Innovative precast concrete adjacent-box-beam system implemented in the St. Clair Road bridge in Michigan

Chuanbing S. Sun, Maher K. Tadros, Kyle C. Kopper, and Talia N. Belill

- The St. Clair Road bridge over the Maple River in Clinton County, Mich., is a precast concrete adjacent-box-beam bridge with an innovative transverse post-tensioning system, which eliminates the need for intermediate diaphragms.
- The transverse post-tensioning system accelerates bridge construction and reduces the construction cost.
- Because the transverse post-tensioning is not performed until after the longitudinal joints are grouted, the joints are in permanent compression and the risk of water leakage at the joints is essentially eliminated.

Precast concrete adjacent box beams are widely used for short- and medium-span bridges due to their relatively shallow structural depth and their ability to minimize the amount of forming required to cast the bridge deck. The adjacent-box-beam system is also prevalent in accelerated bridge construction. Various adjacent-box-beam systems are implemented, including adjacent box beams with an overlay and composite adjacent box beams with a cast-in-place concrete deck slab.[1,2] Both systems are used with or without transverse post-tensioning.

This paper summarizes the common practices in Michigan for the construction of adjacent-box-beam bridges. It also describes the St. Clair Road bridge over the Maple River in Clinton County, Mich., including the precast, prestressed concrete box beams, details of the shear keys, transverse post-tensioning design, beam production, and bridge construction. In particular, a unique transverse post-tensioning method is highlighted.

Practices in Michigan

A conventional adjacent-box-beam bridge typically involves the use of transverse post-tensioning tendons or high-strength threaded rods, which are housed in intermediate diaphragms and are located such that the centroids of the post-tensioning tendons are at or near midheight of the box beams. Reflective cracks and leakage have occurred at the longitudinal joints between adjacent beams due to improper design or detailing. To address this issue, the Michigan Department of Transportation's (MDOT's) *Bridge Design Manual*[3] specifies a 6 in. (150 mm) thick reinforced concrete deck that is made composite with the box beams through slab ties embedded at the top of the beams. A hot mix asphalt wearing surface is allowed on local roadways with a side-by-side, prestressed concrete box-beam bridge and average daily traffic of fewer than 500 vehicles, of which commercial traffic is less than 3%. Also, the MDOT's *Bridge Design Guides*[4] specify the amount of required transverse post-tensioning, including the following:

- The number of post-tensioning tendon locations is determined based on the bridge span lengths (**Table 1**). The tendon location herein refers to either an intermediate diaphragm (away from the beam end) or an end block.
- The required prestressing force is 120 kip (534 kN).
- The number of post-tensioning tendon locations corresponding to various beam depths is specified in the *Bridge Design Guides* (**Table 2**).

Figure 1 shows typical adjacent box beams that are stored in a precast concrete producer's storage yard. Two post-tensioning ducts are provided in this beam section, one at each one-third point of the beam depth. Slab ties project beyond the beam top flange, allowing for composite action between the beam and the deck slab. **Figure 2** illustrates a transverse post-tensioning detail, including the shear key between adjacent box beams. The shear keys are grouted prior to transverse post-tensioning. Seal washers are included to prevent the grouting in the shear keys from entering the post-tensioning conduits. The post-tensioning conduits are grouted after transverse post-tensioning is applied. Michigan practice is superior to other practices in the U.S. in that post-tensioning is introduced after the longitudinal joints are grouted, thus ensuring compression across the joints. However, it still has some drawbacks, which are attempted to be remedied in this paper.

Description of St. Clair Road bridge

The St. Clair Road bridge is a simple-span bridge with a span of 85 ft (26 m). The bridge is 25 ft 2 in. (7.67 m) wide. The bridge superstructure includes six adjacent precast concrete box beams (**Fig. 3**). It also includes a 4 in. (100 mm) thick hot mix asphalt wearing surface installed over a waterproofing membrane. The bridge has a skew of 12 degrees (**Fig. 4**). The layout of transverse post-tensioning is discussed in detail in the following sections.

Table 1. Required amount of transverse post-tensioning tendon locations along the span length specified in the Michigan Department of Transportation *Bridge Design Guides*

Span length	Transverse post-tensioning tendon locations	Total
Up to 50 ft	One at each end of beam with two at center of span (11 ft apart)	4
Over 50 to 62 ft	One at each end of beam with one at center of span and one at each quarter point	5
Over 62 to 100 ft	One at each end of beam with two at center of span (11 ft apart) and one at each quarter point	6
Over 100 ft	One at each end of beam with five equally spaced between	7

Note: 1 ft = 0.305 m.

Table 2. Transverse post-tensioning tendon locations along the beam depths specified in the Michigan Department of Transportation *Bridge Design Guides*

Beam depth	At each location	Total
12 in.	One tendon 5½ in. below top of beam	1
17, 21, and 27 in.	One tendon at middepth of beam	1
33, 39, 42, and 48 in.	One at each ⅓ point of beam depth	2
54 and 60 in.	One at each ¼ point of beam depth	3

Note: 1 in. = 25.4 mm.

Figure 1. Typical Michigan box beams stored in a precast concrete producer's storage yard.

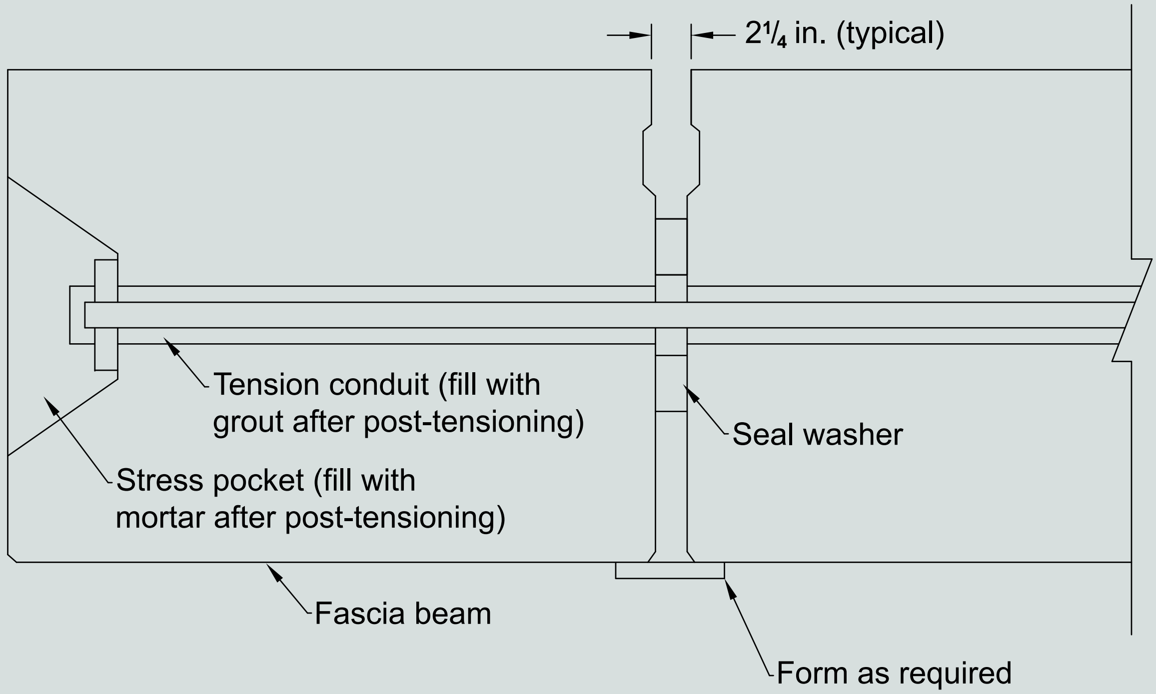

Figure 2. Transverse post-tensioning details from the Michigan Department of Transportation's *Bridge Design Guides.* Note: 1 in. = 25.4 mm.

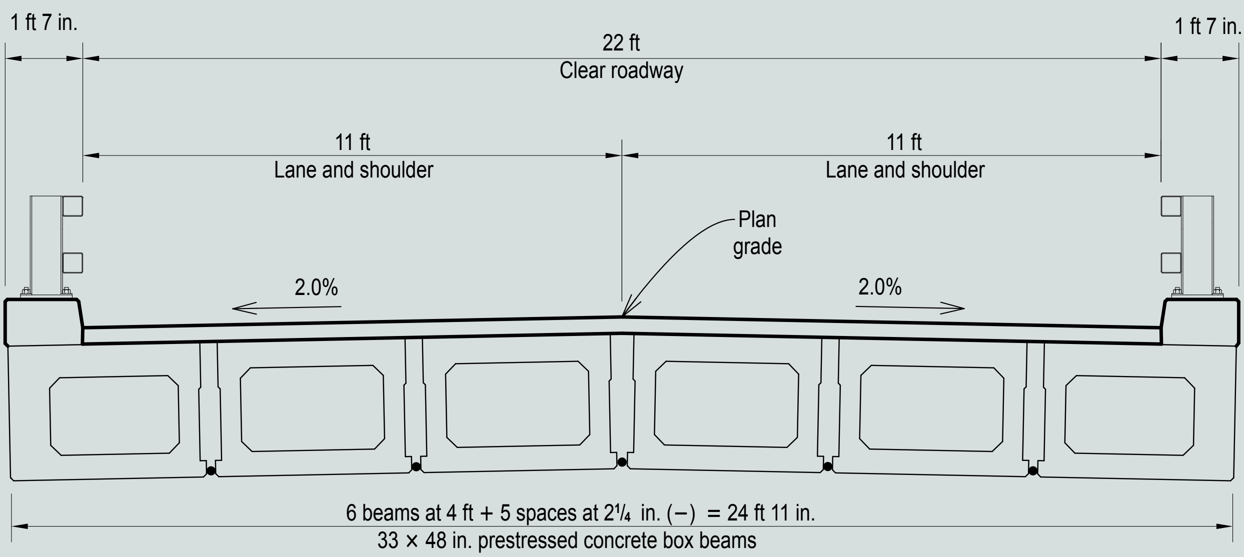

Figure 3. Cross section of the St. Clair Road bridge. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

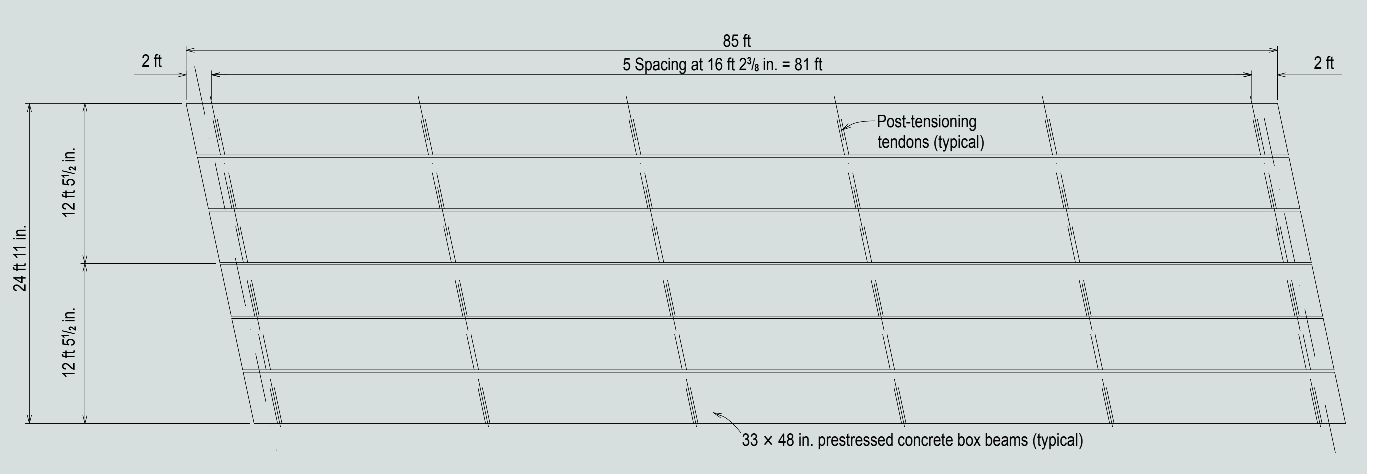

Figure 4. Plan view of the bridge. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

Precast concrete box beam

Figure 5 shows a partial three-dimensional model of two beam lines, including a fascia beam and its adjacent interior beam. **Figures 6** and **7** illustrate the dimensions of the beams, away from the post-tensioning location (section A-A in Fig. 5) and at the post-tensioning location (section B-B in Fig. 5), respectively. The beams are 2 ft 9 in. (0.84 m) deep. The interior box beam is 4 ft (1.2 m) wide at the bottom flange and 3 ft 10 in. (1.17 m) wide at the top flange. The flange thickness is 6 in. (150 mm) at the bottom and 6½ in. (165 mm) at the top. Both webs are 5 in. (130 mm) thick at the interior beam.

The fascia beam section has similar dimensions to those of the interior beam, except for the following:

- The width of its top flange is 3 ft 11 in. (1.19 m), slightly more than that of the interior beam, because the exterior face of the fascia beam does not have vertical shear keys.
- The top flange thickness is increased to 8 in. (200 mm) for sufficient embedment of the anchor bolts used for connecting the bridge railing.
- The exterior web is widened from 5 in. (130 mm) to 10 in. (250 mm) to accommodate the transverse post-tensioning anchorages.

Shear key

Both vertical and horizontal shear keys are prefabricated in the beams for overall structural integrity. At the shear key locations away from the post-tensioning tendons, the width of the vertical shear key is 2¼ in. (57 mm) at the bottom of the beams and is widened to 5¼ in. (133 mm) at the beam webs (Fig. 6). The width of the shear key is then reduced to 4¼ in. (108 mm) at the top of the beams. At the transverse post-tensioning locations, the shear key is 5¼ in. wide along most of the beam height (Fig. 7). The shear key is widened at the post-tensioning locations to allow access and provide space to

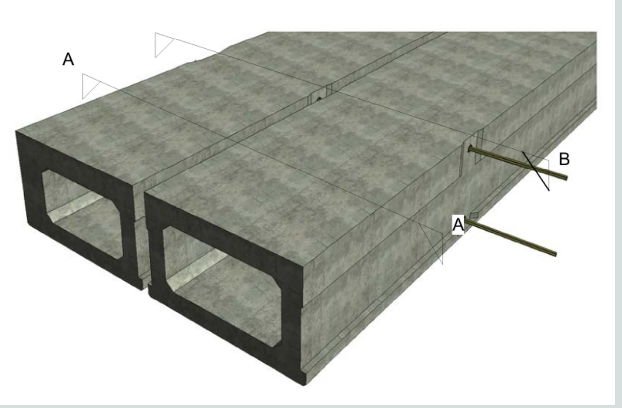

Figure 5. Three-dimensional model of the fascia and interior beams.

maneuver the tendons at the joint so that they can be threaded through all beams properly. Further, horizontal shear keys are created at the post-tensioning locations due to the wider joint compared with typical shear keys.

Longitudinal beam design

The longitudinal beam was designed using concrete bridge design and analysis software. The beam concrete strength was 8000 psi (55 MPa) at 28 days and 6000 psi (41 MPa) at prestressing force release. The interior beam includes 21 bottom strands in two rows (0.6 in. [15 mm] diameter, Grade 270 [1860 MPa], low-relaxation strands) and two top strands (**Fig. 8**). The fascia beam includes 22 bottom strands in three rows and two top strands (**Fig. 9**). The number and locations of the strands at the fascia beam differ slightly from the interior beam. The strand locations are arranged to avoid conflicts with the post-tensioning anchorages while satisfying the particular loads at the fascia beam. Also, the strand layout in the beams was determined so that the calculated differential cambers between the interior and fascia beams was no more than ⅛ in. (3 mm) at the time of beam erection.

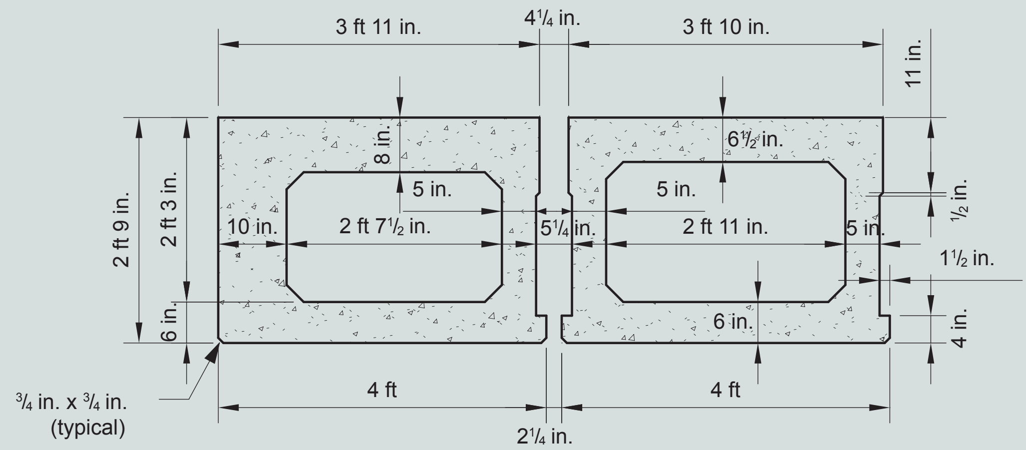

Figure 6. Sections of the fascia and interior beams away from the post-tensioning location. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

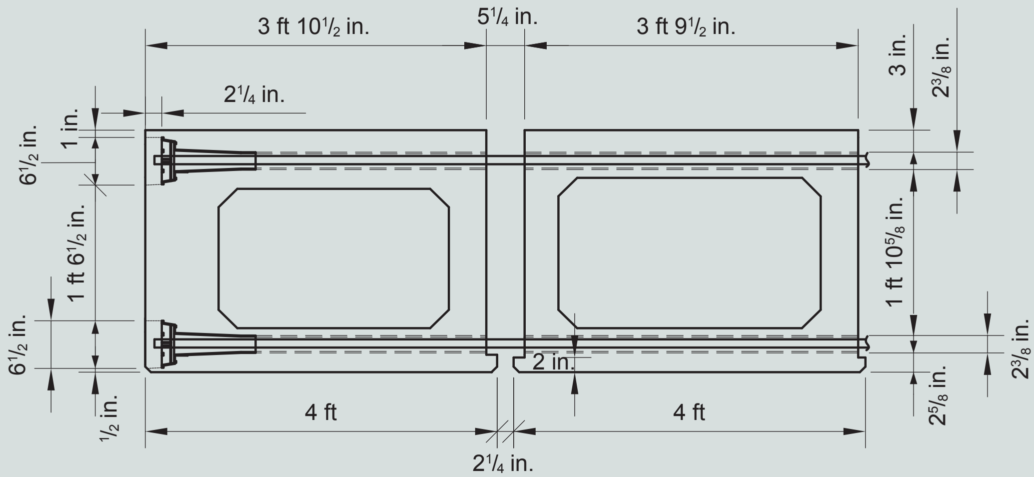

Figure 7. Shear key between the fascia and interior beams at the post-tensioning location. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

Transverse post-tensioning design

The *PCI Bridge Design Manual*[1] suggests the required transverse post-tensioning force developed by El-Remaily et al.[5] to achieve sufficient transverse stiffness and keep differential deflection within an acceptable limit. The *PCI Bridge Design Manual* provides charts showing the required transverse post-tensioning force accounting for beam dimensions, bridge span, width, and skew. These charts were developed based on a grid analysis considering the American Association of State Highway and Transportation Officials (AASHTO) HS-25 truck load. Hanna et al.[6] followed the same approach and updated the charts in the *PCI Bridge Design Manual*, accounting for the AASHTO HL-93 live loads. They further suggested the following equation to determine the required post-tensioning force:

$$P = \left(\frac{0.9W}{D} - 1.0\right) K_L K_S \le \left(\frac{0.2W}{D} + 8.0\right) K_L K_S \qquad (1)$$

where

P = required transverse post-tensioning force

W = bridge width

D = box beam depth

K_L = correction factor for span-to-depth ratio

$= 1.0 + 0.003\left(\frac{L}{D} - 30\right)$

K_S = correction factor for skew angle more than 0 degrees $= 1.0 + 0.002\theta$

L = bridge span

θ = skew angle

This equation was developed for an adjacent-box-beam bridge that includes intermediate diaphragms housing transverse

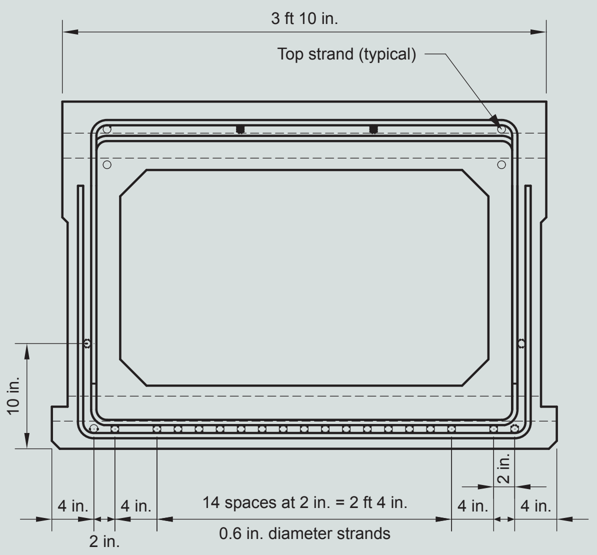

Figure 8. Strand pattern in the interior beam. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

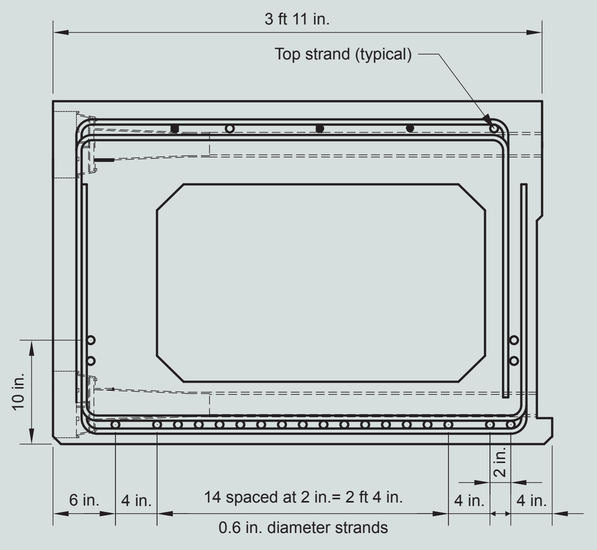

Figure 9. Strand pattern in the fascia beam. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

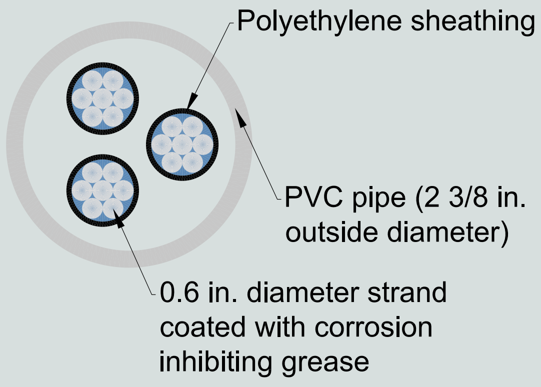

Figure 10. Unbonded post-tensioning monostrand tendon. Note: 1 in. = 25.4 mm.

post-tensioning. As a starting point, it was used to determine the required post-tensioning force for this bridge, which is 7.4 kip/ft (110 kN/m), or 120.4 kip (536 kN) for 16.2 ft (4.94 m) post-tensioning tendon spacing.

This required post-tensioning force was further verified through a finite element analysis model, where the box beams were modeled as plate elements. Beam elements were included at the transverse post-tensioning locations assuming that shear keys remain uncracked under service loads. The applied loads include HL-93 modified live load, the weight of concrete brush blocks for railings, and the railing weight. HL-93 modified live load consists of 1.2 times the combination of design truck or a single 60 kip (270 kN) load and design lane load. Because the bridge skew is less than 15 degrees and its effect on the required post-tensioning force is negligible, it is simply ignored in the analysis.[7] The required post-tensioning force as a result of the finite element analysis was slightly lower than the force as determined by Eq. (1). As a result, a total of six pairs of post-tensioning tendons were conservatively used in this bridge at a spacing of 16 ft 2⅜ in. (4.94 m). Each pair of tendons consists of one tendon at the beam top flange and one at the bottom flange. Each tendon has three 0.6 in. (15 mm) diameter, Grade 270 (1860 MPa) monostrands.

Unbonded post-tensioning system

The individual seven-wire strands were coated with corrosion-inhibiting grease and encased in polyethylene sheathing according to ASTM 416[8] (**Fig. 10**). Corrugated steel ducts, with a 2⅜ in. (60 mm) outside diameter, were originally specified in the contract drawings. To reduce the fabrication cost, the corrugated steel ducts were replaced with polyvinyl chloride (PVC) pipes, as requested by the precast producer. Also, PVC pipes are much stiffer than corrugated steel ducts, which avoids possible deformation along the ducts during concrete placement. The ends of the PVC pipes were firmly secured by attaching them to the steel forms. It was critical to place the PVC pipes accurately in the box beams to ensure appropriate installation of tendons at the bridge site. The fabrication tolerance of the PVC pipes was specified to be ¼ in. (6 mm) in the contract drawings. Before the installation, the ends of the pipes were required to be sealed to prevent entry of water and debris.

The strands were encased in greased polyethylene sheathing, which was then encased in the PVC pipe. This duct-in-duct system was used to connect the top and bottom flanges of the adjacent boxes. Not only was the post-tensioning placed where it was needed the most (the extreme fibers) but the webs were free of ducts. This allowed the elimination of the heavy intermediate diaphragms, thus reducing the precast concrete weight, concrete quantities, and final load on the bridge.

This bridge also eliminates the need for a cast-in-place concrete deck slab, in accordance with the bridge owner's standard practice for a low-volume local bridge. The proposed transverse post-tensioning system provides the additional warranty of eliminating of the cast-in-place concrete slab due to its unique features. Eliminating the need for cast-in-place concrete placement and curing results in accelerated bridge construction, as promoted by the Federal Highway Administration. The use of unbonded post-tensioning allows for the possible removal of the post-tensioning and widening of the bridge in the future.

Most important, the post-tensioning was not performed until the longitudinal joints were grouted. Thus, the joints are in permanent compression and the risk of water leakage at the joints is essentially eliminated (**Fig. 11**). The joints are wider than the standard box-beam joints, ensuring high-quality grouting. No grouting was required after the transverse post-tensioning, which further accelerated the bridge construction. It also allows for simpler future bridge widening.

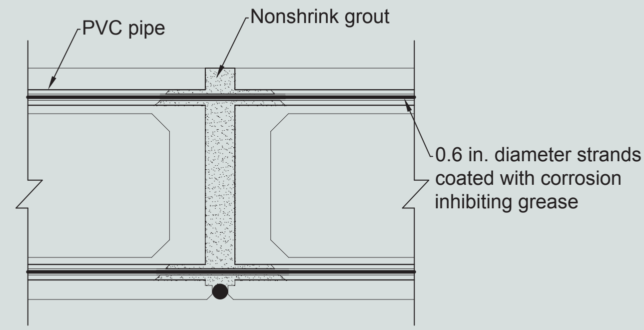

Figure 11. Grouting of shear key before post-tensioning. Note: 1 in. = 25.4 mm.

Beam production

Figure 12 shows the reinforcement setup in a box beam before concrete placement. Also shown are the PVC pipes that house the transverse post-tensioning tendons. **Figure 13** shows the shear key at the location of the transverse post-tensioning.

Figure 12. Reinforcement setup in a beam before concrete placement.

Bridge construction

The bridge construction sequence was as follows:

1. Installing the precast concrete box beams
2. Sealing the longitudinal joints between beams
3. Threading the transverse post-tensioning tendons
4. Grouting the longitudinal joints
5. Performing the transverse post-tensioning
6. Encapsulating the post-tensioning anchorages with high-strength nonshrink grout
7. Placing the concrete brush block for the bridge railing
8. Placing the bridge railings
9. Installing the waterproofing membrane and hot mix asphalt wearing surface

The most critical construction step was related to the transverse post-tensioning, particularly installation of the post-tensioning tendons. The post-tensioning tendons were threaded once one beam was installed in its position. As a result, the transverse post-tensioning procedure was performed smoothly. The bridge was opened to traffic in July 2014 (**Fig. 14**).

Figure 13. Shear key at the post-tensioning location. Courtesy of Horacio Lopez.

Conclusion

Precast concrete adjacent box beams were used on this bridge due to their relatively shallow structural depth and

Figure 14. Completed bridge.

to minimize the amount of formwork required to construct the superstructure. In particular, an innovative transverse post-tensioning system was successfully implemented. The innovations and accomplishments of this project are summarized as follows:

- The transverse post-tensioning strands were encased in greased polyethylene sheathing, which was in turn encased in a PVC tube. This unique duct-in-duct system was used to connect the top flanges as well as the bottom flanges of the box beams.

- The box-beam webs are free of post-tensioning ducts; therefore, intermediate diaphragms are eliminated, which reduces the precast concrete weight, concrete quantities, and final load on the bridge.

- Elimination of intermediate diaphragms made it possible to include a reusable steel void-forming system instead of stay-in-place expanded polystyrene, resulting in a possible improvement in production economy.

- This system facilitates bridge construction and future widening due to the use of unbonded post-tensioning tendons without the need for grouting the transverse post-tensioning ducts.

- This system accelerates bridge construction by eliminating the need to form and cast a concrete deck on top of the box beams.

- The transverse post-tensioning is not performed until after the longitudinal joints are grouted. Thus, the joints are in permanent compression and the risk of water leakage at the joints is essentially eliminated.

- The transverse post-tensioning system greatly enhances the ability to control differential twisting between adjacent boxes and eliminates reflective cracking above the longitudinal joints, resulting in a virtually maintenance-free structure.

- This simple-span bridge features an economical solution that results in a span-to-depth ratio of 31:1.

- This innovative system achieves improved durability by eliminating possible water leakage and reflective cracks at joints.

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Notation

D = box beam depth

K_L = correction factor for span-to-depth ratio

K_S = correction factor for skew angle more than 0 degrees

L = bridge span

P = required transverse post-tensioning force

W = bridge width

θ = skew angle

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Abstract

The St. Clair Road bridge over the Maple River in Clinton County, Mich., uses an innovative unbonded post-tensioning system in precast concrete adjacent box beams that eliminates the need for grouting post-tensioning ducts and for a cast-in-place concrete deck slab, resulting in accelerated bridge construction. The transverse unbonded post-tensioning tendons in both the top and bottom flanges of the beams eliminate the need for intermediate diaphragms. More important, this system enhances the overall structural performance by eliminating reflective cracks above the longitudinal joints because the joints are in permanent compression. As a result, it will likely reduce long-term costs by potentially reducing the frequency of repairs and maintenance.

Keywords

Adjacent-box-beam bridge, beam, bridge, crack, post-tensioning, reflective cracking, transverse post-tensioning, unbonded post-tensioning.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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