

Case study: Value engineering of cast-in-place box-girder bridges into precast concrete superstructures

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Concrete box-girder bridge systems have become one of the most widely used solutions for modern highway bridges because of their structural efficiency, durability, and adaptability to various geometric configurations. Among these systems, single- and multicell box-girder bridges provide significant advantages in terms of torsional rigidity, load distribution, and overall structural performance. These characteristics make box-girder systems particularly suitable for bridges with curved alignments, wide decks, and complex geometric and loading conditions.

- This paper presents a method for splitting a box girder into two unsymmetrical precast concrete tub girders, cast separately and joined on-site to form a complete closed box. The design combines the strength of box girders with the speed of precast concrete construction.
- The goal was to preserve a box girder's structural performance and appearance while reducing the on-site formwork, shoring, and traffic disruption common with cast-in-place construction in urban settings.
- Because each half-girder is unsymmetrical before joining, engineers faced added challenges: eccentric centers of gravity; coupled bending-torsion effects; and lateral instability during lifting, transport, and erection required specialized bracing and three-dimensional analysis.

The box-girder cross section consists of a closed structure formed by a top slab, bottom slab, and two or more vertical webs that divide the section into hollow cells. This configuration provides a higher torsional stiffness compared with traditional open-girder systems, enabling efficient resistance to combined bending, shear, and torsional forces. In addition, the enclosed geometry improves structural stability and allows for optimized distribution of materials.

Cell box-girder bridges are commonly constructed using cast-in-place or segmental construction techniques. Cast-in-place construction is frequently used for bridges with complex geometries. In seismically active regions, such as California, owners also may choose a box-girder bridge system to provide a continuously monolithic superstructure for seismic resistance. Box-girder bridges also provide flexibility in span arrangement and alignment. Segmental construction methods, including balanced cantilever and incremental launching, have also expanded the feasible span range of box-girder bridges.

Despite the advantages of box-girder systems, their use is limited in highly developed cities. A major concern is that on-site work to install shoring and forming could disrupt traffic. These concerns may be addressed by using precast concrete components to add to existing infrastructure or to widen existing bridges. Another factor limiting the use of full-width box girders in urban settings is that their structural behavior is more complex than that of conventional stringer bridges. When handling individual precast concrete components, which are often unsymmetrical before joining them together to form a complete box, effects such as shear lag, torsion, distortion, and deflection control can pose challenges that must be considered carefully during analysis and design. Addressing these challenges often requires refined analytical methods and accurate modeling approaches to ensure adequate structural performance.

Background

The development of cast-in-place box-girder bridges began in the mid-20th century, led by the state of California. Initially, the primary aim was to ensure a continuous, monolithically cast superstructure that has superior seismic resistance and an elegant appearance. Subsequently, France and other European countries and eventually North America introduced precast concrete segmental box-girder bridges. Segmental bridges offer several advantages over other types, including sophisticated structural solutions, allowance for complex curved alignments, and high-quality prefabricated segments. However, because mobilization and erection equipment are expensive, segmental bridge construction has been limited to large projects.

The innovation described in this paper uses precast concrete segments to construct box girders with closed cross-sectional geometry. The technology combines the significant advantages of full-width box girders with those of the superior quality, cost-effectiveness, and construction speed of precast concrete stringer bridges. In this method, the segments are connected transversely, rather than longitudinally as in segmental box-girder construction. This restores the full torsional resistance and structural efficiency of full-width box girders needed for resisting in-service demands.

Box-girder bridges can be classified based on the number of internal cells formed by the vertical webs within the cross section. The selection of the appropriate configuration depends on several factors, including deck width, span length, structural efficiency, and construction considerations. Single-cell sections are often used for bridges with moderate deck widths, whereas multicell sections are typically preferred for wider decks that require improved load distribution and stiffness.

Case study: Converting a cast-in-place design into a precast concrete system

Located in Riyadh, Saudi Arabia, the King Abdullah Financial District is a mixed-use development that features com-

mercial offices as well as retail and residential spaces. In this high-traffic area, existing roads are being upgraded to improve traffic flow, reduce traffic bottlenecks, and increase access to the district. The project includes the construction of multiple bridges to provide additional access to the existing highway network. A design using cast-in-place box girders was proposed, but the owner determined that the prolonged road closure required for construction was too inconvenient; however, maintaining the original shape and aesthetics of the cast-in-place box girder system was a key requirement for the owner. A conversion to a precast concrete system that would provide the required structural performance while maintaining the original aesthetic intent was proposed and accepted. This paper describes its implementation.

System description

Original cast-in-place system

The bridge project consisted of more than 100 spans, with a typical span length of 45 m (148 ft) and typical bridge widths of 6.7 and 9.5 m (22.0 and 31.2 ft) (**Fig. 1**). The bridge network consists of a combination of approximately half straight spans and half curved spans with varying radii from 100 to 800 m (328 to 2630 ft). The original system used cast-in-place, single-cell box girders, with expansion joints provided at intervals of every three or four spans. Structural continuity across multiple spans was achieved using draped post-tensioning tendons located within the webs of the box girders. The original system provided an aesthetically pleasing solution but required extensive formwork. It also required extensive falsework due to the considerable elevation of the bridge, as illustrated in **Fig. 2**, which resulted in prolonged lane closures during construction. In contrast, the use of precast concrete girders substantially reduced the need for extensive formwork and falsework, offering a more efficient construction solution.

Options for conversion to a precast concrete system

Several precast concrete alternatives were investigated to evaluate feasible solutions for achieving the required structural configuration (**Fig. 3**). In all options, draped post-tensioning is replaced with straight tendons for the bottom and top flanges with vertical deviations only at the anchorages. The rationale for using straight tendons involves the following factors:

- reduced friction losses
- reduced potential for strand corrosion due to salt and air voids in the ducts
- significantly reduced web widths and thus component weights

Option 1 The first option considered was a spliced precast concrete U-shaped tub girder system with pier segments

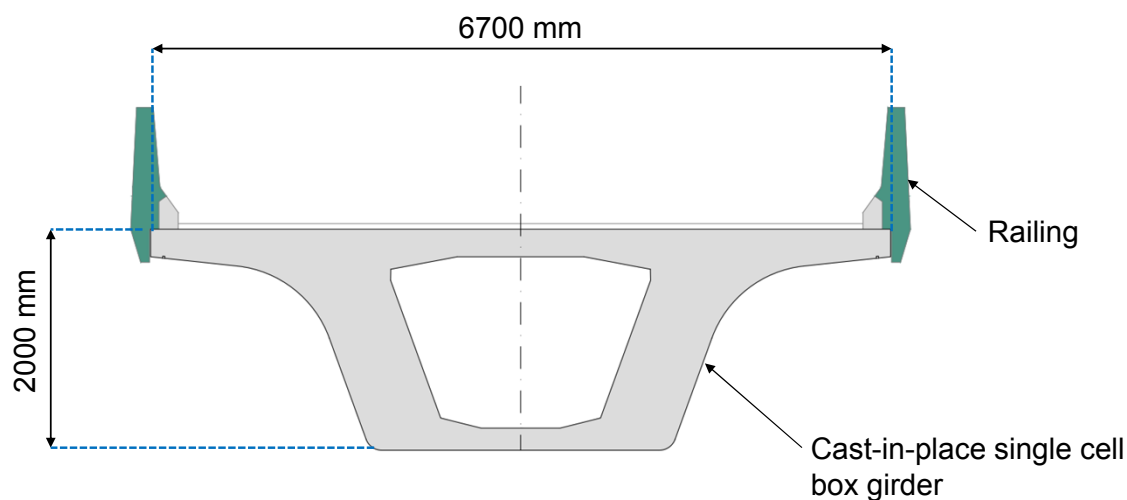


Figure 1. Typical cross section for the originally proposed cast-in-place concrete box-girder bridge. Courtesy of e.construct. Note: 1 mm = 0.0394 in.

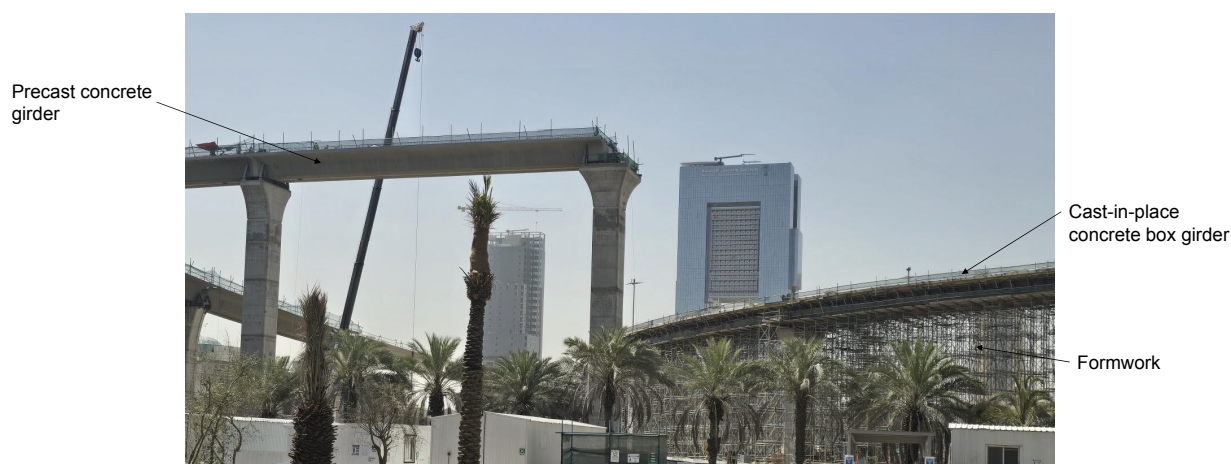


Figure 2. Comparison of formwork requirements for cast-in-place and precast concrete girder. Courtesy of e.construct.

supported on cast-in-place piers. Center precast concrete girder segments are erected between adjacent pier segments and supported at each end by the pier segments. The precast concrete segments are connected longitudinally using post-tensioning tendons to form a continuous girder system. A composite precast concrete slab system, overlaid with a cast-in-place concrete deck, is then constructed over the precast concrete girders to complete the bridge superstructure. This option is feasible only for spans with slight or no curvatures and when the width of the precast concrete U-shaped tub girder does not exceed hauling limits. This

option uses precast concrete deck subpanels and precast concrete TL-4 railing.

Option 2 In option 2, two symmetric precast concrete tub girders are arranged adjacent to each other. The precast concrete subpanels and the cast-in-place topping are made composite with the tubs as in option 1. The soffit is made continuous with nonstructural precast concrete cladding. Compared with the original system and option 1, option 2 has reduced torsional stiffness and the precast concrete cladding may require additional maintenance.

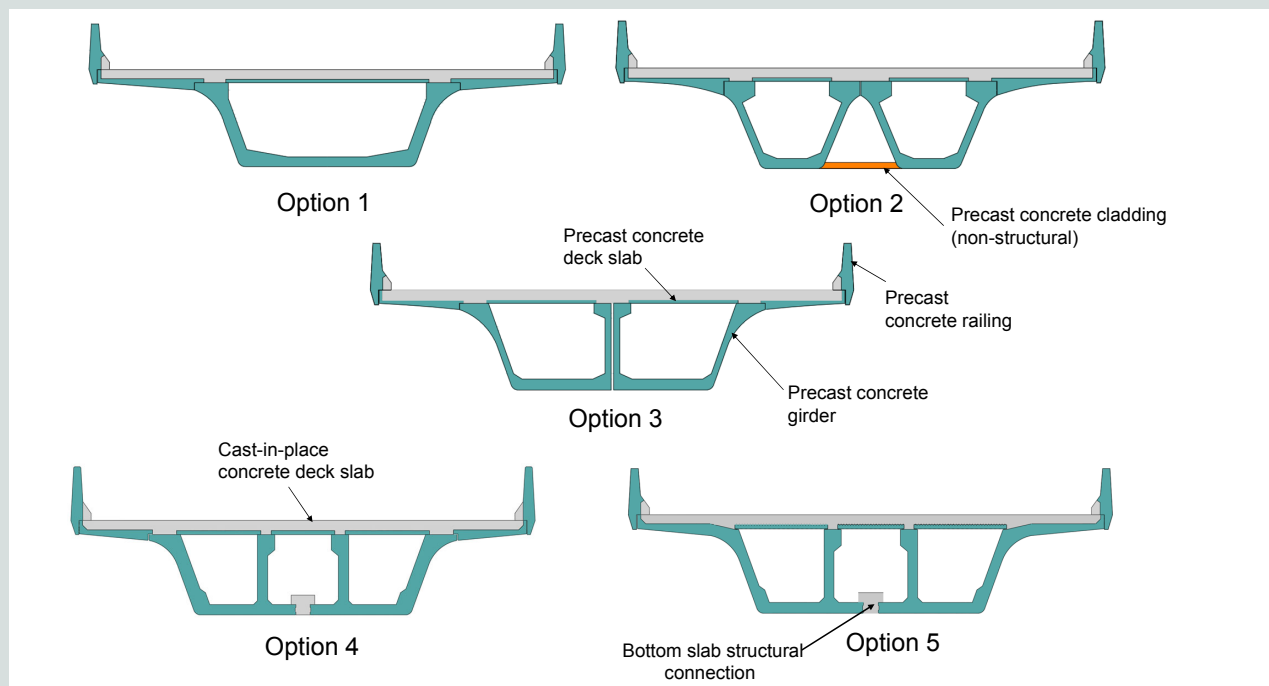


Figure 3. Typical cross section of the bridge for various precast concrete alternatives. Courtesy of e.construct.

Option 3 In option 3, two unsymmetrical precast concrete tub girders are arranged adjacent to each other to support a composite precast concrete slab system with a cast-in-place concrete deck topping. The two precast concrete components are connected in a way that ensures that they work together as a full box under service loads. The system may be simpler to construct than the preferred options 4 and 5; however, option 3 is not as structurally optimized as options 4 and 5 because those designs have more space between the interior webs.

Option 4 The fourth option has a precast concrete unsymmetrical open tub girder supporting a composite precast concrete slab system with a cast-in-place concrete deck. This option ensures the integrity of the full box under service conditions by structurally connecting the bottom flange with a reinforced concrete closure pour.

Option 5 This option is the same as option 4 except for one simplification in site operations. Option 5 integrates the tub girder with the precast concrete overhang of the exterior web. This method eliminates the tedious work of forming the overhang for the cast-in-place topping. Although having a large overhang increases the structural design burden, it greatly simplifies deck concrete placement. The design team proposed option 5, and the contractor and owner endorsed it. The following sections include discussion of the challenges that this choice introduced.

Proposed unsymmetrical precast concrete system

The bridge project adds to an existing, heavily traveled highway. To accelerate construction and minimize disruptions

to live traffic, the design team developed an innovative precast concrete girder system. The proposed solution splits the original cast-in-place concrete box girder longitudinally into two adjacent, unsymmetrical precast concrete tubs (**Fig. 4**). These tubs are erected independently on the pier supports and placed side by side. Following placement, the bottom flanges of the two tubs are stitched together using cast-in-place concrete to form a unified section. Precast concrete panels are then installed between the webs to act as permanent composite formwork for the cast-in-place deck slab. Once completed, the final superstructure replicates the geometry, structural behavior, and visual appearance of the originally proposed cast-in-place box-girder system.

Post-tensioning is applied in three stages using straight tendons (**Fig. 5**). First, bottom post-tensioning is applied to each unsymmetrical precast concrete tub immediately after casting in the precast concrete plant. The tubs are designed to resist self-weight, lifting, handling, and transportation loads during this stage.

Second, after erecting and stitching the bottom flange, additional bottom post-tensioning is applied to the now symmetrical section. This bottom post-tensioning resists the weight of the fresh concrete and construction live load and puts the cast-in-place stitch in precompression. In addition, the second-stage post-tensioning resists the positive moment due to the deck slab, superimposed dead loads, and live loads in the continuous spans.

The design team investigated several options for the top post-tensioning to achieve continuity over the piers, including

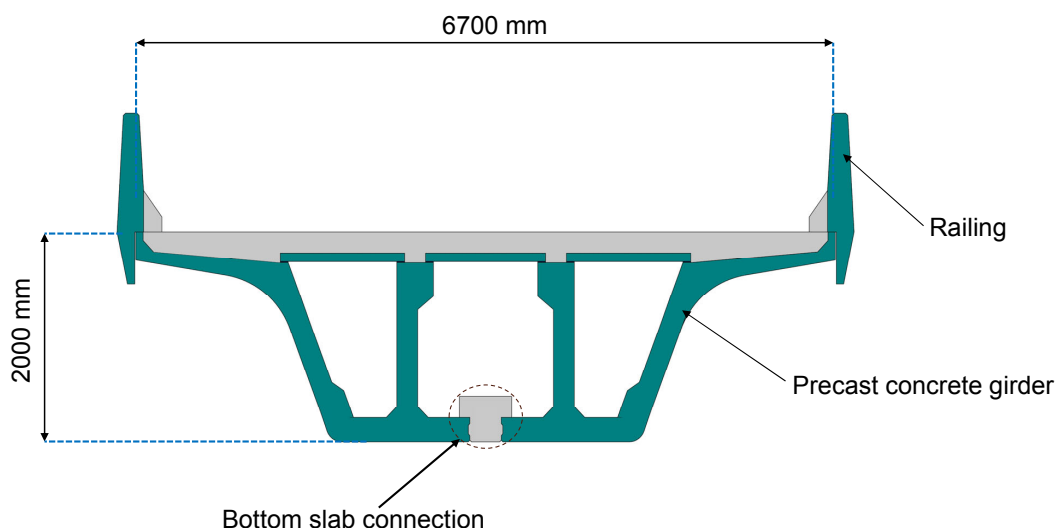


Figure 4. Precast concrete cross section of the 6.70 m wide bridge (option 5, proposed and accepted). Courtesy of e.construct. Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft.

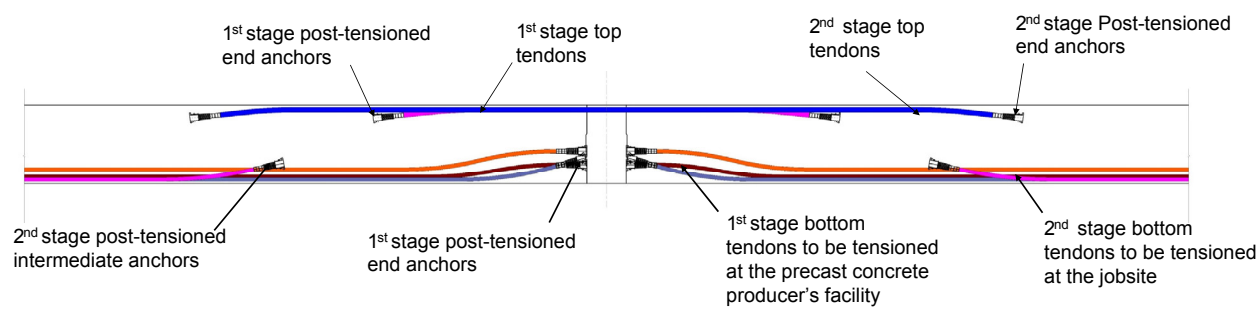


Figure 5. Post-tensioned tendon profile elevation (proposed design). Courtesy of e.construct.

placing straight tendons within the tops of the precast concrete girders or within the deck slab. The design team decided to place the top post-tensioning tendons within the deck slab over the piers to resist negative moment in the continuous spans. This choice was suitable for this project; however, in cold environments, where deicing chemicals are used and deck replacement may be required, placement of the top post-tensioning in the bulbs of the precast concrete girders, below the deck, may be preferred.

Previous research

Ma et al.¹ presented the concept of precast concrete unsymmetrical girders in a paper that describes the assembly of prestressed concrete box girders using precast, prestressed concrete unsymmetrical sections and I-sections. That paper inspired the creation of the system presented herein for King Abdullah Financial District's bridges.

Construction challenges

The use of unsymmetrical precast concrete girders presented several challenges during production and construction. This included the need to produce custom formwork and carefully analyze stability during lifting, storage, transportation, and erection. Additional challenges involved ensuring the constructibility of the bottom slab connection and providing access openings for future maintenance.

Form configuration

The precast concrete girder form was made of steel so it could be used repeatedly. It consisted of one internal piece and two external pieces, one vertical and one inclined (**Fig. 6**), to form the required girder geometry. The form was specifically configured to accommodate the unsymmetrical tub girder cross section, with independent adjustment of the inclined and vertical sections to

control web thickness, flange width, and overall geometry. The forming system was designed to accommodate both longitudinal and lateral movements of the unsymmetrical precast concrete tub girder. Longitudinal restraint was minimized to allow free axial shortening during transfer of the prestressing force. In addition, controlled lateral movement was permitted to accommodate the lateral movement resulting from the self-weight and prestressing effects that were expected because of the unsymmetrical cross section. The design incorporated low-friction support interfaces to allow these movements while maintaining support and overall geometric stability. This approach reduced the potential for locked-in stresses and unintended torsional effects during curing and prestress transfer. The project team verified the effectiveness of the form configuration by observing longitudinal shortening and lateral movement during prestress transfer and by comparing those observations with analytical expectations.

Lifting considerations

Once the required concrete strength was achieved and the first post-tensioning application was complete, a specially

designed multipoint lifting system was used to lift the tub girders from the form. The lifting anchors were positioned at two locations at each end to align with the total girder center of gravity (**Fig. 7**). Furthermore, the contractor had to ensure that each girder was lifted in a strictly vertical orientation. This procedure ensured safe and controlled handling of the girders from the form to the storage location.

The design team gave special consideration to the curved girders. The lifting inserts were placed at a specific distance from the girder ends designed to ensure proper lifting stability without girder tilting. **Figure 8** illustrates the lifting of a straight and curved precast concrete girder.

Storage configuration

The straight precast concrete girders were stored on blocks at both ends (**Fig. 9**). Because of their highly unsymmetrical cross sections, the girders exhibited an eccentric center of gravity, making them susceptible to lateral instability. To mitigate this risk, workers installed a steel stability frame above

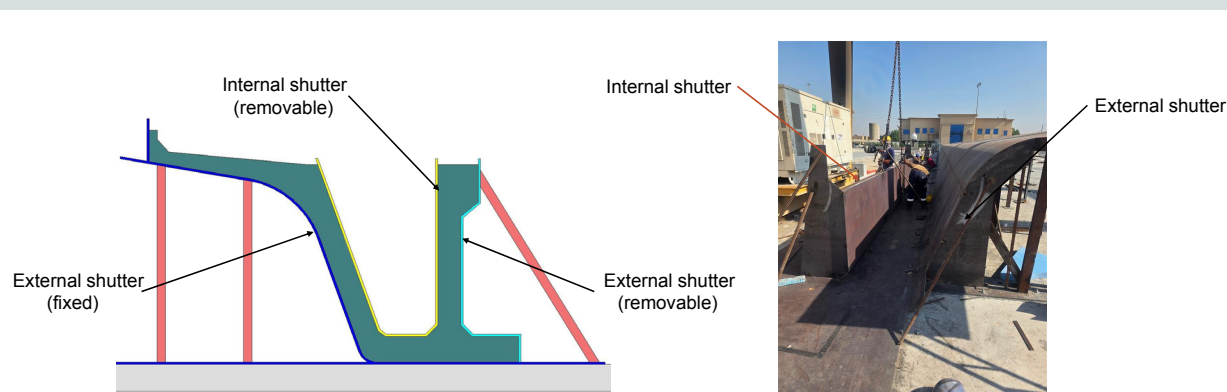


Figure 6. Form geometry. Courtesy of e.construct.

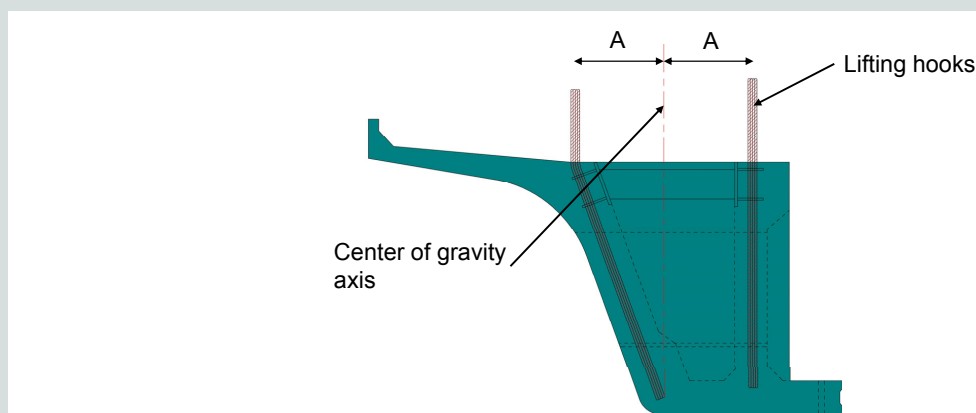


Figure 7. Lifting hook arrangement in cross sections. Courtesy of e.construct.



Straight Girder



Curved Girder

Figure 8. Lifting of the precast concrete girders. Courtesy of e.construct.

the supports to provide both lateral and torsional restraint, thereby ensuring safe storage conditions.

The storage configuration also maintained adequate spacing between the two girder halves to facilitate safe handling, lifting, and inspection, while minimizing the development of secondary stresses resulting from elastic shortening or lateral displacement.

In some cases, girders with sharp horizontal curvature may require a third support near the midspan to enhance stability. For this project, a third support was not necessary.

Transportation

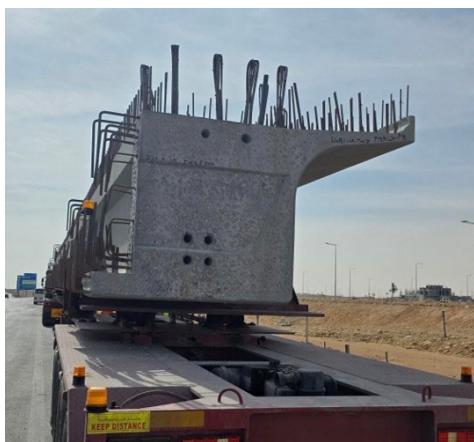
Transport of the unsymmetrical precast concrete open tub girders was challenging because of the eccentric center of gravity of the precast concrete pieces. Before transport, each girder was assessed to confirm that its lifting anchor condition, dimensional tolerances, camber, and lateral movement conformed with analytical predictions and were compatible

with the transport supports and restraints. The girders were transported by multiple-axle trailers mounted with custom-designed steel frames. The support points were located near the girder ends for the straight girders and at specified offsets for the curved girders (**Fig. 10**) and aligned vertically under the bottoms of the webs, maintaining consistency with the storage and lifting support configuration and minimizing bottom-flange bending stresses. Because diaphragms and post-tensioning anchors caused nonuniform, eccentric mass distribution, it was important to carefully select the support layout to minimize torsional rotation and uneven bearing pressures during transit. To control lateral stability and torsional response, stability steel frames were used. Elastomeric bearing pads were incorporated at support interfaces to accommodate minor rotations, differential settlements, and dynamic effects arising from road irregularities, and to prevent stress concentrations at contact points. Tie-down systems were designed to secure the girders against longitudinal, lateral, and uplift forces generated during braking, acceleration, turning, and uneven road profiles. The trailers were driven at controlled speeds, and the route was planned to

Stability frame



Figure 9. Temporary support during storage. Courtesy of e.construct.



Straight Girder



Curved Girder

Figure 10. Transport of precast concrete girders on a long trailer. Courtesy of e.construct.

limit sharp turns, steep gradients, and abrupt elevation changes. Continuous visual monitoring was carried out during transport, and periodic checks were performed along the route to verify restraint integrity and girder stability. When the girders arrived at the site or intermediate storage locations, unloading procedures mirrored the controlled lifting methodology used at the precast concrete producer's yard. Temporary lateral restraints remained in place until the girder was fully supported.

Erection on substructure

The precast concrete unsymmetrical open tub girder was erected using a synchronized dual crane lift to control tilting

with some cases requiring a single heavy crane due to limited crane accessibility (**Fig. 11**). Lifting points were defined through stage analysis to limit tensile stresses. Stability frames were installed and tied to each pier to restrain rotation until the mating girder was placed and connected to form the full symmetrical section (**Fig. 12**).

Bottom slab connection

The bottom slab connection between adjacent unsymmetrical precast concrete tub girders is designed to provide structural continuity while accommodating construction tolerances during girder erection. Because precast concrete



Straight Girder



Curved Girder

Figure 11. Erection of the precast concrete girders on piers. Courtesy of e.construct.

elements are fabricated off-site and installed in the field, minor dimensional deviations and alignment differences are unavoidable. Accordingly, the connection detail must ensure reliable transfer of shear and bending forces while providing sufficient tolerance to facilitate practical and efficient construction. A cast-in-place closure strip is provided at the bottom slab between adjacent girders to accommodate erection tolerances and to complete the structural connection after girder placement. Reinforcement projecting from the precast concrete girders is detailed with overlapping bars, and a shear key is incorporated to enhance shear transfer across the joint. This detailing allows the connection to accommodate minor positional variations that may occur during erection while maintaining the required structural performance. Following girder alignment, the closure region

is completed by installing temporary formwork hanging from the top of the bottom slab, adding the required reinforcement, and filling the joint with nonshrink grout or cast-in-place concrete. After curing, the closure strip provides continuity in the bottom slab and enables the adjacent girders to act integrally as a symmetrical box girder (Fig. 4 and Fig. 13).

Access openings within the full box

The designers added access openings along the entire length of the girder for inspection and maintenance activities. A bottom-access opening measuring 600 × 600 mm (24 × 24 in.) is located in the soffit slab between the two precast concrete girders at approximately 1/3 of the girder spans from

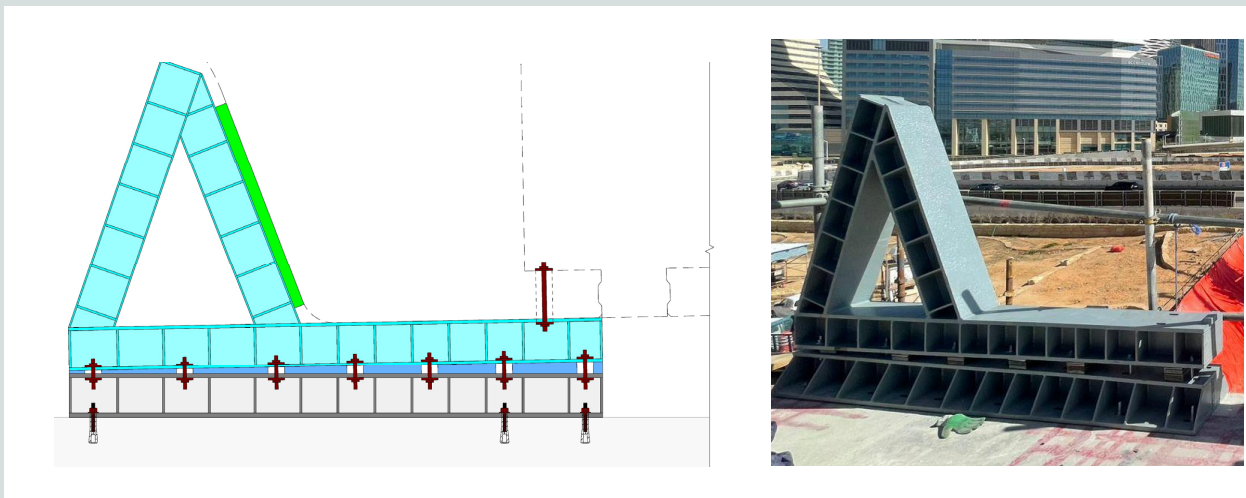


Figure 12. Temporary stability bracket details. Courtesy of e.construct.

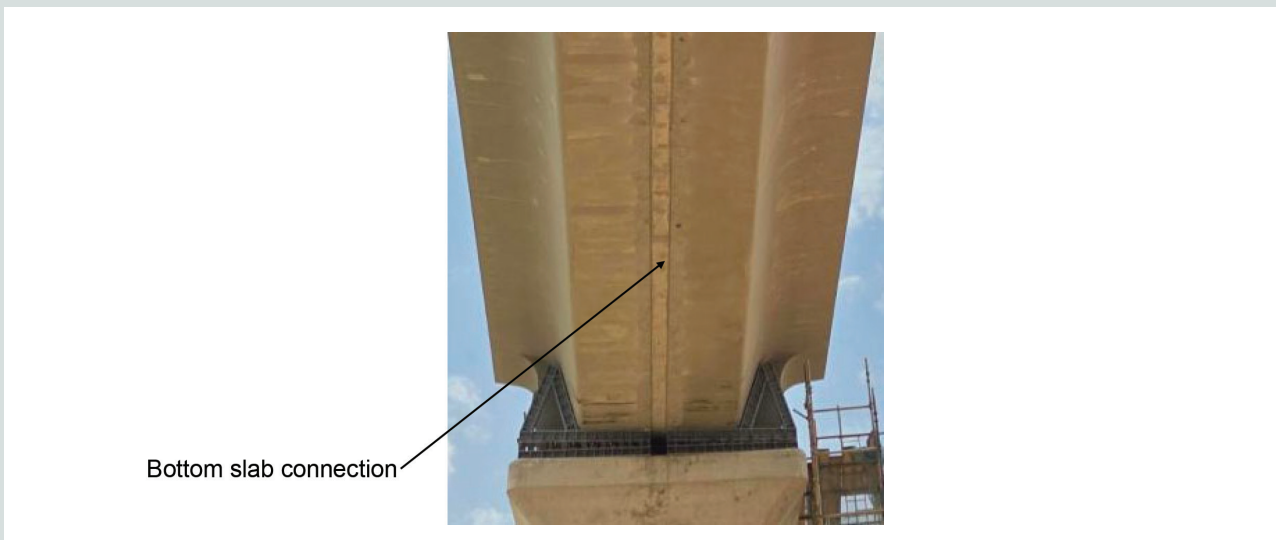


Figure 13. View of the bottom slab connection for the precast concrete girders. Courtesy of e.construct.

the support. In addition, the design included 600×600 mm access openings in the internal webs of each precast concrete girder to allow internal access. Similar openings are also provided in all intermediate diaphragms. These openings were considered in the finite element analysis to account for the loss of section, and additional reinforcement was provided around the openings to control possible cracking at high-stress points.

Design challenges

From a design perspective, the unsymmetrical girder system was highly complex. The sectional asymmetry created unique torsional effects that required advanced analytical techniques to properly evaluate. In addition, prestressing strand arrangements needed to be determined based on the changing section properties before and after connection of the adjacent girders. Ultimately, this level of complexity required the use of advanced finite element analysis modeling, including full three-dimensional shell modeling.

Unsymmetrical cross section

The unsymmetrical configuration of the precast concrete girder introduces several design challenges. The large overhang incorporated into the precast concrete section shifts the center of gravity significantly away from the bottom flange, resulting in inherent eccentricity that generates torsional moments in addition to flexural demands. These torsional effects must be explicitly considered in structural analysis and in the design of both prestressed and nonprestressed reinforcement. The uneven distribution of mass and stiffness can influence deflection, cracking behavior, and long-term performance, potentially necessitating enhanced reinforcement, torsional capacity checks, and stricter serviceability controls.

This eccentricity causes the principal axes of the section to rotate relative to the vertical and horizontal geometric axes. As a result, flexural and torsional behaviors become more complex and do not align with the obvious top-bottom or left-right directions. Bending about one axis induces coupled lateral or torsional deformation. Determining the principal axes is therefore required for accurate analysis of stresses and deflections (**Fig. 14**).

Prestressing strand arrangement

During the lifting stage, it is important that the bottom prestressing strand locations in the unsymmetrical girder minimize the girder's lateral movement and resist self-weight effects during handling and erection. After the girder is connected to the second girder to form the full symmetrical box section, additional bottom strands are introduced to achieve the final required prestress. This staged strand arrangement ensures construction stability while satisfying the design requirements of the completed section. **Figure 15** shows the prestressing strand arrangement and sequencing, which were designed to minimize the tendency of the lateral movement induced by the prestressing to be outward (away from the total box centerline) and to direct that movement toward the centerline.

Analysis methodology

Traditionally, for stringer bridges each I-beam line is assigned a code-mandated fraction of the live load. That design methodology, which converts a three-dimensional structure into a linear component analyzed as a frame element, is inaccurate for full-width box-girder bridges. Instead, designers often need to use grillage analysis to perform preliminary and, sometimes, final design. For highly complex or unsymmetrical sections, a full-shell three-dimensional finite element analysis is needed to accurately model the geometry; capture

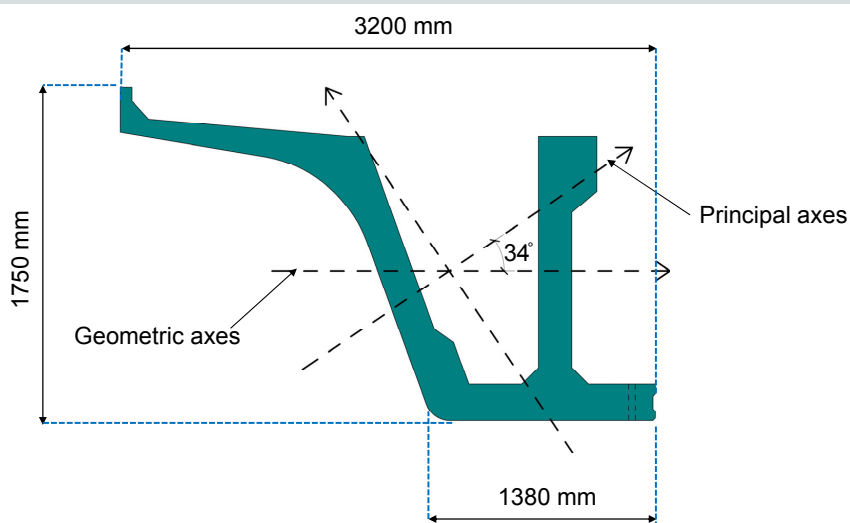


Figure 14. Typical cross section of an unsymmetrical precast concrete girder. Courtesy of e.construct. Note: 1 mm = 0.0394 in.

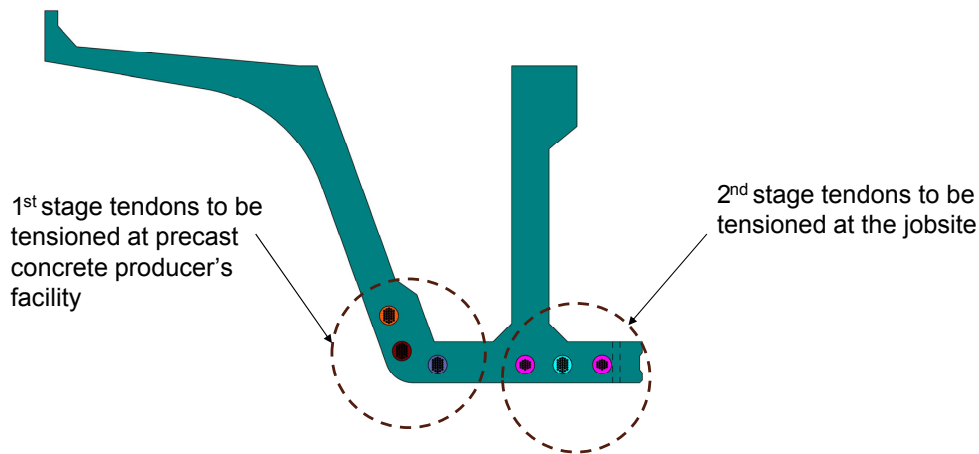


Figure 15. Arrangement of the bottom post-tensioned tendons in the precast concrete girder. Courtesy of e.construct.

torsional effects, lateral movements, and local stress distributions; and ensure the reliable design of prestressing, mild reinforcement, and construction-stage stability.

In addition to the unsymmetrical cross section, several other aspects of the bridge project required rigorous construction-stage analysis and enhanced detailing to ensure structural performance and constructibility. Specifically, the strand arrangement and the open U-shaped precast, prestressed concrete girder presented challenges related to handling and erection stability, temporary and final condition behavior, torsional crack control, camber deflection prediction, construction tolerances, and volume change (creep, shrinkage, and temperature) effects.

The analysis focused on evaluating the vertical deflection at the bottom slab and at the overhang cantilever region. The measured vertical deflection and lateral movement values were of particular importance during the erection stage, especially at the bottom stitching zone, where compatibility between adjacent precast concrete girders was required. The analysis results indicated that the vertical deflection of the bottom slab for each girder would be approximately equal, ensuring uniform behavior and minimizing differential displacement during assembly. The same observation was recorded for lateral movement values.

Construction steps

Following are the steps to construct the bridge superstructure:

1. Place a temporary steel stability bracket on top of the cast-in-place substructure.
2. Place the precast concrete girder on the piers and attach it to the temporary steel stability bracket. For curved spans, temporary shoring towers at midspan may be provided to ensure stability during erection (**Fig. 16**).

3. Cast the concrete for the bottom slab connection, stitching the unsymmetrical girders together into a symmetric section (**Fig. 17**).
4. Install the permanent bearing beneath the cast-in-place diaphragm above the cast-in-place pier.
5. Cast the concrete for the intermediate and end diaphragm connections between the precast concrete girders (**Fig. 18**).
6. Tension the second-stage bottom post-tensioning tendons (the first stage having been completed at the precast concrete plant).
7. Place precast concrete deck panels for the first stage of the deck above the piers.
8. Cast the concrete deck and diaphragm at the piers (**Fig. 19**).
9. Perform the first stage of the top post-tensioning in the deck.
10. Install the precast concrete deck panels for the middle part of the span.
11. Place the concrete for the remaining deck topping.
12. Complete the second stage of top post-tensioning through an opening left in the topping slab and close after tensioning.
13. Install the precast concrete railing and cast the connection between the railing and the topping.
14. Apply the asphalt wearing surface.

Worked example

The following example illustrates the concepts used in the design of the King Abdullah Financial District access bridge

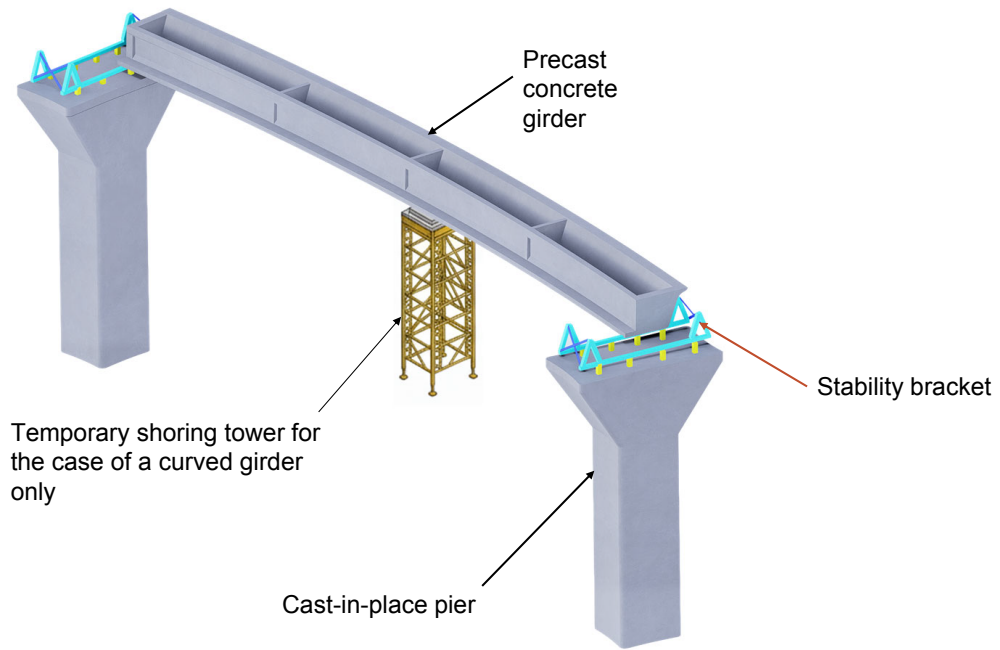


Figure 16. Temporary steel stability brackets are placed on the completed cast-in-place concrete substructure units. Then the precast concrete girders are placed on the piers and attached to the stability brackets. Courtesy of e.construct.



Figure 17. Bottom slab connection. Courtesy of e.construct.

project for one of the structure units between the expansion joints. The example bridge is a four-span structure with a combination of curved and straight alignments (**Fig. 20**). The first span is 45 m (148 ft) and follows a horizontal curve with a radius of 250 m (820 ft), transitioning into two intermediate straight spans, each with a length of 45 m. The final span consists of a 45 m span aligned along a horizontal curve with a radius of 500 m (1640 ft).

The section properties (**Fig. 21**) were evaluated based on both the geometrical axes and the principal axes of the cross

section. The geometrical properties are defined with respect to the centroidal axes, with moments of inertia denoted as follows:

$$I_x = 4.74 \times 10^{11} \text{ mm}^4 (1.14 \times 10^6 \text{ in.}^4)$$

where

$$I_x = \text{moment of inertia of the section about the horizontal axis}$$

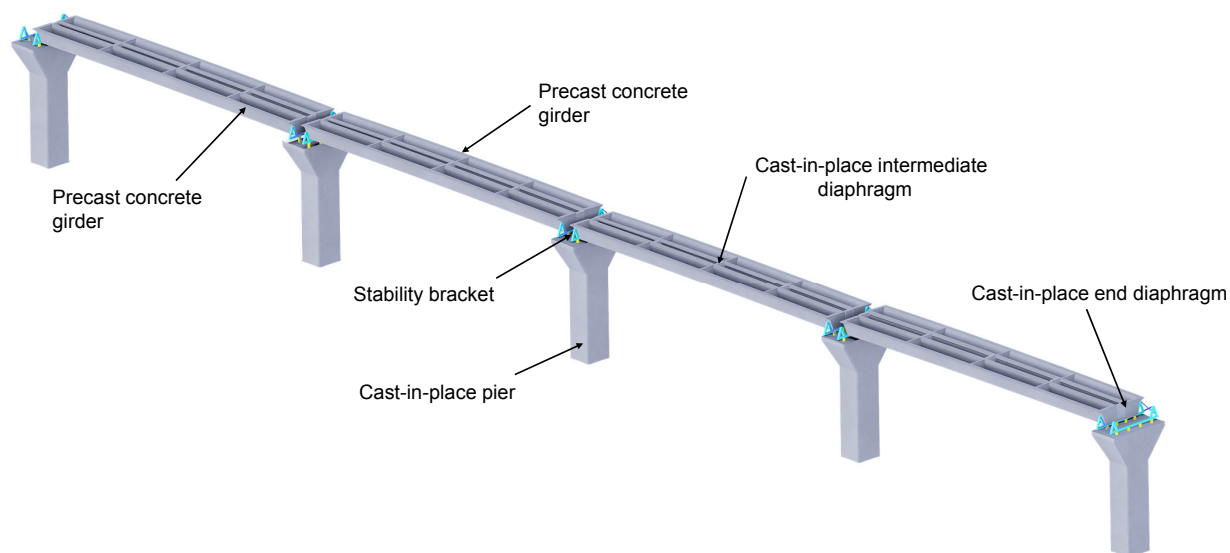


Figure 18. Bridge spans between expansion joints. Courtesy of e.construct.

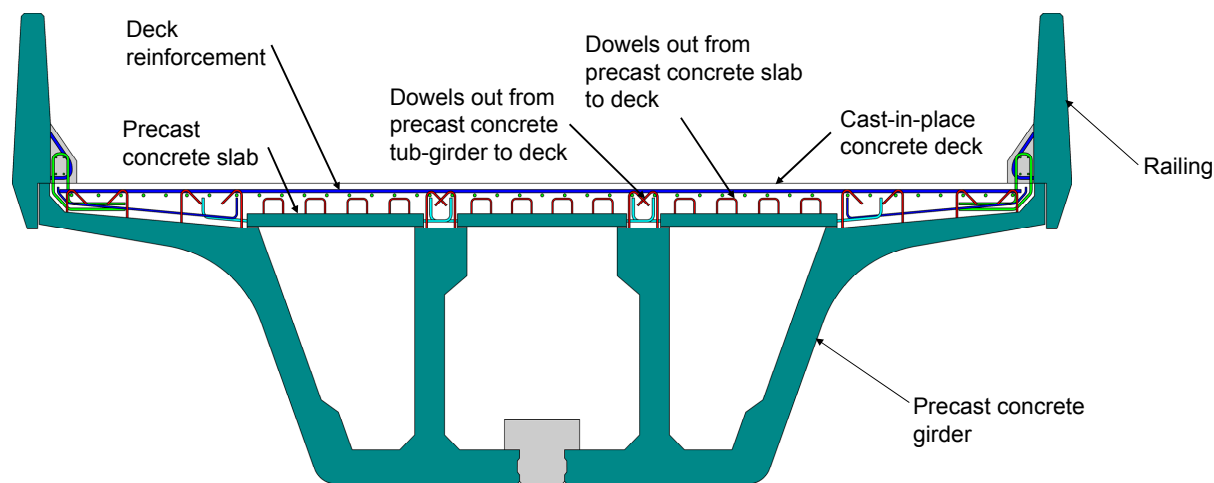


Figure 19. Typical reinforcement details between a precast concrete tub-girder and cast-in-place concrete deck slab. Courtesy of e.construct.

and

$$I_y = 7.47 \times 10^{11} \text{ mm}^4 (1.80 \times 10^6 \text{ in.}^4)$$

where

I_y = moment of inertia of the section about the vertical axis

In addition, the principal axes properties (Fig. 14) are determined as follows:

$$I_u = 2.28 \times 10^{11} \text{ mm}^4 (5.48 \times 10^5 \text{ in.}^4)$$

where

I_u = moment of inertia about principal axis u

and

$$I_v = 9.92 \times 10^{11} \text{ mm}^4 (2.38 \times 10^6 \text{ in.}^4)$$

where

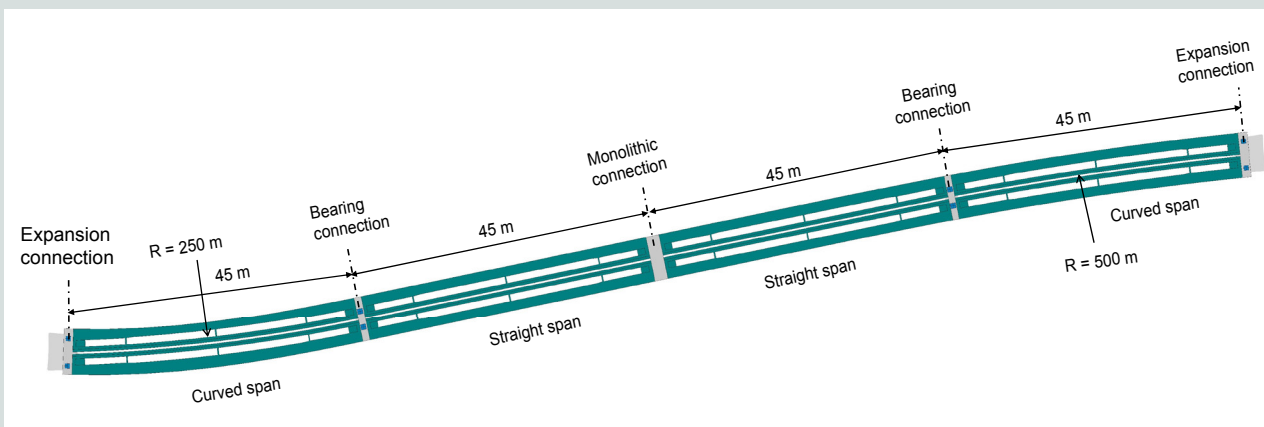


Figure 20. Worked example bridge layout. Courtesy of e.construct. Note: R = radius. 1 m = 3.281 ft.

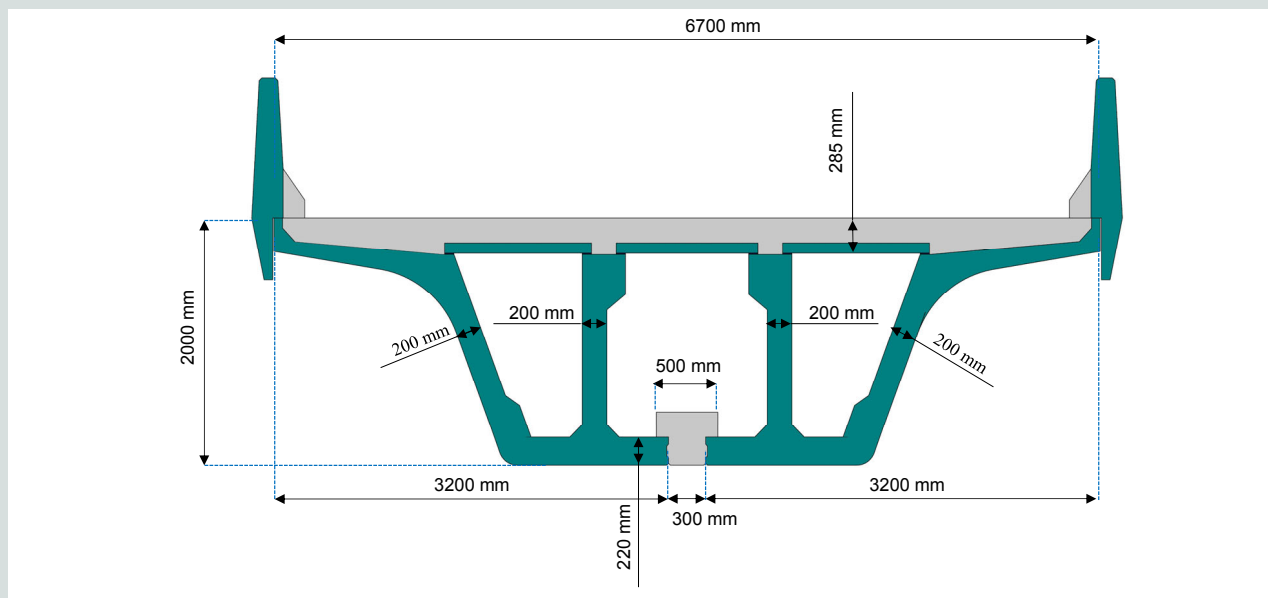


Figure 21. Worked example bridge cross section. Courtesy of e.construct. Note: 1 mm = 0.0394 in.

I_v = moment of inertia about principal axis v

The weight of the precast concrete girder is approximately 145 tons (290 kip).

The precast concrete segments are typically fabricated using concrete with a specified compressive strength of 50 MPa (7.3 ksi) at 28 days. At the time of prestress transfer, the concrete is required to achieve a minimum compressive strength of 40 MPa (5.8 ksi).

Bottom post-tensioning is applied in two stages. The first stage is carried out at the precast concrete plant, while the second stage is applied on-site after connecting the precast concrete girders through the bottom slab connection, as illustrated in **Fig. 22**. The bottom post-tensioning layout is

described in **Table 1**. The average bottom post-tensioned rate is 23.0 kg/m² (4.70 lb/ft²).

Continuity is achieved through top post-tensioning, which is installed after casting the diaphragm over the pier. The top tendons are provided as straight tendons and are tensioned in two stages consisting of short tendons followed by long tendons (**Fig. 23**). **Table 2** describes the top post-tensioning layout. The average top post-tensioned rate is 9.0 kg/m² (1.84 lb/ft²).

Table 3 shows a comparison of the quantities of materials for the cast-in-place box girder and the precast concrete systems. As this comparison indicates, the quantities of materials used were similar for both systems; however, the structural depth of the cast-in-place system is deeper and the driving desire was to

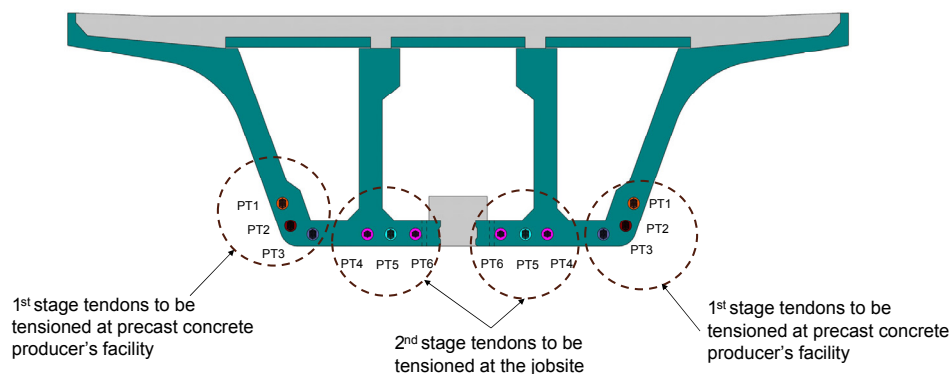


Figure 22. Bottom post-tensioning arrangement. Courtesy of e.construct. Note: PT1 = post-tensioning tendon 1; PT2 = post-tensioning tendon 2; PT3 = post-tensioning tendon 3; PT4 = post-tensioning tendon 4; PT5 = post-tensioning tendon 5; PT6 = post-tensioning tendon 6.

Table 1. Bottom post-tensioning for the worked example bridge

Span placement	First stage	Second stage	Total strands
First span	Three 19-strand tendons and one 14-strand tendon with 15.24 mm diameter strands	Two 19-strand tendons with 15.24 mm diameter strands	109
Second and third span	Three 19-strand tendons with 15.24 mm diameter strands	One 17-strand tendon and one 18-strand tendon with 15.24 mm diameter strands	92
Fourth span	Three 19-strand tendons with 15.24 mm diameter strands	Two 19-strand tendons and one 14-strand tendon with 15.24 mm diameter strands	109

Note: 1 mm = 0.0394 in.

avoid the formwork and the specialized equipment not available to the contractor to implement the cast-in-place solution.

For the curved first and last spans, with radii of 250 and 500 m (820 and 1640 ft), respectively, the lifting device locations are adjusted slightly to account for the torsional effects introduced by curvature.

For the intermediate, second, and third straight spans, devices are positioned near the girder ends to correspond with the weight distribution and center of gravity.

For curved spans, horizontal steel bracing is used temporarily within the open U girder to increase torsional stiffness during handling, transportation, and erection until the closed box

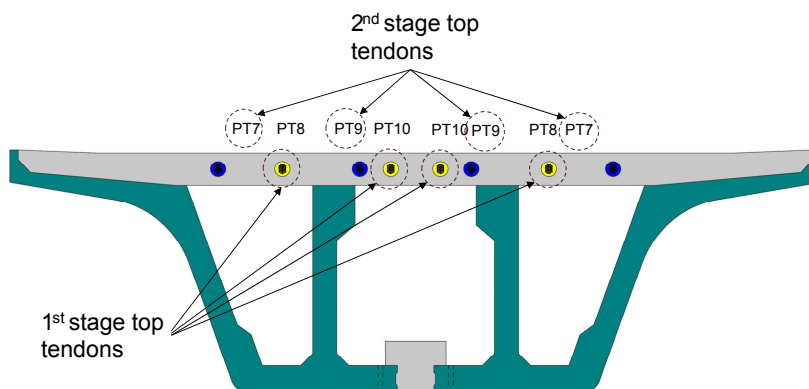


Figure 23. Continuity top post-tensioning arrangement. Courtesy of e.construct. Note: PT7 = post-tensioning tendon 7; PT8 = post-tensioning tendon 8; PT9 = post-tensioning tendon 9; PT10 = post-tensioning tendon 10.

Table 2. Top post-tensioning for the worked example bridge

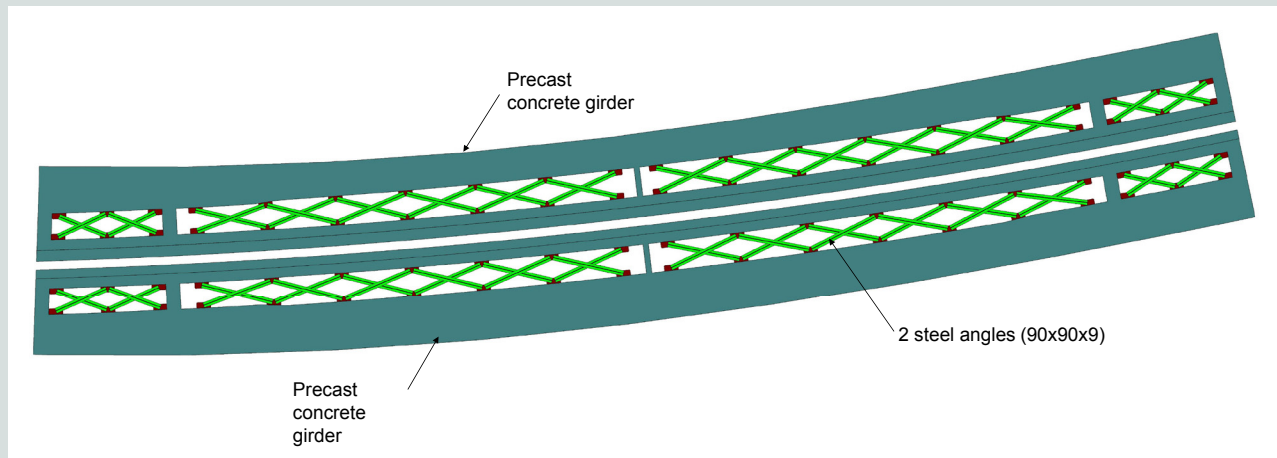
Pier placement	Tendon description	Total strands
First and third piers	Four 27-strand tendons with 15.24 mm diameter strands	108
Intermediate pier	Four 24-strand tendons with 15.24 mm diameter strands	96

Note: 1 mm = 0.0394 in.

Table 3. Quantity comparison between the originally proposed cast-in-place concrete box girder and the value-engineered precast concrete bridge system

Item description	Original cast-in-place box-girder system	Precast concrete system
Concrete quantity, m ³ /m ²	0.75	0.69
Prestressing steel, kg/m ²	38.5	32.0
Reinforcing steel, kg/m ²	160	200

Note: 1 m³/m² = 12.15 yd³/100 ft²; 1 kg/m² = 0.205 lb/ft².

**Figure 24.** Temporary steel bracing layout for curved precast concrete girder. Courtesy of e.construct. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

girder is formed as recommended by PCI's *Guide Document for the Design of Curved, Spliced Precast Concrete U-Beam Bridges*.² The system consists of two steel angles, each measuring 90 × 90 × 9 mm (3.5 × 3.5 × 0.35 in.), that are placed back to back and installed transversely between the webs at strategic locations along the span (**Fig. 24**).

The two adjacent precast concrete unsymmetrical open U-girder curved spans exhibit distinct structural responses due to differences in their geometry, loading conditions, and curvature effects. In terms of vertical deflection, the computed deflection at the bottom slab connection is 22.8 mm (0.90 in.) for the long girder and 23.0 mm (0.91 in.) for the short girder, resulting in a negligible differential deflection of 0.20 mm (0.01 in.).

For lateral movement, the computed displacement at the bottom slab connection is 3.50 mm (0.14 in.) for the long

girder and 1.75 mm (0.07 in.) for the short girder, both acting toward the inner web. The result is a combined relative lateral movement of 5.25 mm (0.21 in.). This magnitude of movement can be safely accommodated within the 300 mm (11.81 in.) width of the bottom cast-in-place connection, ensuring adequate structural compatibility between the adjacent girders.

For the precast concrete bridge girders, a full-shell three-dimensional finite element analysis provides a detailed evaluation of both flexural and shear stress distributions, enabling a more accurate representation than that provided in traditional beam theory approaches. The results indicate that the maximum stress in the bottom slab at midspan is tension stress equal to +2.70 MPa (+0.39 ksi), which is less than the allowable limit of $0.50\sqrt{f'_c}$ equals +3.53 MPa (+0.51 ksi) specified in the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge*

*Design Specifications*³ and the *PCI Bridge Design Manual*.⁴ Similarly, the maximum stress in the top of the precast concrete girder is a compression stress equal to -9.80 MPa (-1.42 ksi), remaining within the permissible compression limit of $0.60f'_c = -30$ MPa (-4.35 ksi). At the pier location, the maximum stress in the top of the precast concrete girder is a compression stress equal to -4.30 MPa (-0.62 ksi), which is less than the allowable compression limit of $0.60f'_c$ equals -30 MPa, whereas the stress in the bottom slab is a compression stress equal to -26.5 MPa (-3.84 ksi). Furthermore, the maximum stress in the deck slab over the pier is tension stress equal to +2.40 MPa (+0.35 ksi), which is less than the allowable tensile stress limit. The deck slab at midspan behaves as a nonprecompressed element and is subjected to tensile tension forces primarily due to shrinkage effects; however, these stresses are effectively resisted by the main cast-in-place deck reinforcement as well as supplementary reinforcement provided in selected spans. Overall, the comparison demonstrates that all computed stress values are within the allowable limits, confirming that the girder system satisfies both serviceability and strength requirements.

Full-shell three-dimensional finite element analysis was also used to evaluate the shear stresses resulting from both direct shear and torsional effects; this model captures the interaction among shear flow, warping, and torsional resistance with high accuracy. The computed shear stress distribution along the girder web, particularly near the supports and regions of high torsional demand, was compared with the allowable limits specified in the AASHTO LRFD specifications. The maximum shear stress in the girder webs at the support is 7.20 MPa (1.04 ksi), which is less than the allowable limit for shear. Accordingly, the required shear and torsional reinforcement have been calculated and properly detailed in accordance with code provisions.

Conclusion

Following are the authors' conclusions:

- The proposed construction approach provides a practical means of achieving the architectural appearance and structural performance of a cast-in-place multicell box girder while using precast concrete elements of manageable sizes for fabrication, transportation, and erection.
- The use of unsymmetrical precast concrete box-girder components introduces design and construction challenges, particularly with respect to prestressing, stripping, handling, hauling, and torsional stability before the two halves are connected to create a closed-cell box.
- Girder alignment and the sequencing of concrete placement in closure pours required careful consideration in both design and construction planning. To ensure that the stresses in the longitudinal closure pour were below cracking limits, additional post-tensioning was needed after the closure-pour concrete had gained strength.

- Lack of symmetry in the preassembled components required total post-tensioning instead of combining pretensioning in the precast concrete plant and post-tensioning in the field, which is more common.
- Temporary horizontal bracing, together with a well-defined erection sequence, provided adequate stability during construction until the closed box section could provide adequate torsional stiffness.
- This project demonstrates that the proposed construction methodology is a viable option for accelerated construction of multicell box-girder bridges where minimizing traffic disruption and achieving a flat soffit are important objectives.
- Findings from this project are relevant to the development of design guidelines for similar systems. Such guidelines should address the prestressing method and the stability of unsymmetrical girders during various stages of construction.
- Research into optimizing structural systems and, more importantly, simplifying construction procedures is needed as more clients opt for precast concrete to widen and replace existing box-girder bridges. Such research should include prestressing layouts, temporary bracing systems, and connection details.

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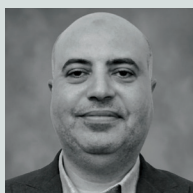
Notation

- I_u = moment of inertia about principal axis u
- I_v = moment of inertia about principal axis v
- I_x = moment of inertia of the section about the horizontal axis
- I_y = moment of inertia of the section about the vertical axis

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Abstract

Multicell box-girder bridges are traditionally constructed using precast concrete segmental or cast-in-place methods. Although cast-in-place construction accommodates complex geometries, it can involve lengthy schedules, traffic disruptions, and substantial on-site labor. Fully precast concrete systems offer an attractive alternative by accelerating construction and improving quality control. This paper presents prestressing, erection, and assembly considerations for unsymmetrical precast concrete box-girder components assembled to form full-bridge-width multicell box girders. The ap-

proach enables construction from manageable precast concrete components while maintaining the structural efficiency and appearance of a closed box-girder system. Key construction challenges include prestressing unsymmetrical sections, lifting and placement stability, torsional behavior during erection, alignment of adjacent segments, temporary support requirements, and sequencing of bottom closure pours to achieve a continuous flat soffit. Practical methods for addressing these challenges are discussed based on their implementation in several bridges, including the King Abdullah Financial District access road network project in Riyadh, Saudi Arabia.

Keywords

Curved, unsymmetrical precast concrete girder; multicell precast concrete bridge; post-tensioned, precast concrete girder; precast concrete segmental bridge; unsymmetrical precast concrete box girder.

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