Design of Long Span Concrete Box Girder Bridges: Challenges and Solutions

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Abstract

Long span concrete box girder bridges first appeared in the 1950's. From the beginning, this bridge type was built segmentally using the balanced cantilever method of construction with form travelers and cast-in-place segments. After half a century of developments, concrete box girder bridges have a positive track record, are widely used, and have reached spans of up to 988 ft.

These bridges present specific challenges to the designer that have to be addressed in the context of design codes, available materials, prevailing construction methods and project constraints. This paper describes current design trends for cross-section design, post tensioning layout and superstructure articulation. It also discusses the opportunities provided by high strength and lightweight concrete, and the impact of the new AASHTO LRFD code. The design of the Kanawha River Bridge in West Virginia is used to illustrate these topics. This river crossing, recently designed by T.Y. Lin International, will have a 760-foot main span, the longest concrete box girder span in the United States, and a total length of 2,975 ft.

Introduction

Reinforced concrete appeared as a new construction material at the end of the nineteenth century and started to be used for bridge construction at the beginning of the twentieth century. Most long span reinforced concrete bridges built during this period were arches, although box girder bridges were also used for medium spans. One example is the Villeneuve-St. George Bridge, built in 1939 over the Seine River near Paris, a reinforced concrete box girder bridge with a main span of 78 meters (256 ft).

After the Second World War, prestressed and post-tensioned concrete started to be widely used for bridge reconstruction in Europe. In 1950, the German engineer Ulrich Finsterwalder built the Balduisnstein Bridge, with a 62-meter (203-foot) span. This was the first post-tensioned box girder bridge using the cantilever construction method with form travelers and cast-in-place segments. Cantilever construction had been used before for reinforced concrete box girders and other bridge types, but combined with post-tensioning, it helped to quickly expand the span range of box girder bridges. Pre-cast segment for box girder bridges were first used in the early 1960's.

After half a century of developments, concrete box girder bridges have a positive track record and are widely used. The longest concrete box girder span in the United States is the Houston Ship Channel Bridge, in Texas, built in 1982 with a main span of 229 m (750 ft). The world record span is the Stolma Bridge in Norway, opened to traffic in 1998, with a main span of 301 m (988 ft).

The Box Cross Section

Long span concrete girder bridges use a box cross-section because of its structural advantages. This section is able to resist both positive and negative moments present in continuous bridges because it has both top and bottom flanges. The large torsional strength and rigidity of a closed section is favorable for resisting torsional moments due to curved alignments or eccentric live load.

The box girder section requires less post-tensioning than other sections. The required post-tensioning is related to the efficiency of the section which can be measured by the ratio:

$$\rho = \frac{I}{A y_t y_b}$$

where I is the moment of inertia, A the area and y_t, y_b the distances from the neutral axis to the top and bottom fibers. A typical box girder section has a ρ equal to 0.60 whereas for a rectangular section ρ is equal to 0.33.

The only disadvantage of the box girder section is the cost associated with forming the section, higher than for other cross sections. This additional cost is more than justified for long span lengths because a box section can be designed to reduce dead load to a minimum.

Cross-section types

Some of the most common cross sections used in long span box girder bridges are shown in Figure 1. The two-web box section shown in Figure 1(a) has been used for widths up to 26 m (85 ft). Single box girder bridges with a large width to span ratio may loose efficiency due to the effect of shear lag, cross section distortion and transverse bending moments. To avoid these potential negative effects some bridges, usually wider than about 50 ft, have been designed with other types of box sections.

A two-cell, three-web section is shown in Figure 1(b). This section has less shear lag and distortion than a single-cell section because the distance between webs is reduced. It also has smaller transverse bending moments due to the reduction in the transverse span. However, a three-web section is more difficult to build due to the fact that two internal forms are needed. Similar results can be achieved with the multiple box girders of Figure 1(c). Other approaches to increasing the transverse stiffness are shown in Figure 1(d), a stiffened box with diagonal struts, and Figure 1(e), a two-web section with a ribbed top slab.

Current trends in cross-section design lead to single cell box girders for increasingly wider bridges. Ribs or struts are used to provide additional transverse capacity.

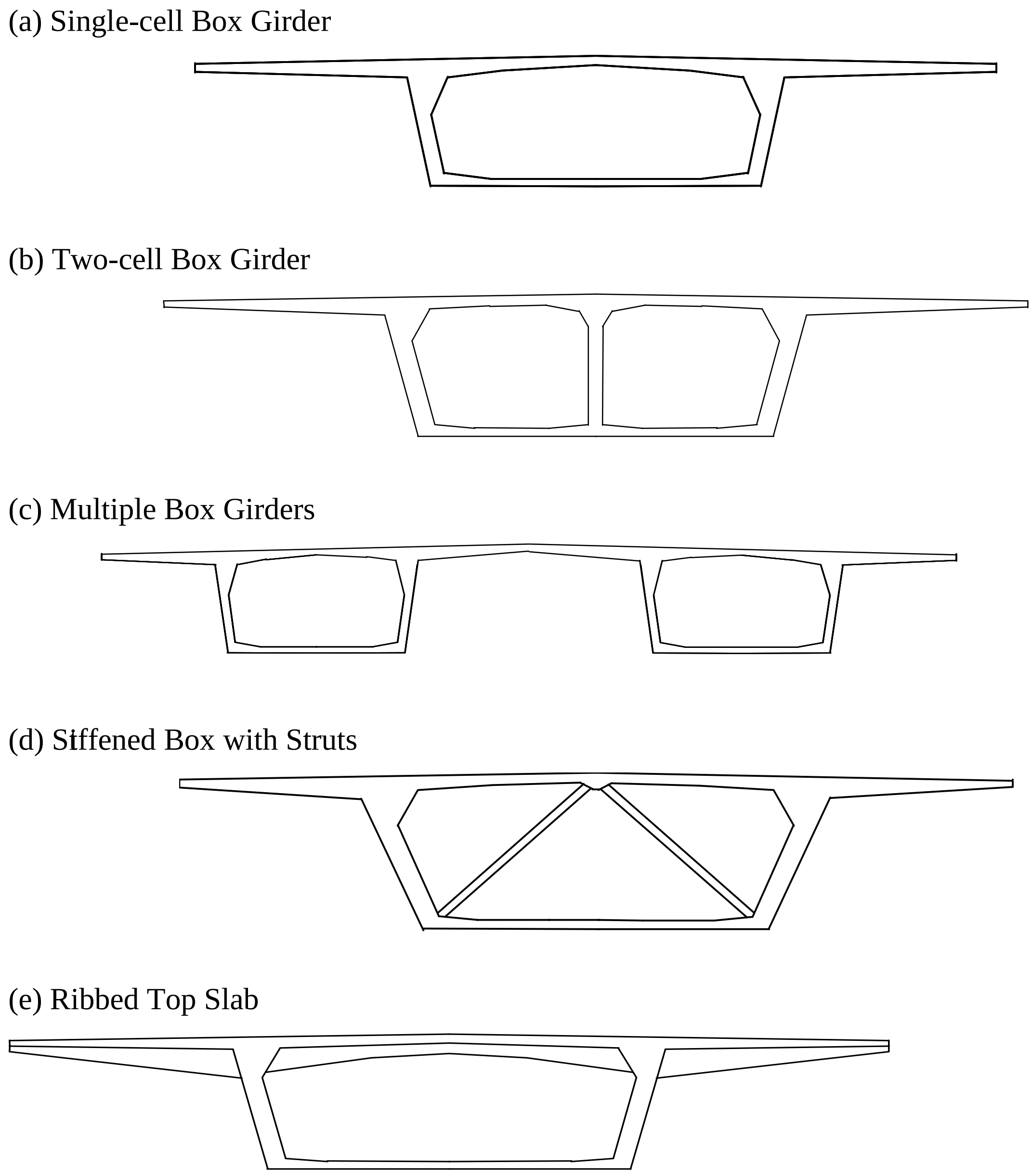

Figure 1. Box Section Types

Cross Section Dimensioning and Post-tensioning Layout

The dimensioning of the cross section is a critical step in the design of a long span concrete bridge. The cross section design is influenced by the construction method and the post-tensioning layout. It must meet functionality and structural requirements with a minimum weight. Figure 1(a) shows a typical two-web cross section. The most important considerations in cross section design are summarized below.

Top Slab

The top slab has very diverse functions that need to be accounted for in its design. First of all, the top slab must accommodate the roadway. Top slab width and superelevation are determined based on the highway alignment. The top slab also needs to resist local longitudinal and transverse bending due to dead load and traffic. The top slab thickness must be sufficient to house the longitudinal tendons needed for cantilever construction, transverse tendons (if transverse post-tensioning is used), and mild reinforcement with the appropriate concrete covers. And finally, the top slab needs to have enough concrete area to work as the top flange of the box girder.

The design of the top slab is usually governed by the transverse bending due to traffic loads. However, for long spans the thickness required for internal longitudinal tendons needed for cantilever construction may also be significant. A typical top slab has variable thickness with maximum thickness at the webs and minimum thickness, between 8 and 10 inches, at the cantilever and in between the webs. This distribution of thickness follows the shape of the transverse bending moment envelope and reduces shear lag effects by concentrating material near the webs. The top slab generally has the same shape along the entire length of the span.

Bottom Slab

The bottom slab spans between the webs and provides the bottom flange of the box girder. It is subjected to local loads due to its own weight and may be subjected to some transverse bending due to the traffic load on the top slab. The bottom slab is usually designed with uniform thickness in the transverse direction except for haunches near the webs. In the longitudinal direction it is typically thicker at the supports where negative moments are greater. In the middle of the span, the bottom slab has a minimum thickness between 8 and 10 inches. The bottom slab needs to accommodate continuity bottom slab tendons. These tendons are typically located near the webs.

Webs

The main structural function of the webs is to resist shear stress due to global shear and torsion. They are also subjected to transverse bending due to top slab loads. When draped internal continuity tendons are used, the web thickness must be sufficient to allow for proper concrete placement. The minimum web thickness is usually between 10 and 12 inches. Vertical PT bars may be used in the webs to enhance the shear capacity. Post-tensioning tendon layout can be simplified by avoiding draped continuity tendons in the webs. Webs may be vertical or inclined. They usually have uniform thickness with fillets near the top slab to accommodate the anchorage of the longitudinal cantilever tendons.

Superstructure Articulation

Long concrete box bridges require expansion joints to accommodate displacements due to temperature changes, and creep and shrinkage of the concrete. Increasingly longer bridges are designed without intermediate expansion joints in order to simplify construction, improve rideability and reduce maintenance. However, this may be difficult when using monolithic connections between piers and superstructure. The location of intermediate expansion joints may affect the cantilever construction sequence that is typically used for these bridges. Intermediate expansion joints may be located in three different locations, at midspan, at the quarter point of the span, or at the piers. Both midspan and quarter point joints require hinges for shear transfer.

Midspan joints are very simple to build because they do not interfere with balanced cantilever construction. Midspan joints were frequently used in the first concrete box girder bridges built using this method. However, some of those bridges exhibited excessive long-term deformation due to unforeseen creep of the concrete resulting in angular discontinuities in the deck. There are methods for avoiding this problem such as designing a proper camber that accounts for all the time dependent deformations of the concrete or balancing dead load with post-tensioning. However, the serviceability problems associated with some early concrete box girder bridges have given midspan hinges a bad reputation.

Another way of avoiding angular discontinuities is the use of steel girders in midspan hinges. This design results in hinges that allow longitudinal displacements and also transfer moment. The moment transferred through the steel girder is always a small part of the moment that would develop in a continuous system, as the moment developed is a function of the relative stiffness between the steel girder and the concrete box. Hinges near the midspan with steel girders were designed for the Benicia-Martinez Bridge in California with a total length of 2,266 meters (7,434 ft) and spans ranging from 84 to 200.8 meters (276 to 658 ft).

Angular discontinuities are not a problem if the hinge is located at a point where a continuous system would have zero moment. The area of minimum moment for a variable depth continuous girder is usually located between the quarter and third point of the span. This is the idea behind quarter point hinges that only transfer shear. Since cantilever construction requires building up to the midspan point, hinges are temporary blocked during construction. Hinge blocking needs special details and temporary post-tensioning that complicate the cantilever construction cycle. Quarter span hinges were used for the Jamuna Bridge in Bangladesh with a total length of 4,800 meters (15,748 ft) and 100-meter spans (328 ft).

Expansion joints located on top of intermediate piers do not require hinge blocking during construction. Spans adjacent to the expansion joint are usually between one half and three quarters of the typical span length. The portions of the adjacent spans exceeding one half of the typical span length cannot be built by balanced cantilever and require falsework or intermediate temporary supports. The H-3 North Halawa

Valley Viaduct in Oahu, Hawaii, was built with expansion joints over intermediate piers.

Materials

The use of high strength or lightweight concrete presents structural advantages for long span bridges for which dead load represents a very significant percentage of the total load. Any reduction of the cross-section weight translates into a corresponding reduction of the post-tensioning required and of the foundation loads. In addition high strength concrete may have additional durability.

High strength concrete can lead to weight reductions when thinner concrete elements can be used. The top slab thickness is usually not affected by higher concrete strength because its dimensions are governed by detailing and serviceability requirements. The web thickness can be reduced byusing higher concrete strength but not in a significant way. According to most design codes, the shear capacity provided by concrete is proportional to the square root of the concrete strength. There are also slenderness and detailing requirements that impose a minimum web thickness. The most important reduction in weight when using high strength concrete takes place in the bottom slab near the piers. In the negative moment area the bottom slab thickness can be significantly reduced when increasing concrete strength. The ideal concrete strength depends on many project specific parameters related to the type of cross-section. Most long span concrete box girder bridges tend to have concrete strength between 31 and 52 MPa (4,500 and 7,500 psi)

High strength lightweight concrete has a lot of potential for long span concrete box girder construction. With lightweight concrete, the overall section weight, including top slab, webs and bottom slab is reduced without reducing the actual thickness of the cross-sectional elements. However, design specifications such as the AASHTO LRFD Bridge Design Specifications penalize the use of lightweight concrete by reducing the shear capacity provided by the concrete by a factor of between 0.75 and 0.85. Both the Guide Specifications for Design and Construction of Segmental Bridges and the LRFD code also reduce the resistance factors for lightweight concrete.

Lightweight concrete also has a lower Young Modulus, resulting in larger instantaneous deflections and, for the same creep coefficient, greater long-term deflections. The availability and cost of lightweight aggregate becomes an important issue. A limited number of concrete suppliers able to produce the material and a conservative design approach can dissipate some of the advantages of lightweight concrete.

Design Codes

The design of a long span concrete box girder bridge takes place in the context of design codes and specifications. Traditionally these bridges have been designed for service stresses and then checked for ultimate capacity. In the United States the first applicable design specification was the first edition of the Guide Specifications for Design and Construction of Segmental Bridges published in 1989. A second edition followed in 1998. The AASHTO LRFD Bridge Design Specifications incorporates most of the provisions of the second edition of the Segmental Guide Specifications.

A comparison of the AASHTO LRFD code with the first edition of the Guide Specifications for Design and Construction of Segmental Bridges reveals that AASHTO LRFD sets allowable stresses in compression higher than those included in the first edition of the Segmental Guide Specifications. The allowable compressive stress for permanent loads changed from 0.40 f'_c to 0.45 f'_c. This increase must be applied with caution since concrete creep accelerates for stresses exceeding 0.50 f'_c. The Strength IV limit state, included in AASHTO LRFD, has a 1.5 load factor for dead load. This strength limit state may govern the design of long span structures with a high dead load to live load ratio.

AASHTO LRFD also presents a new approach for checking shear capacity that can result in thinner webs. On the other hand, the combination of truck and lane loads of the LRFD code can result in higher ultimate bending moments for the top slab and the webs.

Design of the Kanawha River Bridge in West Virginia

The Kanawha River Bridge recently designed by T. Y. Lin International for the West Virginia Department of Transportation, Division of Highways, is an example of a long concrete box girder span.

The eight-span structure has span lengths of 144+247+295+295+460+760+540+209 feet. The total length between the centerlines of abutment bearings is 2,950 feet (Figure 2). Spans 1, 2, 3, 4, 5, 7 and 8 have a curved alignment including a circular curve with a 1,910-foot radius and a spiral transition. The main span has a tangent alignment.

A single structural type, a continuous concrete box girder, was chosen for the full length of the bridge. A box girder superstructure using cantilever construction allows longer approach spans that make the span layout simpler and reduces the impact of the bridge on its surroundings. Another advantage of using a continuous concrete box for the full length of the bridge is that the same construction methods and equipment can be used for the entire structure.

The structure was designed according to the segmental provisions in the AASHTO LRFD code. The 1990 CEB/FIP Model Code for Concrete Structures was used for evaluating concrete creep and shrinkage.

Superstructure

The bridge cross-section accommodates three travel lanes, one auxiliary lane, and shoulders, with a total roadway width of 64 feet (Figure 3). The cross section of the superstructure consists of a single cell box with inclined webs. The total length of the bridge uses the same cross-section with minor differences between the cross section of the main span and the approach spans.

The structural depth varies along the main span from 38 feet at the piers to 16 feet at midspan. The bottom slab thickness is variable with a maximum thickness of 5 feet at the main span piers and a minimum of 9 inches at midspan. The approach spans have a constant depth of 16 feet and a constant bottom slab thickness of 9 inches, with the exception of the pier tables where the bottom slab thickness transitions to 1 foot 9 inches. The webs have a constant thickness of 1 foot 6 inches. The top slab has constant dimensions for the full length of the bridge. Its thickness varies transversely from a minimum of 9 inches to a maximum of 2 feet at the intersection between the webs and the top slab. The maximum 2-foot depth of the top slab is needed to accommodate all the cantilever tendons needed for the main span.

The box girder cross-section has variable superelevation from plus to minus 8%. The superelevation is achieved by keeping top and bottom slabs parallel and by distorting the box section while maintaining all horizontal dimensions constant. The superstructure was designed with normal weight concrete with strength of 45 MPa (6500 psi).

Post-Tensioning

The concrete box section will be post-tensioned longitudinally, transversely, and vertically. The longitudinal post-tensioning consists of two sets of tendons, cantilever tendons located in the top slab and span tendons located in the bottom slab. Draped tendons in the webs are not used in order to simplify construction and to fully take advantage of the shear capacity of the webs.

The cantilever tendons will be stressed during cantilever construction immediately after a new segment has been cured and the necessary strength is achieved. Tendons' anchorages are located at the construction joints where the top slab intersects with the webs. Typically, there are two tendons per web at each segment. Each tendon consists of 22-0.6" strands. There are a total of 90 cantilever tendons in the section at the main span piers.

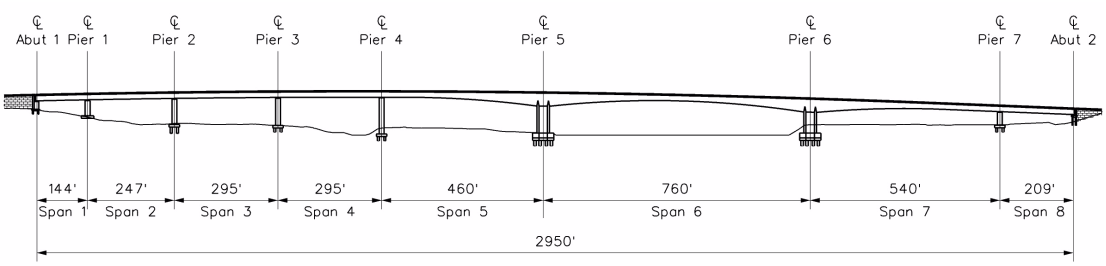

Figure 2. Kanawha River Bridge Elevation

The span tendons are only used in the central part of the spans where positive moments are expected. These tendons are stressed shortly after casting the closure segments. They provide continuity between adjacent cantilevers. The span tendons are anchored in anchorage blisters located inside the box at the intersection between the webs and the bottom slab. The anchorage blisters accommodate two anchorages per web. Each span tendon consists of 19-0.6” strands. A maximum number of 34 span tendons are needed at the main span.

Transverse post-tensioning is utilized in the top slab. Transverse tendons consist of 4-0.6” strands in flat ducts located above the longitudinal cantilever tendons. The anchorages are located at the edge of the slab, covered by the edge barrier. The typical spacing between transverse tendons is 2 feet 8 inches.

Vertical post-tensioning is required in the webs, in the proximity of the piers, where shear forces are high. The vertical post-tensioning was designed to limit tensile principal stresses in the webs. High strength 1 3/8-inch bars with anchorage plates at the top and bottom of the web will be used. The bars will be stressed from the top.

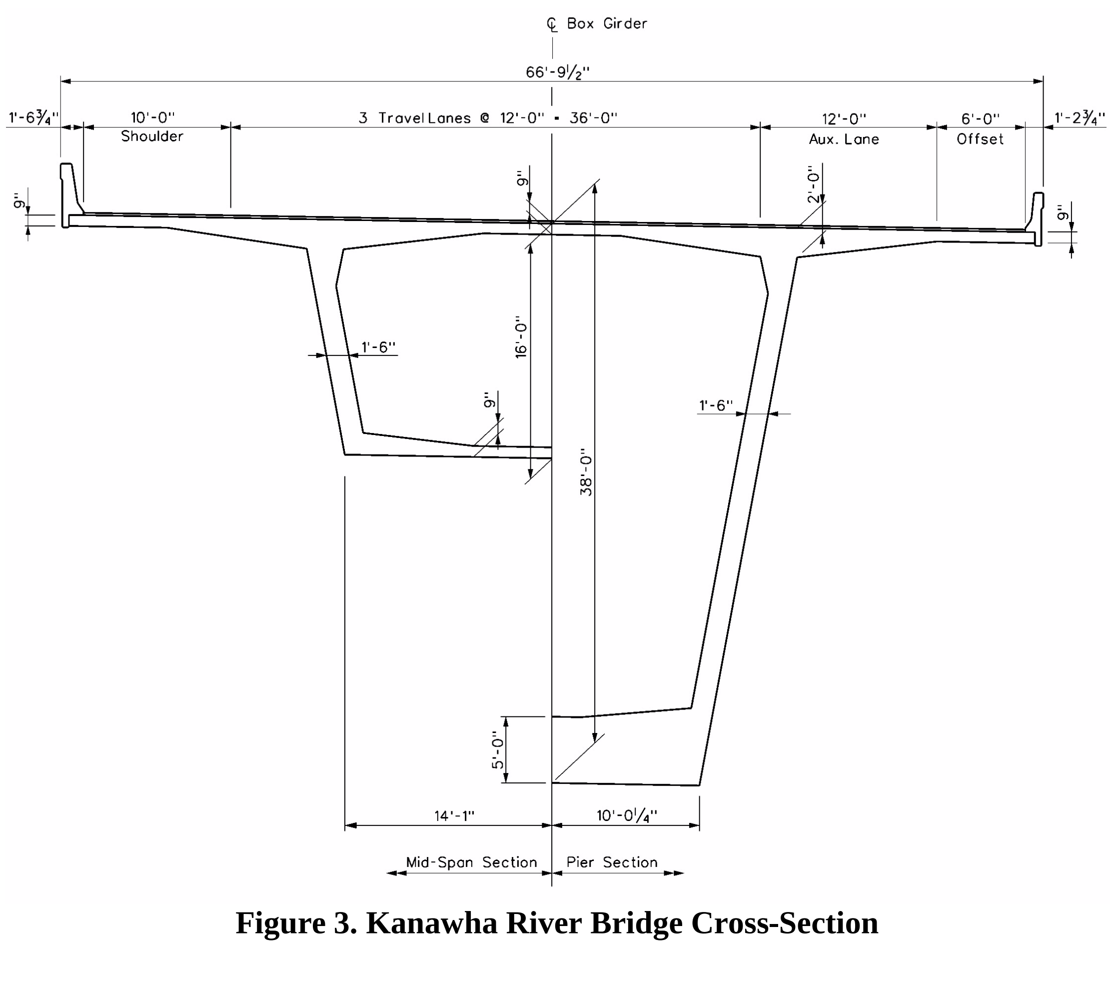

Figure 3. Kanawha River Bridge Cross-Section

Expansion Joints

The continuous box girder will have expansion joints at the abutments only. The advantages of this design approach are to reduce maintenance, improve serviceability, and simplify the construction process, as intermediate hinges are not needed. The superstructure is fixed at the main piers and is supported on unidirectional bearings at the approach piers and abutments. The bearings restrain the transverse displacements and allow longitudinal displacements.

A large modular expansion joint with a displacement capacity of 30 inches is needed at the west abutment to accommodate displacements caused by temperature, creep, and shrinkage. The east abutment requires a joint with a 16-inch displacement capacity.

Substructure

The main span piers, Piers 5 and 6, consist of twin concrete walls which frame into the superstructure. These piers provide the necessary strength and stiffness during cantilever construction and, at the same time, are longitudinally flexible to accommodate deformations caused by creep, shrinkage, and temperature changes. Each of the pier walls has a thickness of 6 feet 2 inches and a width of 26 feet that frames the bottom slab of the superstructure. The twin pier walls continue inside the concrete box as pier diaphragms. The main piers carry high axial loads with a monolithic connection that does not require bearings.

The approach piers, Piers 1, 2, 3, 4, and 7, have a hollow rectangular section with 45-degree chamfers. The piers are 26 feet wide, 14 feet deep, and have a wall thickness of 1 foot 9 inches. The superstructure is supported by two bearings per pier. The approach piers are designed with sufficient strength and stiffness so that they can take the unbalanced moments due to cantilever construction without the use of temporary supports. The bearings will be blocked during construction and the pier will be temporarily fixed to the superstructure.

The superstructure will be supported on two pot bearings per approach pier or abutment, one unidirectional and one multidirectional. The unidirectional bearing provides a restraint in the transverse direction. This restraint eliminates transverse displacements at the abutment expansion joints and provides a load path for wind loads. The multidirectional bearing allows transverse movements caused by shrinkage and temperature changes in the concrete.

Bearings are designed to take a seismic lateral load equal to 20% of the dead load. The largest bearings will have a service vertical capacity of 7,000 kips.

The foundations consist of reinforced concrete footings and concrete drilled shafts socketed in the underlying hard sandstone. A total of nine 84-inch diameter drilled shafts will support each of the main piers. Approach piers will be supported on four 72-inch diameter drilled shafts. The average length of drilled shafts is about 45 feet.

Conclusions

Long span concrete girder bridges present specific challenges to the designer that have to be addressed in the context of design codes, available materials, prevailing construction methods and project constraints. The current design trends for cross-section design, post tensioning layout and superstructure articulation were applied to the design of the Kanawha River Bridge in West Virginia. This river crossing, recently designed by T.Y. Lin International, will have a 760-foot main span, the longest concrete box girder span in the United States, and a total length of 2,975 ft.