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17
Arch Bridges

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17.1 Introduction

17.1.1 Definition of Arch

An arch is sometimes defined as a curved structural member spanning an opening and serving as a support for the loads above the opening. This definition omits a description of what type of structural element, a moment and axial force element, makes up the arch. Nomenclature used to describe arch bridges is outlined on Figure 17.1. The true or perfect arch, theoretically, is one in which only a compressive force acts at the centroid of each element of the arch. The shape of the true arch, as shown in Figure 17.2, can be thought of as the inverse of a hanging chain between abutments. It is practically impossible to have a true arch bridge except for one loading condition. The arch bridge is usually subject to multiple loadings (dead load, live load, temperature, etc.) which will produce bending moment stresses in the arch rib that are generally small compared with the axial compressive stress.

17.1.2 Comparison of Arch Bridge with Other Bridge Types

The arch bridge is very competitive with truss bridges in spans up to about 275 m. If the cost is the same or only slightly higher for the arch bridge, then from aesthetic considerations the arch bridge would be selected instead of the truss bridge.

For longer spans, usually over water, the cable-stayed bridge has been able to be more economical than tied arch spans. The arch bridge has a big disadvantage in that the tie girder has to be constructed before the arch ribs can function. The cable-stayed bridge does not have this disadvantage, because deck elements and cables are erected simultaneously during the construction process. The true arch bridge will continue to be built of long spans over deep valleys where appropriate.

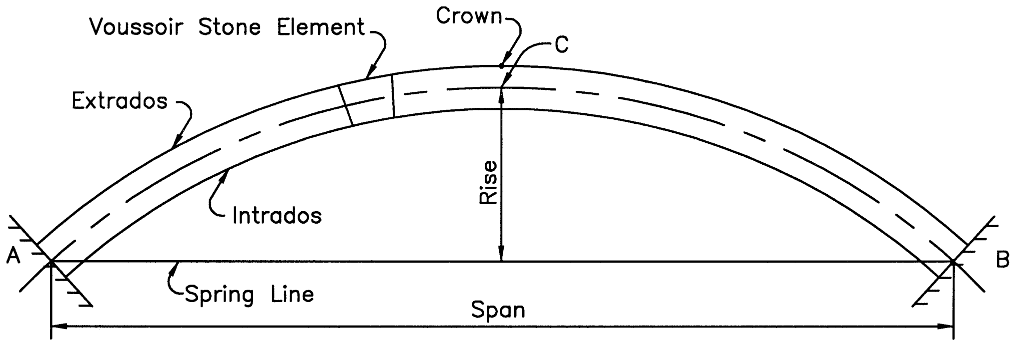

FIGURE 17.1 Arch nomenclature.

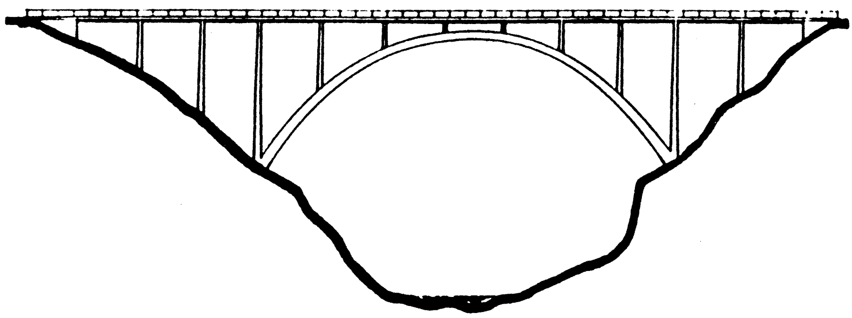

FIGURE 17.2 Concrete true arch.

17.1.3 Aesthetics of Arch Bridges

There is no question that arch bridges are beautiful, functional, and a pleasure for the motorist to drive over. Long-span arch bridges over deep valleys have no competitors as far as aesthetics is concerned. Arch bridges are better looking than truss bridges.

Many of the masonry arch bridges built for the last 2000 years are in the middle of cities whose residents consider these bridges not only necessary for commerce but also for their beautiful appearance. It is regrettable that masonry arches, in general, will not be constructed in today's environment since stonework has become too expensive.

17.2 Short History of Arch Bridges

Even before the beginning of recorded history, humans had a need to cross fast-moving streams and other natural obstacles. Initially, this was accomplished by means of stepping-stones and later by using felled tree trunks that either were supported by stones in the stream or spanned the entire distance between shores. Humans soon discovered that a vine attached to a treetop enabled them to swing across a wide river. This led to the construction of primitive suspension bridges with cables of vines or bamboo strips twisted into ropes. Post and lintel construction utilizing timber and stone slabs, as exemplified by the monument at Stonehenge, soon followed.

The arch came much later as applied to bridge building. The Sumerians, a community that lived in the Tigris-Euphrates Valley, made sunbaked bricks that were used as their main building material. To span an opening, they relied on corbel construction techniques. Around 4000 B.C. they discovered the advantages of the arch shape and its construction and they began to construct arch entranceways and small arch bridges with their sunbaked bricks [1].

Other communities with access to stone soon began to build arches with stone elements. By the time of the Romans most bridges were constructed as stone arches, also known as masonry or Voussoir arches. Empirical rules for dimensioning the shape of the arch and the wedge-shaped stones were developed. The Romans were magnificent builders and many of their masonry bridges are still standing. Probably the most famous is the Pont du Gard at Nimes in France, which is not only a bridge but an aqueduct as well. It stands as a monument to its builders. Excellent descriptions of other great Roman bridges can be found in Reference [1]. Stone arch bridges are very beautiful and much admired. A number have become centerpieces of their cities. There were few failures since stone is able to support very large compressive forces and is resistant to corrosive elements. Also, the arch is stable as long as the thrust line is contained within the cross-sectional area. Masonry arch bridges are very durable and most difficult to destroy [2].

Today, arch bridges are generally constructed of concrete or steel. However, there is still a great deal of research on stone arches directed toward determining their ultimate load capacity, their remaining life, their stability, their maintenance requirements, and also to determine the best methods to retrofit the structures. The reason for this great interest is, of course, that there are thousands of these stone arch bridges all over the world that are still carrying traffic and it would be an enormous cost to replace them all, especially since many of them are national monuments.

In 1779, the first Cast Iron Bridge was constructed at Coalbrookdale, England to span the Severn River. It is a semicircular arch spanning 43 m. By the year 1800, there were very few long-span masonry bridges built because they were not competitive with this new material. The 19th century was really the century of iron/steel bridges, suspension bridges, trusses, large cantilever bridges, viaducts, etc. Gustave Eiffel designed two notable steel arch bridges, a 160-m span at Oporto, Portugal and a 165-m span over the Truyeres River at St. Flour, France. Another notable arch bridge is the Eads steel bridge at St. Louis which has three spans of 155 m. In addition, a very beautiful shallow steel arch, the Pont Alexandre II, was constructed in Paris over the Seine River.

Concrete bridges began to be constructed at the end of the 19th century, and the arch designs of Robert Maillart should be noted since they are original and so beautiful [3].

17.3 Types of Arch Bridges

There are many different types and arrangements of arch bridges. A deck arch is one where the bridge deck which includes the structure that directly supports the traffic loads is located above the crown of the arch. The deck arch is also known as a true or perfect arch. A through-arch is one where the bridge deck is located at the springline of the arch. A half-through arch is where the bridge deck is located at an elevation between a deck arch and a through arch.

A further classification refers to the articulation of the arch. A fixed arch is depicted in Figure 17.1 and implies no rotation possible at the supports, A and B. A fixed arch is indeterminate to the third degree. A three-hinged arch that allow rotation at A, B, and C is statically determinate. A two-hinged arch allows rotation at A and B and is indeterminate to one degree.

A tied arch is shown in Figure 17.3 and is one where the reactive horizontal forces acting on the arch ribs are supplied by a tension tie at deck level of a through or half-through arch. The tension tie is usually a steel plate girder or a steel box girder and, depending on its stiffness, is capable of carrying a portion of the live loads. A weak tie girder, however, requires a deep arch rib and a thin arch rib requires a stiff deep tie girder. Since they are dependent on each other, it is possible to optimize the size of each according to the goal established for aesthetics and/or cost.

While most through or half-through arch bridges are constructed with two planes of vertical arch ribs there have been a few constructed with only one rib with the roadways cantilevered on each side of the rib.

Hangers usually consist of wire ropes or rolled sections. The hangers are usually vertical but truss-like diagonal hangers have also been used as shown in Figure 17.4. Diagonal hangers result in smaller deflections and a reduction in the bending moments in the arch rib and deck.

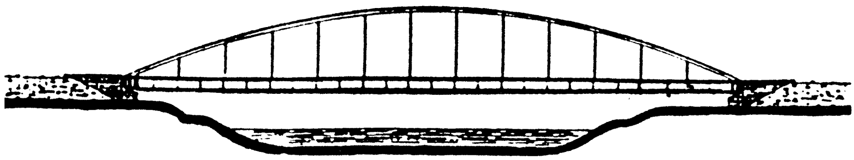

FIGURE 17.3 Steel tied-arch bridge.

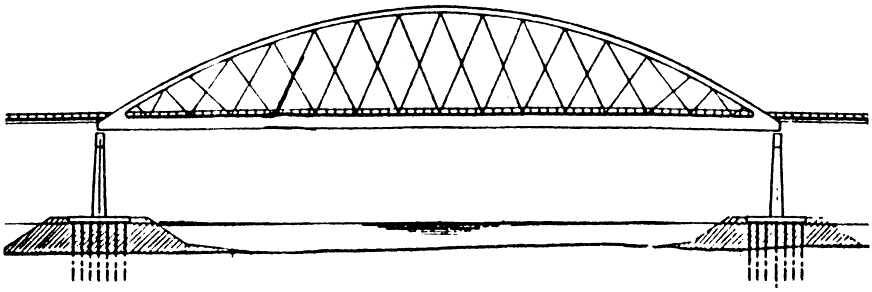

FIGURE 17.4 Arch with diagonal hangers.

There have also been arch bridges constructed with the arch ribs tilted so they can be connected at the crown. This is done for aesthetic reasons but it does add to the lateral stiffness of the arch bridge and could result in reduced bracing requirements.

17.4 Examples of Typical Arch Bridges

The Cowlitz River Bridge in the State of Washington, shown in Figure 17.5, is a typical true concrete arch that consists of a four-rib box section that spans 159 m with a rise of 45 m. Practically all concrete arches are of this type.

Multiple concrete arch spans have also been constructed such as the bridge, shown in Figure 17.6, across the Mississippi River at Minneapolis. The bridge consists of two 168-m shallow arch spans.

The longest reinforced concrete arch span in the world is the Wanxian Yangtze Bridge located in China with a span of 425 m and a rise of 85 m which gives a rise-to-span ratio of 1:5 [4]. It is unusual in that a stiff three-dimensional arch steel truss frame consisting of longitudinal steel tubes filled with concrete as the upper and lower chords was erected to span the 425 m. It served as the steel reinforcing of the arch and supported the cast-in-place concrete that was deposited in stages. This bridge is really a steel–concrete composite structure.

The Chinese have built many long-span concrete arches utilizing steel tubes filled with concrete. They have also constructed one half of an arch rib on each bank of a river, parallel to the river flow, and when completed, rotated both into their final position [5].

The longest steel true arch bridge has a span of 518 m and crosses the New River Gorge at Fayetteville, West Virginia. The arch rib consists of a steel truss. The deck, which is also a steel truss, is supported by transverse braced steel frames that are very slender longitudinally. The arch has rise-to-span ratio of 1:4.6 and was opened to traffic in 1977.

Most tied arch superstructures are of steel construction. A typical tied arch through structure is the Interstate 65 Twin Bridges over the Mobile River in Alabama as shown in Figure 17.7. The bridges are constructed of weathering steel. Also note the good appearance of the Vierendeel bracing between the arch ribs.

The Milwaukee Harbor Bridge is a three-span half-through steel-tied arch as shown in Figure 17.8. The steel tie at deck level is deep and very stiff while the arch rib is very thin. The main span length is 183 m with 82 m flanking spans. Again, note the appearance of the bracing between ribs.

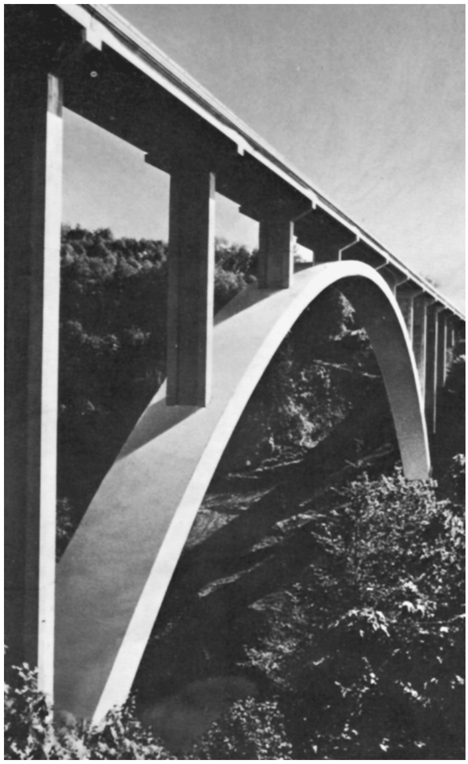

FIGURE 17.5 Cowlitz River concrete arch.

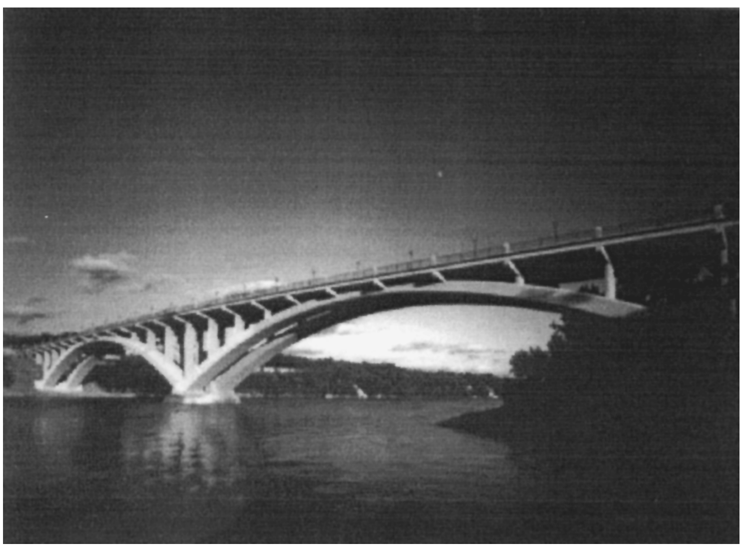

FIGURE 17.6 Two shallow concrete arch spans.

Another three-span half-through steel-tied arch is the Fremont Bridge across the Willamette River in Portland, Oregon, as shown in Figure 17.9. It is a double-deck structure with an orthotropic top deck and a concrete lower deck. The main span of the arch is 383 m between spring points which makes it one of the longest tied-arch spans, if not the longest, in the world.

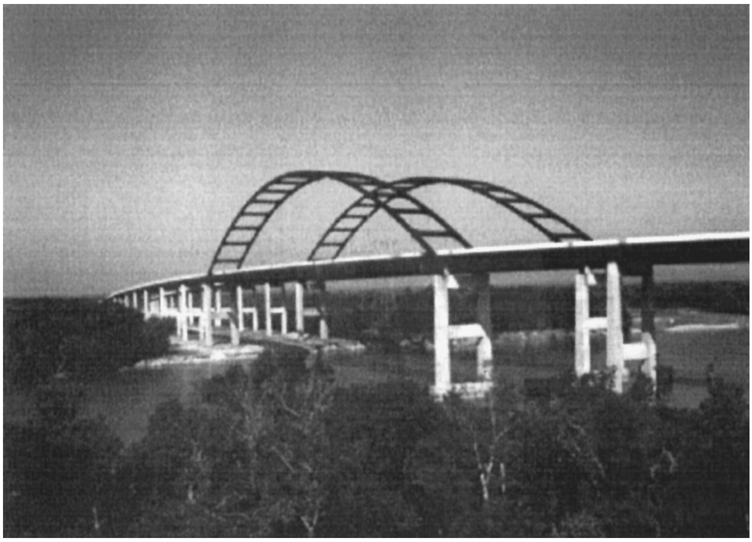

FIGURE 17.7 Steel twin-tied arches over the Mobile River.

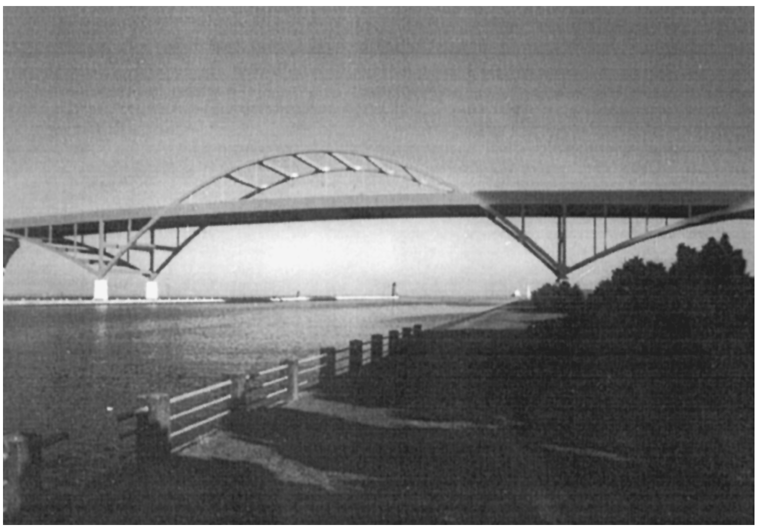

FIGURE 17.8 Milwaukee Harbor half-through arch.

An unusual long-span half-through arch, shown in Figure 17.10, is the Roosevelt Lake Bridge in Arizona. The level of the lake is to be raised, and above the 200-year level of the lake the arch ribs and bracing are constructed of steel and below this level in concrete. To preserve structural continuity at the junction of the steel and concrete, the steel ribs are prestressed into the concrete rib. The arch is not a tied arch and spans 335 m with a rise-to-span ratio of about 1:5. Extensive wind tunnel testing was performed on models of this arch structure during the design phase.

17.5 Analysis of Arch Bridges

The dead load, live load, and temperature loads are covered in Chapter 6 of this Handbook. Wind effects are covered in Chapter 57 and seismic effects in Part IV.

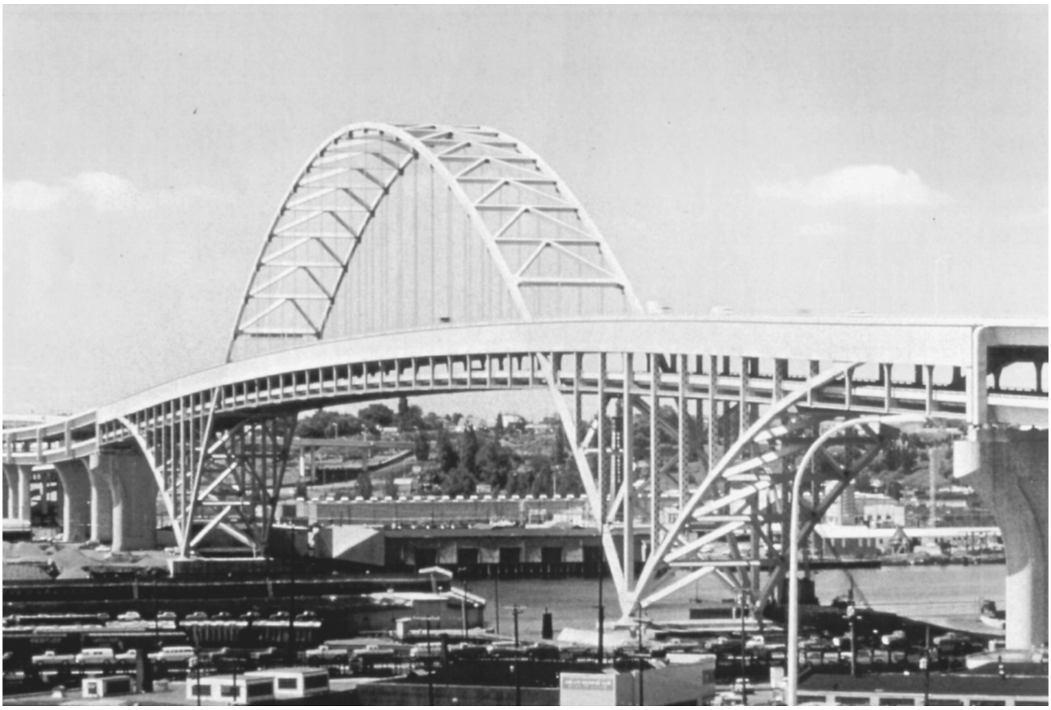

FIGURE 17.9 Fremont Bridge across the Willamette River.

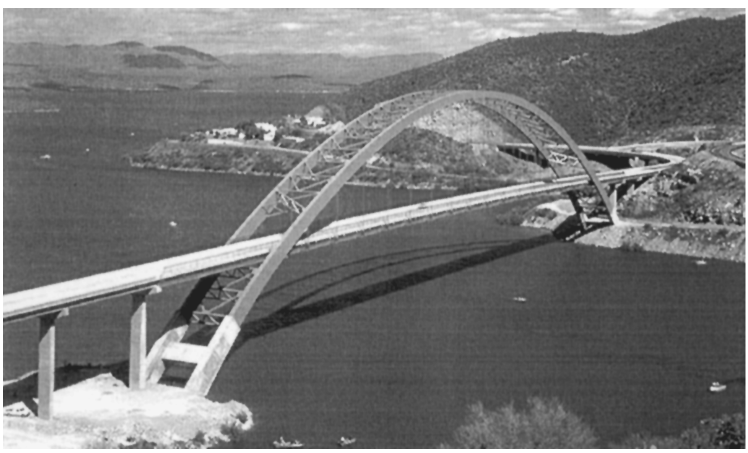

FIGURE 17.10 Roosevelt Lake Bridge, Arizona.

Before the age of structural analysis by computer methods, analysis of arches was not too difficult to accomplish with the help of a slide rule. In general, the analysis was a force method approach. For example, a two-hinged arch is statically indeterminate to the first degree and therefore has one redundant reaction. In the force method, the structure is made determinate, say, by freeing the right horizontal support and letting it move horizontally. The horizontal deflection ($d1$) at the support is then calculated for the applied loads. Next the horizontal deflection ($d2$) at the support is calculated for a horizontal force of 1 N acting at the support. Since the sum of these two deflections must vanish, then the total horizontal reaction (H) at the support for the applied loading must be

$$H = -\frac{(d1)}{(d2)} \tag{17.1}$$

Having the horizontal reaction the moments and axial forces can be calculated for the arch. A good example of early design procedures for a tied two-hinged arch is contained in a paper on the "Design of St. Georges Tied Arch Span" [6]. This arch, completed in 1941, spans the Chesapeake and Delaware Canal and was the first of its type in the United States to have a very stiff tie and shallow rib. The designer of the bridge was Professor Jewell M. Garrelts who was for many years head of the Civil Engineering Department at Columbia University. While this design procedure may be crude compared with modern methods, many fine arches were constructed using such methods.

Modern methods of analysis, of course, utilize a three-dimensional nonlinear finite-element computer program. For information on the finite-element method refer in this Handbook to Chapter 7 on Structural Theory and Chapter 36 on Nonlinear Analysis. Additional information on nonlinear analysis with accompanying computer programs on disk is available in Reference [7]. To use the finite element program it is necessary to have a preliminary design whose properties could then serve as the initial input to the computer program. In a published discussion of the St. Georges paper referred to above, Jacob Karol derived an approximate formula for calculating influence values for the horizontal force in the arch which depends only on the rise-to-span ratio. He also in the same discussion paper gave an approximate formula for the division of the total moment between the tie and the rib depending only on the depths of the rib and the tie girder [8]. These formulas are very useful in obtaining a preliminary design of a tied arch for input to the finite-element program.

17.6 Design Considerations for an Arch Bridge

17.6.1 Arch Bridge Design

Many chapters of this Handbook in Part II, Superstructure Design, have information concerning the design of decks that also apply to the design of decks of arches. By deck is meant the roadway concrete slab or orthotropic steel plate and its structural supports.

The rise-to-span ratio for arches may vary widely because an arch can be very shallow or, at the other extreme, could be a half-circle. Most arches would have rise-to-span ratios within the range of 1:4.5 to 1:6.

After the moments and axial forces become available from the three-dimensional finite-element nonlinear analysis the arch elements, such as the deck, ribs, ties, hangers, and columns can be proportioned. Steel arch ribs are usually made up of plates in the shape of a rectangular box. The ties are usually either welded steel box girders or plate girders.

In the 1970s there were problems in several arch bridges in that cracks appeared in welded tie girders. Repairs were made, some at great cost. However, there were no complete failures of any of the tie girders. Nevertheless, it caused the engineering community to take a new look at the need for redundancy. One proposal for arch bridges is not to weld the plates of the steel tie girders together but rather to use angles to connect them secured by bolts. Another proposal is to prestress the tie girder with post-tensioning cables. Another is to have the deck participate with the tie girder.

17.6.2 Vortex Shedding

Chapter 57 in this Handbook covers Wind Effects on Long Span Bridges. However, it seems appropriate to discuss briefly some problems in arches that are caused by vortex shedding.

Every now and then an arch is identified that is having problems with hanger vibrations especially those with I-section hangers. The vibrations are a result of vortex shedding. The usual retrofit is to

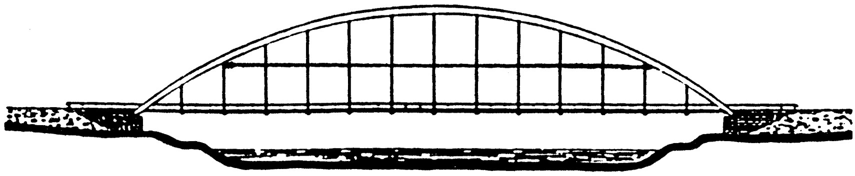

FIGURE 17.11 Horizontal cable connecting hangers.

connect the hangers as shown in Figure 17.11, which effectively reduces the length of the hangers and changes the natural frequency of the hangers. Another method is to add spoiler devices on the hangers [9]. In addition to the hangers, there have also been vortex shedding problems on very long steel columns that carry loads from the arch deck down to the arch rib.

17.6.3 Buckling of Arch Rib

Since the curved rib of the arch bridge is subject to a high axial force, the chance of a failure due to buckling of the rib cannot be ignored and must be accounted for. The subject of stability of arches is very well handled in Reference [10]. Values to use in formulas for critical buckling loads are listed in tables for many different cases of loading and various arch configurations.

As an example, the buckling critical load for a two-hinged parabolic arch rib supporting a uniform vertical deck load distributed on a horizontal projection will be calculated:

Arch span: $L = 120$ m
Arch rise: $S = 24$ m
Rise-to-span ratio = 24/120 = 0.2
Rib moment of inertia: $I = 7.6 \times 10^9$ mm^4
Modulus of elasticity: $E = 20 \times 10^4$ N/mm^2
Horizontal buckling force:

$$H = C_1 \frac{EI}{L^2} \tag{17.2}$$

Uniform load causing buckling:

$$q = C_2 \frac{EI}{L^3} \tag{17.3}$$

$C_1 = 28.8$ and $C_2 = 46.1$ are from Table 17.1 of Reference [10]

$$H = \frac{28.8 \times 20 \times 10^4 \times 7.6 \times 10^9}{\left(120 \times 10^3\right)^2} = 3.04 \text{ MN}$$

$$q = \frac{46.1 \times 3.04 \times 10^3}{28.8 \times 120} = 40.55 \text{ kN/m}$$

The above calculation of critical loads is for buckling in the plane of the arch which assumes very good bracing between ribs to prevent out-of-plane buckling. The bracing types that are generally used include K type bracing shown in Figure 17.12, diamond-shaped bracing shown in Figure 17.13 and Vierendeel type bracing shown in Figure 17.14.

Also the above calculation is for an arch rib without any restraint from the deck. If the deck is taken into account, the buckling critical load will increase.

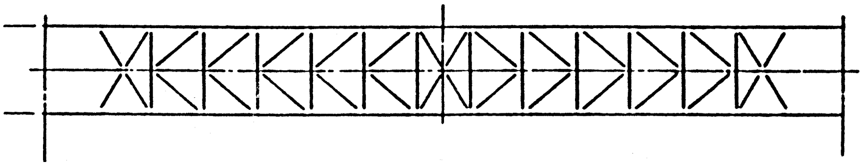

FIGURE 17.12 K-type of bracing.

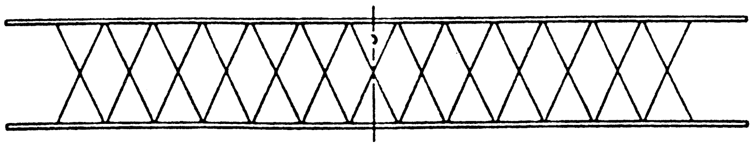

FIGURE 17.13 Diamond type of bracing.

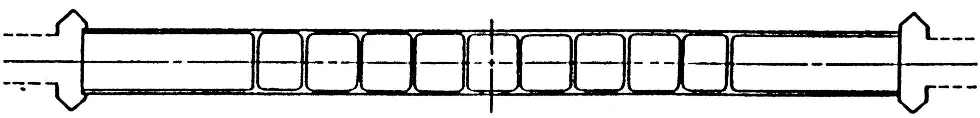

FIGURE 17.14 Vierendeel type of bracing.

17.7 Erection of Arches

Most concrete deck arches have been constructed with the concrete forms and wet concrete being completely supported by falsework. They have also been constructed by means of tieback cables from a tower that is supported by cables anchored into the ground. Each tieback cable would support the forms for a segment length of concrete rib. For multiple arches, the tiebacks would support the forms and wet concrete in balanced cantilever segments off a tower erected on a common pier.

Segmental concrete arches have been erected by cranes that are supported on the ground or on barges. They pick up a concrete segment and connect it to a previously erected segment. Another way of delivering and erecting the concrete segments is by means of a cableway spanning between tower bents.

Steel deck arches have also been erected in segment lengths by means of tieback cables. Another erection method is to have steel rib segments span the distance between temporary erection bents. The New River Gorge steel arch bridge was erected by means of both a cableway and tiebacks. Good examples of steel arch bridge construction are presented in Chapter 45 on Steel Bridge Construction.

For the usual tied-arch span the deck and steel tie can be erected on temporary erection bents. When this operation has been completed, the ribs of the arch, bracing, and hangers can be constructed directly off the deck. An alternative erection scheme that has been used is one in which the deck, steel ties, and ribs are erected simultaneously by means of tieback cables. A more spectacular erection scheme, that is economical when it can be used, involves constructing the tied-arch span on the shore or on piles adjacent and parallel to the shore. When completed the tied arch is floated on barges to the bridge site and then pulled up vertically to its final position in the bridge. For example, Figure 17.15 shows the Fremont Bridge 275 m center-tied arch span being lifted up vertically to connect to the steel cantilevers.

Some arches have had a rib erected on each shoreline in the vertical position as a column. When completed, the ribs are then rotated down to meet at the center between the shorelines.

FIGURE 17.15 Fremont tied arch being lifted into place.

Acknowledgments

My thanks to Lou Silano of Parsons Brinckerhoff for furnishing the two pictures of the Fremont Bridge and thanks to Ray McCabe of HNTB Corp. for the rest of the photos. I appreciate the help I received from Dr. Lian Duan of Caltrans, Professor Wai-Fah Chen of Purdue University, and the people at CRC Press. They are all very patient, for which I am very grateful.

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