component of the cable tension was determined. Then, measurements were made to determine the shape of the cables in the center portion of the main span. The horizontal component of the cable tension, required to support the known dead load for both cable sets, was calculated. The horizontal component for the lower cables was then equal to the horizontal component for both cable sets in the main span minus the horizontal component for the upper cables as determined from the side-span calculations. The maximum stress borne by the upper cables (live load plus dead load) was calculated to be 41,000 psi. The maximum stress borne by the lower cables (live load plus dead load) was calculated to be 27,000 psi (19).

ROEBLING'S OHIO RIVER BRIDGE AT COVINGTON

Many changes in component design have been effected since Roebling completed the Ohio Bridge at Covington (Figure 2). Most of those have been due to the use of new materials and erection practices. More recent design theories have also yielded improvements, yet it is remarkable how most newer suspension bridges mirror Roebling's pioneering structure (20).

A suspension bridge is made of five major component groups: towers, anchorages, main cables, suspenders, and deck and truss system (Figure 3). A brief description of the Ohio Bridge will serve as an introduction to the major features of suspension bridges.

The towers of the Ohio Bridge rest on wooden foundations sunk 12 feet below the low-water mark. The wood courses were built on gravel beds on both sides of the Ohio River between Covington and Cincinnati. The two towers were built on 1,057-foot centers to provide an open main span of 1,005 feet. Each tower weighed 30,000 tons. The lower 25 feet of masonry was of limestone. The upper courses were Buena Vista
Figure 2. The Ohio Bridge in 1880 (5).
Figure 3. Typical Modern Suspension Bridge.
Sandstone. The sandstone blocks used in the towers measured up to 60 cubic feet in size and were laid with mortar.

The upper portion of each tower consisted of a massive buttressed Gothic arch (strut) connecting two vertical legs. The legs have a tee cross section and were spaced 30 feet apart to accommodate the truss and roadway. The strut served to reinforce the lateral strength of the legs. The legs were tied by iron bars located in the strut. The inward cant of the cables, between the towers (cradling), was intended by Roebling to confer compressive forces on the struts, giving the tower arches additional strength. The towers rise 75 feet above the road. The height of the towers from the river bed to the tower peaks was 242 feet. Each tower had an internal well, 20 by 30 feet in cross section, under the roadway.

At the top of the upper masonry courses, cast-iron bearing plates 11 by 8 feet were bedded to support the original cables. Each cable rested on two large cast-iron saddles. Each saddle rested on 32 rollers, which bear on the plates. When a second pair of main cables was added to the bridge in 1898, similar assemblies were encased in turrets atop the towers. The roller assemblies for the new cables rest on massive steel girder tables mounted over the original bearing plates.

The cables were connected to land by gravity anchorages, located at the ends of the cable-supported spans. The end of each original cable was enclosed in an anchor block, 75 feet long by 12 feet wide by 25 feet high. A 25-foot wide roadway separated each pair of anchor houses. The original cables entered the anchor blocks on 36-foot centers. Each cable was separated into seven strands at splay saddles located on the faces of the anchorages. In the anchor chambers, the strands were individually looped about anchor shoes. The shoes were connected to wrought-iron eyebars by two long pins. One pin was superimposed over the other, separating the strand and eyebar sets into two levels. When first completed, the original anchor chambers were filled with mortar to seal the strand ends from the atmosphere.

The wrought-iron eyebar chains consisted of nine pin-connected links having a total length of 92 feet. The chains curved about a cast-iron bearing plate and proceeded vertically downward through the anchor-block masonry. The lowest eyebar links were pinned to a large cast-iron anchor plate, whose face was elliptically shaped having a major axis of 17 feet and a minor axis of 14 feet. Each anchor block is made of 8,400 tons of masonry. Two-thirds of that weight acted vertically on the anchor plates, resisting the tensile pull of the cables.

The secondary cable anchorages, added in 1898, were ashlar masonry. On the Kentucky shore, the secondary anchorages were built adjacent to the original ones in such a manner as to make the two anchorages appear continuous. However, secondary anchorages on the Ohio side were built some 70 feet landward from the original anchorages and also served as piers for the Ohio approach span. The secondary anchor blocks measured about 63 feet long by 23 feet high by 28 feet wide. The secondary cables splayed into 21 strands at the entrances of the anchor houses. The strands looped around anchor shoes attached to an anchor assembly by pins. The anchor assemblies consisted of steel plates, holding the shoes on three vertical tiers. The anchor assemblies were pinned to steel eyebars, part of an 8-link eyebar chain connected on the other end to a 14-foot diameter anchor plate bedded under the anchor block.
masonry. That was similar to the original anchorages. The secondary anchorages weighed 7,300 tons each and resisted a maximum design pull of 3,000 tons.

The original cables, each 1,700-feet long and 12 1/3 inches in diameter consisted of 5,180 No. 9 gage wrought-iron wires of 1/60 square inch cross sectional area. The cables had a sag of 90 feet and were cradled so as to lie 50 feet apart at the tower saddles, 36 feet at the anchorages, and 24 feet at the center of the span. Each of the original cables had a specified breaking strength of 8,400,000 pounds.

The secondary cables consisted of bright (non-galvanized) steel wire. The new cables were 1,970 feet long and 10 1/2 inches in diameter. The cables were each made of 2,226 No. 6 gage wires in 21 strands with a specified breaking strength of 12,000,000 pounds per cable.

Both cable sets, original and secondary, were constructed segmentally in strands to facilitate construction. Prior to stringing the cables, a walkway was suspended between the anchorages, through the completed towers. A guide wire was laid across the river to mark the location of each cable. A heavier endless hauling rope was laid over the guide rope. That rope was suspended on pulleys at the towers and driven by engines at the anchorages. A gooseneck bracket mounting the spinning sheave was clamped on the endless rope. That allowed the hauling rope to carry the spinning sheave through the towers and anchorages.

The strands were completed by a "spinning" process devised by the Frenchman Vicat, although Roebling developed the method to a practical procedure. One wire was looped around the spinning sheave and transferred from one anchorage to the other by travelling the endless rope. Each pass of the sheave transferred two wires. These were attached to temporary eyebars located adjacent to the anchor assemblies (made of permanent eyebars and steel pins).

When sufficient wires were spun to form a strand, the two free wire ends were spliced. Each strand was compressed into a circular cross section and seized with tie wires. The strand was then lowered from the carrying sheaves into their final resting position. The sag of the strand was adjusted in relation to the guide wire. The looped ends of the strand were pinned to the permanent eyebars in the anchorages.

After all strands were completed, ties on the strands were removed for a short distance. The strands were compressed to form the circular cross section of the main cable. Then, that section was tightly wrapped with galvanized wire (Figure 4) to provide corrosion protection and, according to Roebling, unify stresses throughout the cable (though it is doubtful that wrapping would accomplish that task). When finished, the cables were completely wrapped to the anchorage splay saddles.

After the cables were completed, suspension bands were attached to the cables. The original cable bands were wrought-iron plates that were heated and then hot-bent around the cables in the field. Wire-rope suspenders were attached to the cable bands and truss floor beams. Suspending tension was accomplished by adjusting threaded U-bolts attached to the truss floor beams and to the end fittings of the suspender cables. Roebling's redundant deck-suspension system which combined vertical suspenders and inclined stays, was widely criticized. However, he was
Figure 4. Wrapping Cables on the Ohio Bridge (1866) (5).
probably prompted to that feature by numerous failures of his predecessors. In his original design, Roebling placed the vertical suspenders on 5-foot centers, corresponding to spacing of the deck beams. Short bars were used for the central 100 vertical suspenders. The rest were wire rope, having an ultimate tensile strength of 45 tons near the center spans, and 36 tons near towers (where they were reinforced by stays). Most of the inclined stays were attached to the top chords of the truss and interconnected the side spans with the main span through the towers. Those were intended to support the truss and stiffen the system. Thirty-eight 2.25-inch diameter wire-rope stays were employed at each tower.

When the bridge was modified in 1898, the stay system was retained. However, the vertical suspension system was changed. Now, vertical hangers are secured between the main cables. The hangers are attached to vertical suspenders that, in turn, are connected to deck beams at each suspension point. The spacing of the vertical suspenders was also increased to match the increased deck beam spacing of the new truss. The backstay portion of the secondary cables do not support the trusses.

The bridge has two 281-foot side spans and a main span of 1,057 feet. The original truss girders were 20 feet 9 1/2 inches apart. The truss was continuous, running 1,619 feet through both towers and side spans. That truss was slightly curved, about 1.5 feet per 100-foot run. Some stiffness was gained by making the truss continuous through the towers. The truss was also hinged at the center. In a temperature range of \pm 60^\circ F from normal, it was calculated that the bridge would rise or fall 1 foot at the hinge. The original truss was made of wrought-iron built-up beams. The beams were fabricated by riveting and interconnected by pinning. The original truss was 10 feet deep. The deck beams were 7-inch I-beams, spaced on 5-foot intervals. Those beams were reinforced by a 9-inch central longitudinal stringer on top of the deck beams and a 12-inch I-beam below, which served as a king post for the support of tie rods.

The new stiffening trusses, erected in 1898, were 31 feet 3 inches apart and were ordinary pin-connected Pratt trusses with intersecting diagonals in each panel and adjustment sleeve nuts in all diagonals. The trusses were continuous from anchorages to the middle of the main span, where expansion is accommodated by a telescopic joint. The channel span trusses were 13 feet 6 inches deep at the towers and 28 feet deep at the centers, all the top chords being curved and all the bottom chords being essentially straight. The new truss members were made of steel.

The 1898 modifications were accomplished to strengthen the bridge for electric streetcar traffic (Figure 5). The designer was William Hildenbrand who had previously worked with Washington Roebling on the Brooklyn Bridge.

After the secondary cables were spun, floor beams for the new truss were lifted from the river to a position under and supporting the original truss. A jacking system that allowed the original cables to swing from their initial position to their final position under the secondary cables was employed. The new truss was installed and the old truss removed. The cable pairs, the upper secondary cables, and the lower original cables were tied through adjustable tie rods (hangers) at the cable bands (Figure 6). At each new cable-band location, two
Figure 5. The Ohio Bridge (KY17) in 1976.

Figure 6. Detail of Suspenders on the Ohio Bridge.
additional vertical suspenders were paired with the original suspenders. Each group of suspenders was intended to support a load of 91,000 pounds, 51,000 pounds of which was to be borne by the secondary cables (21, 22).

CONSTRUCTION OF MORE RECENT SUSPENSION BRIDGES

While the major components of suspension bridges have not changed radically since construction of the Ohio Bridge, numerous improvements have taken place. Most of those were intended to produce more economical structures (23, 24). The order of discussion of those changes follows the sequential phases of suspension bridge construction, which are

1. construction of piers;
2. construction of anchorages;
3. erection of towers;
4. placing of footbridges, guide wires, and stringing cables;
5. installation of cable saddles on towers and bents;
6. erection and compaction of main cables;
7. installation of cable bands and suspender ropes;
8. erection of the stiffening truss, floor beams and stringers;
9. placing of the floor; and
10. wrapping and painting of the main cable.

The construction of modern suspension bridge piers does not differ from that of other types of bridges, except for the usual greater spacing between them. Reinforced concrete has replaced the masonry used through the beginning of this century. The introduction of steel towers has eliminated the need for massive piers to support masonry towers. Tower design may affect the need for the pier to resist bending stresses. There have been no exceptional requirements for any piers on the newer Ohio River suspension bridges.

Gravity anchorages have been the predominant type used in America (Figure 7). Reinforced concrete also became a prime construction material soon after the turn of the century. With the advent of cable bents or side towers mounted at the ends of the side spans, designers gained more freedom in locating the anchor blocks. Cast steel replaced cast iron for anchor plates. In some cases, reaction girders of rolled shapes were used in place of cast anchor plates. As with Roebling's Ohio Bridge, eyebar chains were pinned to anchor plates and were attached to anchor shoes located in an open chamber (anchorage house). However, in newer bridges, the eyebar chains were shorter and the anchorage plates rested perpendicularly to the line of the cable in back of the anchor block rather than resting horizontally under the block. Hot-rolled steel replaced wrought iron for use in eyebars. As an additional economy measure, some suspension bridges such as the Portsmouth Bridge employed hollow anchorages filled with sand or earth to resist the cable tension.

The Newport Bridge (1968) across Narragansett Bay in Rhode Island employed a novel "pipe anchorage" system. Pipes were embedded in the anchorage block and the strands passed through the pipes. The strand
Figure 7. Kentucky Anchor Block of the Maysville Bridge.
sockets were seated directly against the back face of the anchor block. That design resulted in a substantial savings in cost over that of conventional anchorage systems.

In the late 1920's, a series of self-anchoring, short-span suspension bridges was built in America. Included were three eyebar chain bridges at Pittsburgh and a helical-strand bridge in Missouri. The cables of a self-anchoring bridge terminate at the ends of the side spans and confer an inward thrust on the stiffening truss.

Considerable cost savings have been achieved by substituting steel for masonry in suspension bridge towers. Early steel towers were rigid, as with Roebling's earlier designs. Use of steel in the early rigid towers offered several advantages, including lower cost. Also, it permitted use of higher towers that gave more favorable cable sag ratios (allowing the cables to support greater loads), and the thermal expansion of the towers balanced some of the elongation in the cables. However, use of rigid towers still necessitated complicated saddles to accommodate cable movement.

Rocker towers were introduced in the United States in 1915 on a chain-cable bridge at Dresden, Ohio. That design used a rocker base to allow the tower to deflect as cables elongate or contract. Rocker towers eliminated horizontal forces on piers and permitted use of shorter towers to accommodate large cable deflections. They were used in bridges having main spans less than 700 feet. The General U. S. Grant Bridge at Portsmouth, Ohio (referred to as the Portsmouth Bridge), was the first American application of a wire cable suspension bridge (Figure 8). The rocker base of that bridge was a steel casting machined to a 10-foot radius, resting on a planed steel base plate. Problems were encountered during erection, and that type tower was not used for any further cable suspension bridges built over the Ohio River.

Tall fixed-base semiflexible towers were first used on the Manhattan Bridge in 1909. That design was also employed on two Ohio River bridges; at Steubenville, Ohio, and Maysville, Kentucky. Due to the design of such towers, tapered with increasing tower height in the axis normal to bridge line, tower resistance to horizontal cable movements is small. The towers readily deflect horizontally to accommodate movements of the main cables. Semiflexible towers are usually used in long-span bridges and are the most common type in America. The British Humber Bridge uses 600-foot tall semiflexible towers, slip-form cast of reinforced concrete.

Rocker towers of the Portsmouth Bridge were made from standard low-carbon steel using riveted construction. Each tower leg consisted of closed box sections tied at intervals by batten or splice plates. Cast-steel rockers served as the base for each leg. The semiflexible towers of the Maysville bridge were made of riveted construction using silicon steel. The legs were braced by 2-1/2 panels of X-bracing above the roadway and by a horizontal strut at the top of the towers. One-half of a panel of X-bracing and a horizontal strut were located below the bridge-deck floor beam. The legs were closed rectangular box sections having narrow, enclosed side cells. The tower bases were bolted to the piers. In constructing both bridges, the towers were cambered toward the shores during construction to offset the inward bend encountered upon installation of the cables. In construction of
Figure 8. The Portsmouth Bridge Prior to Recabling (1978).
some suspension bridges, the towers remain fixed. The tower saddles were mounted on rollers and offset prior to cable installation. As the construction proceeded, the saddles were allowed to move inward towards the main span. After construction was completed, the saddles were rigidly affixed to the towers.

One major advantage of rocker and semiflexible towers was in the simplicity of design compared to rigid towers, which required more complex saddle-roller assemblies to accommodate cable movement. In many earlier designs employing fixed towers, that was usually accomplished by terminating the wrapping at the towers, separating the individual strands and resting them on rollers as was done on the Ohio Bridge. That feature proved undesirable since it required transitions from a circular cross section to a flat layer of strands. The transition region made wrapping difficult. Also, the unwrapped strands were usually susceptible to corrosion and mechanical damage from the rollers. The roller system required substantial housings to be erected on the tower tops.

Several important changes in cable layout evolved between the erection of the Ohio Bridge and the other bridges over the Ohio River of the 1920's and 1930's. The practice of inclining (cradling) the main cables inward to gain lateral stiffness was abandoned. Designers found the increase in rigidity due to that feature was negligible and its use made cable stress evaluation difficult. With acceptance of the "elastic" and "deflection" theories, practice shifted to mounting the cables in parallel between the anchorages. The cables had a separation that allowed suspenders to hang vertically between the main cables and truss mounting brackets. In most suspension bridges built after 1900, main cables were not sagged below the top of the stiffening truss.

The wire-spinning technique for erecting parallel-wire cables has not changed in principle since it was first devised. On large bridges, the technique has been expanded by using multiple sheaves to achieve higher spinning rates (25, 26). When a wire is spun, its length is individually adjusted. That process is usually accomplished at night or early in the morning to allow all wires to achieve a uniform temperature.

Prior to seizing, a completed strand is "shaken out" to detect loose wires. Incorrect length wires are cut, adjusted, and spliced. The strand is then lowered from the falsework into place on the towers and bents. The strands are formed into a circular cross section and seized with tie wires. After all strands are completed and lowered, final sag adjustment is accomplished by shimming at the anchorage shoes.

When all strands have been adjusted, the outer strands are untied, and a mechanical squeezing device forms the strands into a circular shape. The consolidated cable is seized with stainless steel straps. Cable bands are then attached to the cables. Gaps at the bands have been commonly caulked with oakum, saturated with red lead, and then sealed with lead wool driven into the gaps or with a sealant applied using caulkking guns. The outer surface of the cables of some bridges have been thickly coated with petrolatum, or more commonly a mixture of red lead paste and linseed oil.
Wire is subsequently wrapped about the cables on the panels, between suspender bands. A wrapping machine concurrently applies three or four wires around the main cable. Wrapping wire is tensioned to about 300 pounds by the machine, which travels uphill, bearing against the deposited wire. The wrapping wire is usually cleaned with mineral spirits, followed with a primer and two or more topcoats of paint. Other wrapping methods will be discussed later.

An alternate technique incorporating “ground spinning” of parallel wire strands was developed by Herman Laub at the turn of the century. That method was used for short-span bridges over the Ohio River and its tributaries, earning it the name of the Ohio River Method. The original cables of the Portsmouth Bridge were strung using that technique in 1926. The required length of cable was carefully calculated and measured on flat ground adjacent to a railway siding. Temporary shoes were anchored to the ground and the wires were run from shoe to shoe in a long wooden trough. The wire was fed from a carriage that ran on the rails. After each strand was completed and seized, one end was taken across the river. The strand was attached to anchor shoes and hoisted atop the towers and bents. When all strands were mounted, they were consolidated by the conventional wrapping process.

Wire rope has also been used for main cable construction. The first American application of rope was on the 400-foot main-span La Grasse Bridge at Massena, New York, in 1890. The longest application was probably the 760-foot span over the Yvonne River in France in 1900. However, due to the low and variable modulus of elasticity and low strength-to-effective-cross-sectional-area ratio, few wire-rope suspension bridges were built in America.

Shop-prestressed, pre-sized, twisted, helical strand (structural strand) was first used on the 949-foot main-span Grand Mere Bridge at Quebec, Canada, in 1929. It was also used on the Maysville Bridge (Figure 6) in 1930 (the second American application) and on the second and third cable installations at Portsmouth in 1940 and 1979.

That type of strand consists of an arrangement of wires helically placed about a center wire to produce a symmetrical section. The successive layers of wires are wound about the center wire, each successive layer having opposite lay or rotation. Helical strand has the advantage of being more flexible than parallel-wire strand, thus facilitating handling. It also is useful in suspension bridges of short spans where the cables are subject to short-radius bends.

Normally, helical strands used in suspension bridges have nominal diameters ranging from 0.9 to 1.6 inches. Wire sizes employed in this type of strand vary within the strand, containing some wires smaller than those used in conventional parallel wire strand. The common wire size used in parallel wire strand is No. 6 Roebling gage (0.192-inch diameter), though sizes as small as No. 8 gage (0.162-inch) have been employed. Helical strand usually contains wires ranging in diameter from 0.080 to 0.192 inch. The smaller wires are usually used as fillers. The Maysville bridge employed six 0.942-inch diameter and fifty-five 1.556-inch diameter strands arranged in a hexagon. That provided a smaller-diameter finished cable than one having all strands the same size.
Shop prestretching of wire rope and helical strand has three primary benefits: 1) it doubles the modulus of elasticity (for helical strand to about 24,000,000 psi), 2) it reduces or eliminates structural (irreversible) stretch during erection, and 3) it provides for a constant, predictable modulus throughout the length of the cable. The prestretching operation allows accurate length sizing of the strand in the shop. The strand may be cut to final length prior to spooling and shipment to the job site. Usually, all end fittings are applied to the strand after the strands are sized and cut.

The Maysville strands were shop fabricated using zinc-filled end fittings for attachment at anchor assemblies (Figure 9). Later applications of pre-sized strand employed shop-marked suspension-clamp locations and straight lines painted along the strands to prevent undue rotation of the strands during erection. It is not certain whether this was done for the Maysville bridge.

The socketed, sized strands were delivered to the job site on large wooden reels. One reel was required for each strand. Upon arrival at the job site, the reels were placed on a spindle. Foot bridges and a tramway were erected across the river. The tramway was used to carry the strands from the reel over the towers to anchorages on the opposite shore (Figure 10). The strands were placed in layers on the bearing points at the towers and bents.

Strands in adjacent layers were of opposite lay to assure line bearing instead of point bearing between all turning points of the cable. This also minimized rotation (twisting) of the cables upon application of loads. The Maysville cables were erected in 9 days. Aluminum fillers were placed in the outside strands to give the cable a circular section and the cables were wrapped in the usual manner (27).

The longest-span bridge using helical strand is the 1,995-foot main-span Tancarville Bridge in France. The last American bridge to employ helical strand was the 1,600-foot main-span Chesapeake Bay Bridge built near Annapolis, Maryland, in 1952.

In Europe, a closed-type or locked-coil strand has been widely used for suspension and cable-stayed bridges. That type of strand employs wedge-shaped inner wires surrounded on the outside by interlocking "S"- or "Z"-shaped wires. That provides very tight wire interstices, which European designers feel possesses better inherent corrosion protection than strand made from round wire. That type of wire was first used on the 1,033-foot main-span Cologne-Mulheim Bridge over the Rhine River, Germany, in 1933 (destroyed in World War II).

Shop-fitted parallel-wire strands were first used on the 1,600-foot main-span Newport Bridge, across the Narragansett Bay, Rhode Island, in 1968. The 1,600-foot main-span William Preston Lane Jr. Memorial Bridge (1972) was the last American application of parallel-wire strand. That type of strand is composed of successive layers of wire that do not possess a twist. In that respect, those strands are similar to conventionally spun parallel-wire strands. That type of strand does not require prestretching. The wires are layered in straight alignment in a hexagonal section. The strand is secured with tie wraps, sized and cut, and fitted with zinc-poured end fittings. The preassembled parallel-wire strand installation is the same as used for shop-fitted structural strand. However, aluminum
Figure 9. Anchor Assembly, Maysville Bridge Anchor House.

Figure 10. Hauling a New Strand across the Portsmouth Bridge.
fillers are not required prior to wrapping. The outer parallel-wire strands are untied and the cable is squeezed into circular section.

Shop-fabricated parallel-wire strand has a higher elastic modulus (28,500,000 psi) compared to helical strand (24,000,000 psi). Preassembled parallel-wire strand use wires ranging from 0.177 to 0.255 inch in diameter. Maximum strand sizes of about 2 9/16 inches in diameter are mentioned in literature for this type of strand. However, larger sizes are possible.

Early suspension bridges employed cable bands closely spaced and mounted over wrapped cables. Most bridges built after the turn of the century have greater band spacing, usually corresponding to panel lengths of the stiffening truss. Also, problems with slippage on the wire wrapping led to direct band placement on the shaped strands.

Cast steel has been used for making the cable bands since construction of the Brooklyn Bridge. Cable bands are usually two-piece units clamped to the main cables by bolting. This is accomplished before the wrapping process is initiated. Bands are usually split vertically. Flange faces contain multiple bolt holes, as many bolts are required to achieve sufficient closing force on the cables, and these must be hand-tightened. Exterior faces of most bands contain sloped indentations. Those act as guides for the suspension ropes. Interior faces of the bands are usually rough-machined to give extra grip on the wires. Cable bands serve to form the main cables, unify loading of all the cable strands, and transmit loads from the suspension cables to the main cables at specific points.

The use of rocker and semiflexible towers allowed the employment of fixed cable-support saddles on towers. Those saddles have large curvatures to prevent undue bending of the cables. Saddles are made of cast steel or built-up weldments. Cover plates are bolted to the saddles and sealed from moisture. Bent saddles are constructed in a similar manner. The Maysville Bridge has four additional tie-back strands running from the anchorage to the bent saddle. A larger cable diameter occurs between the bents and anchorages to accommodate those extra strands.

Suspenders used on most suspension bridges are made of prestretched galvanized wire rope. Wire rope consists of strands helically wound about a center strand. Wire rope has more flexibility than helical strand. Prestretched wire rope has a lower elastic modulus (20,000,000 psi) than helical strand. Normal wire rope is used in nominal diameters up to 4 inches. The suspender cables usually hang vertically with the end fittings attached to brackets on either side of the truss. The Humber and Severn bridges employed suspenders slightly inclined to provide some vibrational damping to the flexible bridge deck.

An early practice was to use the foot-bridge or spinning cables for suspenders. After the main cables were spun, auxiliary cables were cut and made into suspenders. New construction methods justified the use of shop-measured-and-fitted complete assemblies in most cases.

Zinc-poured cast-steel end fittings are used on most suspension cables. However, on the third cable installation at Portsmouth, fittings having a solid steel core were used to replace the traditional zinc-poured fittings. On some early bridges, lead had
been used as a filler material instead of zinc. However, the problems with lead melting when fires occurred precluded further use. The higher pouring temperature required for molten zinc has an adverse effect on fatigue performance of drawn wires at strand sockets. An alternate socket-filler material consists of a mixture of plastics and steel balls. This material precludes the fatigue problems associated with the use of zinc. That filler was developed and is being used in Europe for cable-stayed bridges.

End fittings on most modern bridges using prestressed rope employ shims rather than adjustable threaded ends typical of those on the Ohio Bridge (Figure 11). That change was prompted by maintenance-adjustment problems encountered in earlier bridges.

Trusses of suspension bridges built in the 1920’s and 1930’s were usually made of hot-rolled low-carbon or silicon steel plates or shapes. Opposite pairs of truss panels were shop fabricated by riveting and shipped to the job site. Opposing panels were hoisted to the suspenders from barges by a derrick boat and directly connected to the suspender ropes. When the truss units and floor bracing were suspended they were held in place by drift pins and bolts, ready for field riveting. Using that method, the Portsmouth Bridge truss was assembled in two weeks.

The Portsmouth Bridge has a continuous truss running 1,400 feet, including 350-foot long side spans and a 700-foot long main span. It was the second American suspension bridge having a continuous truss, the first being the Rondout bridge built in 1922 at Kingston, New York. The truss consists of 80 side panels, 17 feet 5 inches long by 14 feet deep. To provide a roadway width of 28 feet, the trusses were spaced 31 feet 6 inches apart.

The Maysville bridge has conventional two-hinged stiffening trusses. The side span trusses are 465 feet long, and the main span truss has a length of 1,060 feet. The stiffening trusses are 14 feet deep and 28 feet apart.

Riveted and welded girders have also been employed on suspension bridges. In the case of the Tacoma Narrows Bridge, the girders lacked sufficient rigidity to prevent wind-induced deck undulations. Also, the girders contributed to lift problems that caused the bridge to collapse. The English Severn and Humber bridges employ box girders that have low aerodynamic lift.

Most modern suspension bridges use fewer vertical suspenders than employed on either the Ohio or Brooklyn bridges. The suspenders are usually connected to the trusses at panel points on the upper chords or on the vertical posts. On through-trussed bridges, the latter feature allows the suspenders to stay clear of any salts used on the roadways for deicing. Truss suspender mounting brackets are commonly a pair of angle beams attached to a truss post by bolts or rivets.

Steelwork on modern suspension bridges is usually fabricated from plates and rolled shapes, using welding as the primary joining process. As is customary with other bridge types, the largest manageable sizes are fabricated in shops. Those sections are match-marked with connecting members, then shop drilled and reamed. The members are then shipped to the field, where they are erected, connected by drift pins, and then field-assembled by bolting.
Figure 11. Suspender-End Detail on the Maysville Bridge.
towed to the lift point. Then, the truss is lifted into place by a traveling crane and mounted on the cables.

Both the Portsmouth and Maysville bridges use rocker bents (Figure 12). That type bent is rigidly clamped to the main cables. It supports the truss end on pins and has a curved base or rocker that bears on the support pier. The Steubenville, Ohio, bridge uses a different type bent. On the Ohio end of the bridge, a sharp cable bend was required. Therefore, the cables were terminated on the bents and eye-bars transferred forces from the bents to the anchorages (28).

The Maysville Bridge was built with a concrete bridge deck. The Portsmouth Bridge was originally constructed using a 22-foot wide redwood floor with an asphalt overlay. That was replaced with a concrete-filled steel grid floor in 1940. In the late 1920's, there was a noticeable effort to minimize deck weight on suspension bridges. Various light steel decks were used. However, none of those was very successful. The Ohio Bridge presently has an open steel grid deck.

**BRIDGE WIRE**

The major innovation in suspension bridge cables between 1867 and 1930 was the introduction of steel wire. That material was first used on the Brooklyn Bridge in 1883 and apparently was employed in all subsequent American suspension bridges. As steel was thought to be more corrosion-prone than wrought iron, the Brooklyn Bridge wires were galvanized. However, until the late 1930's, cables using parallel wires were uncoated on some inland applications. Designers were satisfied with limiting galvanizing to the wrapping wires.

Crucible steel wire was specified for use on the Brooklyn Bridge. Due to unethical practices by the vendor, Bessemer steel wire was substituted. As Bessemer wire was originally proposed by Washington Roebling, the bridge was not subject to any physical shortcomings by the change of steel types. However, some of the Bessemer wire placed in the cables would not pass strength requirements. Therefore, Roebling required additional wires to be added to the cables.

The most common bridge wire used over the past 90 years is made from acid open-hearth high-carbon steel. The steel has approximately 0.9 percent carbon and has limitations on phosphorus and sulphur residuals. Chemical content of typical wire is shown in Table 1. The high carbon content is partially responsible for the high strength of bridge wire. Cold drawing also contributes to the mechanical properties of this type of wire.

The wire begins as billets, which are drawn down to rods of a diameter of approximately 0.3 inch. The rods are heated and quenched to produce a fine-grained steel prior to the drawing (cold-working) operation. That process is termed "patenting". The rods are cleaned by acid pickling and are neutralized in a lime bath. Following a low-temperature anneal, the rods are drawn through water-cooled dies to the final diameter in about four separate passes. Sometimes, the drawn wires are stress relieved at low temperatures to reduce residual stresses imparted during the cold-working operation. The resulting steel microstructure is a fine-grained feathery pearlite.
<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>MAYSVILLE BRIDGE</th>
<th>PORTSMOUTH BRIDGE (ORIGINAL)</th>
<th>PORTSMOUTH BRIDGE (REPLACEMENT)</th>
<th>MODERN BRIDGE WIRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.85 Max</td>
<td>0.69 - 0.84</td>
<td>0.85 Max</td>
<td>0.65 - 0.78</td>
</tr>
<tr>
<td>S</td>
<td>0.04 Max</td>
<td>0.031 - 0.037</td>
<td>0.04 Max</td>
<td>0.021 - 0.033</td>
</tr>
<tr>
<td>P</td>
<td>0.04 Max</td>
<td>0.008 - 0.014</td>
<td>0.04 Max</td>
<td>0.01</td>
</tr>
<tr>
<td>Mn</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.20 - 0.78</td>
</tr>
<tr>
<td>Si</td>
<td>N/A</td>
<td>0.03 - 0.14</td>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td>Ni</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.01 - 0.11</td>
</tr>
<tr>
<td>Cr</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Figure 12. Rocker Bent, Maysville Bridge.
In the late 1920's, an attempt was made to employ heat-treated wire on suspension bridges. The ladle analysis of that steel was similar to normal cold-drawn wire. The heat-treated wire was also drawn to size from billets in a similar manner to cold-drawn wire. The heat-treated wires had higher yield points (190,000 psi) than cold-drawn wire (160,000 psi). However, early attempts at using the wire on suspension bridges proved unsuccessful and that type wire was not used in later bridges.

The Brooklyn Bridge was the first American suspension bridge using galvanized (zinc-coated) wires. The zinc-coating provides corrosion protection for the wires. If exposed to corrosive influences, the coating will corrode first and the resulting electro-chemical reaction will protect the steel wire until a large area of the zinc-coating is consumed (i.e., galvanic protection). Most long-span American suspension bridges built since 1900 have galvanized wires in the main cables.

To apply a zinc coating, drawn wires are re-pickled, water-flushed, and fluxed in a weak hydrochloric acid solution. The wire is run through a bath of molten zinc and, then, through a bed of charcoal to smooth the coating. When a thick zinc coating is required, the wire is usually electroplated in an acid bath. That is usually done in a large batching operation.

After cooling, the wire is coated with wax, coiled, and shipped to a reeling plant. There, wires are spliced and rolled onto reels for shipment to the job site (where the wire is to be spun on the bridge). The reels contain up to 60 continuous miles of spliced wire (29). When the wire is to be made into helical strand, the wire is wound onto spools and fed into a stranding machine. That device pulls the wires through a die while continuously rotating it to form the strand. Larger strands are made by adding successive layers of wires on smaller strands in a similar manner. Prestretching is achieved by pulling long lengths of rope or strand with tension jacks or screws. Prestretching is usually done up to 50 percent of the breaking strength. After that, the rope or strand is sized, cut, and capped with end fittings. The rope or strand is then reeled and sent to the job site.

Close control of the galvanized coating process is mandatory or the coating will be discontinuous or crack-prone. Correct cleaning and annealing of the wire prior to plating assures proper retention of the zinc coating. When hot-dip galvanizing is used, control of the molten zinc bath temperature and wire feed rate will affect stability of the coating. Thicker zinc-steel interface layer and zinc coatings promote cracking of the coating. Tensile forces in the hot-dip coating, created by uneven or high cooling rates, may also cause cracking (29). Electroplated zinc coatings do not form an intermetallic layer with steel. Those are applied on coils of wire in large batching tanks.

Mechanical and physical test specifications for bridge wires are shown in Table 2. Until the mid-1920's, ultimate tensile strength and elongation were the only mechanical properties specified for bridge wire. However, in the past 50 years, reduction-in-area and yield-point requirements have been added. Reduction in area provides a better indication of ductility than the elongation. Yield point
<table>
<thead>
<tr>
<th>Property</th>
<th>Maysville Bridge</th>
<th>Portsmouth Bridge (Original)</th>
<th>Portsmouth Bridge (Replacement)</th>
<th>Modern Bridges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength (ksi)</td>
<td>220 Min</td>
<td>242-265</td>
<td>220 Min</td>
<td>217</td>
</tr>
<tr>
<td>Yield Point (ksi)</td>
<td>170 Min</td>
<td>167-185</td>
<td>170 Min</td>
<td>161</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>5 (10 in. ga) Min</td>
<td>0.5-1.7</td>
<td>5 (10 in. ga)</td>
<td>10</td>
</tr>
<tr>
<td>Reduction in Area (%)</td>
<td>30 Min</td>
<td>19.3-47.0</td>
<td>30 Min</td>
<td>N/A</td>
</tr>
<tr>
<td>Mandrel Bend Size</td>
<td>1-1/2 Diameters</td>
<td>N/A</td>
<td>N/A</td>
<td>1-1/2 Diameters</td>
</tr>
<tr>
<td>Standard Freeee Tests</td>
<td>4 One-Minute Immersions</td>
<td>N/A</td>
<td>N/A</td>
<td>5 One-Minute Immersions</td>
</tr>
</tbody>
</table>
provides a better basis for design than ultimate strength. Wire rope and structural strand are usually specified by modulus of elasticity and ultimate tensile strength.


Three zinc-coating thicknesses are specified in those codes. Class A zinc coating is 0.4 to 1.0 ounce per square foot of uncoated surface. Class B and C coatings are two and three times as heavy, respectively. Those coatings are usually specified for severe exposure conditions. As coating thickness increases, breaking stress of the wire decreases. Class A coated wire has an ultimate tensile strength of 220,000 psi compared to 200,000 psi for Class C coated wire. Additional recommended protective coatings are contained in Steel Structures Painting Council publications. Class B and C coatings are generally applied by electroplating. Federal Specification TT-P-641 recommends that zinc dust-zinc oxide paints be used to restore zinc protection in areas damaged during cable installation (31).

Two standard tests generally are used to check for suitability of galvanized-wire coatings. The mandrel test involves wrapping the wire around a mandrel that is some multiple of the wire diameter. The Maysville mandrel specification was 1.5 times the wire diameter. The purpose of that test is to detect cracking or flaking of the galvanized coating. The second test involves determining the weight of the zinc coating on the wire by first weighing a specimen, immersing the specimen in an aqueous acid solution to dissolve the zinc, and subsequently reweighing it to determine material loss (Standard Test Method for Weight of Coating on Zinc-Coated (Galvanized) Iron or Steel Articles, ASTM A 90-81). A similar test is the Preece copper sulfate test, which is a qualitative test to determine uniformity of the zinc coating. Coated wire is immersed in a copper sulphate solution for one minute. The test is usually repeated up to five times for a single specimen. When the zinc coating is dissolved, copper can be detected on the wire. Four, one-minute immersions were required for wire over 0.092 inch in diameter in the Maysville Bridge specifications (32).

Five types of wire splices have been used to join bridge wire: lapped splices, screwed splices, welded splices, brazed splices, and swaged splices. A joint efficiency of 95 percent is usually specified for shop splices and 90 percent for field work.

Lapped splices were accomplished by flattening the ends of two coils, lapping them together and wrapping them with small enameled wire. According to John Roebling, the splices were as strong as the wire. This was the earliest method of joining wire on suspension bridges and the method employed on the original cables of the Ohio Bridge.

Screwed splices use steel ferrules screwed into the threaded ends of wires. The wires have opposite-hand beveled threads to prevent unscrewing. The ends of the wires are mitered so the wires will not twist when the ferrule is attached. After the ferrule is applied, the joint is cleaned and dipped in molten zinc to provide additional
protection (this is done in shop splicing only). That method was first used on the Brooklyn Bridge. It has been used for both field and shop splicing.

Welding is usually of the flash or upset type where electricity is passed between two contacting wires. When sufficient heat is generated at the joint, the wires are pressed together and welded. That splicing technique is usually limited to shop work and yields a joint efficiency of 95 percent. The welded joint provides superior cable consolidation, compared to screwed splices.

Brazing with copper rods or solder is usually used to join wrapping wire, or at times, individual wires in rope. Brazing was used to join wires from different reels on the secondary cables of the Ohio Bridge. It was widely used on French suspension bridges. However, brazed splices yield lower joint strength than other methods. Therefore, the method has not been used widely on American bridges.

"Cabco" mechanical swaged-type splices were developed for the Scottish Forth Road Bridge (1964). Those splices were used on at least four other major bridges, including the Newport Bridge, Rhode Island (1969).

Designers gradually have increased working stresses for suspension bridge cables. The strength of bridge wire has also gradually increased. The Brooklyn Bridge wire had an ultimate tensile strength of 160,000 psi and was designed for a maximum service stress of 50,000 psi. The Williamsburg Bridge wires had an ultimate tensile strength of 200,000 psi and a maximum design service stress of 50,300 psi. In comparison, the Manhattan Bridge, the first American bridge designed by the "deflection" theory, had wires having an ultimate tensile strength of 220,000 psi and a maximum design service stress of 70,000 psi. The Portsmouth Bridge cables (the second cables) had a minimum ultimate tensile strength of 220,000 psi and a maximum design service stress of 76,400 psi. The maximum design service stress of the Maysville Bridge consisted of 1) a 44,000 psi dead-load stress, 2) a 26,300 psi live-load stress, and 3) a 200 psi thermal-contraction stress. In more recent applications, bridge wire having yield points of about 160,000 psi with service stresses in the range of 85,000 - 90,000 psi have been used. D. B. Steinman felt that common high-carbon bridge wire could readily sustain loads as high as 100,000 psi.

The main wire protection system of suspension bridges has been the wire wrapping/paint protection developed by John Roebling. He first employed that method on the Pennsylvania River Aqueduct, over the Allegheny River at Pittsburgh, in 1845. Wrapping wire is usually soft-annealed, galvanized steel wire.

Wire wrapping is applied by powered machines that have multiple spools. That allows placement of up to four wrapping wires simultaneously. Wrapping wires are installed after the cable bands have been fully tensioned. Usually, the wires are started from indentations in a band and wrapped for a complete panel length to the next band. Wrapping progresses from the lowest portions of the cables upward, to maintain close contact between neighboring wires. Bridge specifications have usually required a wrapping wire tension of 300 pounds or more.

The Williamsburg Bridge cables are composed of bare, uncoated wire, impregnated with a mixture of slushing oil and graphite. The
cables were originally wrapped with canvas duck and enclosed by sheet-metal covers. The sheet-metal covers proved inadequate and the cables were recovered with conventional wire wrapping in 1921.

In 1963, Bethlehem Steel Corporation developed a new type of main cable wrapping (33): 1) plastic filler pieces (for structural strand), 2) an inner covering of "Zytel" nylon film, 3) a coating of glass-reinforced acrylic, 4) a weathering coat of "Lucite" syrup, and 5) a finishing coat of "Lucite" syrup containing sand. That coating was used on the Bidwell Bar Bridge near the Oroville Dam in California (1965) and on the Newport Bridge (1969).

Another wrapping system, developed by U. S. Steel Corporation, used stainless-steel tie wraps to maintain the cable section between the bands. The cables were painted with a liquid neoprene adhesive and allowed to dry. Cables were then wrapped with an uncured neoprene sheet having about 50 percent overlap (Figure 13). The neoprene is allowed to air cure; then, the neoprene is coated with chlorinated-rubber paint to protect it from ozone and ultraviolet light. That system was first used on the Mt. Hope Bridge in 1969 (34). It was also employed on the William Preston Lane Jr. Memorial Bridge (1973) and the third Portsmouth Bridge cable installation (1979).

Another method of cable protection involves the encasement of bare, uncoated wires in grout and enclosure of the encased strands with a plastic sheath. That method was first applied on a cable-stayed pedestrian footbridge in Germany (35). It is presently being incorporated on the I-410 cable-stayed bridge at Luling, Louisiana.

John Roebling treated uncoated bridge wire with four separate coats of linseed oil and "spanish brown". Prior to wrapping, Roebling gave the outer wires of the Ohio Bridge a coating of white lead and linseed oil. When Hildenbrand rebuilt the bridge, he used the same procedure. Hildenbrand also charged the original cables with boiled linseed oil by pouring the oil into the cables from the tower saddles (36). The West Virginia Department of Transportation used that treatment on the cables of Wheeling Bridge for a period (37).

Red lead and linseed oil have been used prior to wrapping as a sealant and corrosion preventative on the outer wires of most parallel wire suspension bridges. Various asphalt-based products have been used for sealants, though usually unsuccessfully. Slushing oils, with good penetrating characteristics have been used to protect wire rope used in maritime and lifting service (36). The English Tamar suspension bridge employed a bitumen sealant to protect strands of the main cables (39).

Many of the corrosion-protection systems employed on foreign cable-stayed bridges are fairly elaborate compared to those used on typical American suspension bridges. Thul (40) mentioned a cable that was composed of
1. wires,
2. 83-percent polyurethane - 17-percent zinc chromate cover,
3. a polyester layer,
4. a 4-mm thick polyurethane sleeve, and
5. a long-lasting topcoat of paint.

The Japanese have also employed a multiple-stage corrosion-protection system on the stay cables of the Toyosato-Ohhashi Bridge
Figure 13. Hand-Wrapping Neoprene Sheet, Third Cable Installation, Portsmouth Bridge.
(41). The saddle points were charged with an epoxy resin. The cables consisted of
1. wires;
2. a 1-mm thick layer of polyethylene and polypropylene film;
3. a fiberglass-reinforced plastic layer made of glass mat, acrylic resin, and glass cloth; and
4. an external layer of silicone and acrylic resin.

CLOSURE

While the construction of conventional suspension bridges for further inland applications in the US is doubtful, new economical types of bridges employing high-strength wires are continually being developed. At least one German engineering firm has established offices in the US to market those new designs. With the continued pressure on highway authorities to build more economical bridges, it is likely that several of those new bridge types will be used. Information contained in the other reports should be useful in understanding the potential maintenance problems presented by those new bridge types and in formulating procedures to cope with those problems.

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