Concrete Segmental Bridges—Preliminary Determination of Post-Tensioning Layouts

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This article, which is the fourth in a series discussing preliminary design approximations for concrete segmental bridges, covers the determination of preliminary post-tensioning layouts. With a good preliminary layout, the changes in final design are usually minimal, leading to an efficient final design process.

The moments for dead loads of structural components, nonstructural attachments, the wearing surface, and utilities (DC and DW) and for live loads can be obtained by a simple finite element model with a limited number of nodes and elements, and no consideration of time-dependent effects. Approximations for moments from creep redistribution and temperature gradients can be determined as described in a previous article (see the Summer 2025 issue of *ASPIRE*®).

Longitudinal Post-Tensioning Layouts

For span-by-span bridges, the limiting compression stresses rarely govern the design, and the preliminary amount of post-tensioning can be based on the limiting tension stresses for positive moments at the critical sections near midspan (or the 0.4 times the span length *L* point for end spans). For balanced-cantilever bridges, compression stresses in the bottom slab near the piers must be limited. Setting the bottom-slab thicknesses to control the compression stresses, as well as determining the amount of cantilever post-tensioning, was discussed in the Winter 2025 issue of *ASPIRE*. This article focuses on the method for determining the amount of post-tensioning for span-by-span bridges and the amount of continuity post-tensioning for balanced-cantilever bridges. The process for determining the amount of preliminary continuity post-tensioning for balanced-cantilever bridges is similar to that for span-by-span bridges in that it can be based on the limiting tendon stresses for positive moments at the critical sections near midspan (or the 0.4*L* point for end spans).

The limiting tensile stresses for the longitudinal design of post-tensioned bridges are based on the Service III limit state in the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[1] For concrete segmental bridges and most other post-tensioned bridges, the load factor for live load for the Service III limit state is 0.80. Article 3.4.1 describes load combinations for segmental bridges. Moments are combined to determine the governing design moment as follows:

$$M_{Design} = M_{DC} + M_{DW} + M_{CR} + M_{SH} + 0.80M_{LL} + 0.50M_{TG}$$

(typically governs at critical sections)

or

$$M_{Design} = M_{DC} + M_{DW} + M_{CR} + M_{SH} + M_{TG}$$

where

M_{Design} = design moment for flexural tension
M_{DC} = moment from structural components and attachments
M_{DW} = moment from wearing surface and utilities
M_{CR} = moment from creep (redistribution)
M_{SH} = moment from shrinkage (typically small, except for near the piers for monolithic substructure connections)
M_{LL} = moment from live loads
M_{TG} = moment from temperature gradients (for preliminary design, an equivalent linear gradient can be used, as discussed in the Summer 2025 issue of *ASPIRE*.)

Using the design moments, the governing tension stresses for design σ_{Design} can be calculated using classical beam theory.

As discussed in the Summer 2025 issue of *ASPIRE*, the concept of tendon efficiency can be used to estimate the amount of post-tensioning required. For example, for a tendon where the amount of secondary moment is 25% of the primary moment, the tendon is 75% efficient and the total stresses due to post-tensioning can be calculated from the full axial force and 75% of the primary moment. A preliminary estimate for the amount of post-tensioning can be determined as follows.

First, calculate the compression stresses for one strand for each tendon type being used:

$$\sigma_{PT} = \frac{P_{PT}}{A} + \frac{\alpha\left(P_{PT}ec\right)}{I}$$

where

σ_{PT} = compressive stress from post-tensioning at governing location
P_{PT} = post-tensioning axial force at governing section
A = cross-sectional area at governing section
α = tendon efficiency as described previously
e = tendon eccentricity from neutral axis of the cross section
c = distance from neutral axis to extreme fiber at governing section
I = cross-sectional moment of inertia

Second, select the number of strands n of each tendon type to keep the tension within the stress limits specified by the AASHTO LRFD specifications:

$$\sigma_{Design} + \sigma_{PTi} \times n_i + \sigma_{PTj} \times n_j \leq \sigma_{LIMIT} \quad (1)$$

(Note that compression is negative and tension is positive.)

where

σ_{PTi}, σ_{PTj} = compressive stress from tendon types *i* and *j*

n_i, n_j = number of strands for from tendon types *i* and *j*

σ_{LIMIT} = tensile stress limit from Article 5.9.2.3.2 of the AASHTO LRFD specifications

Note that Eq. (1) shows consideration of two tendon types but may be expanded to consider additional tendon types.

Span-by-Span Layout

For typical span-by-span bridges with only draped tendons anchoring in the pier and end diaphragms, there is typically only one tendon type (draped external) and estimating the number of strands reduces to Eq. (2).

$$n = \frac{-\left(\sigma_{Design} - \sigma_{LIMIT}\right)}{\sigma_{PT}} \qquad (2)$$

The next step is to determine the size and number of tendons to supply the number of strands required. This step involves making sure that the pier and end diaphragms can accommodate the selected number of tendons. **Figure 1** shows a post-tensioning layout for span-by-span construction. Note that temporary external post-tensioning bars located inside the box are needed to facilitate the erection of the precast concrete segments. During the erection sequence, an epoxy adhesive is applied to the joint as each segment is erected and then a clamping force is applied to the joint (epoxy-squeeze technique). The temporary bars are removed after the permanent post-tensioning in each span has been tensioned.

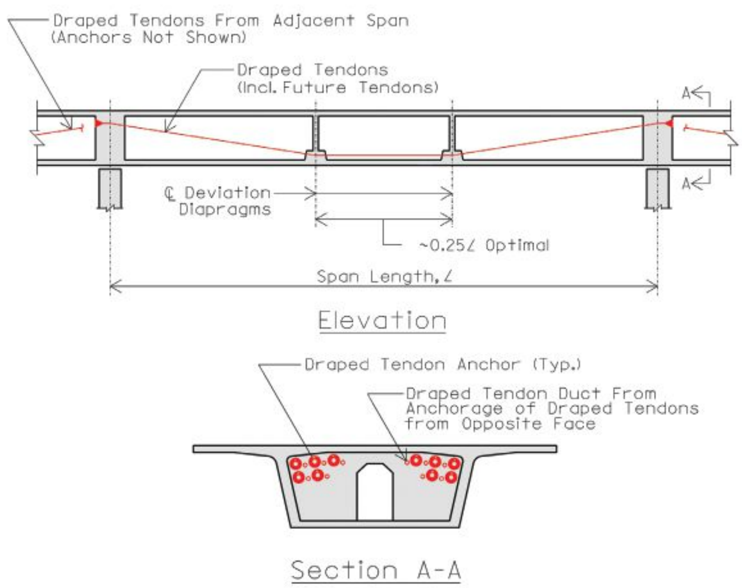

Figure 1. Typical post-tensioning layout for span-by-span construction. All Figures: R. Kent Montgomery.

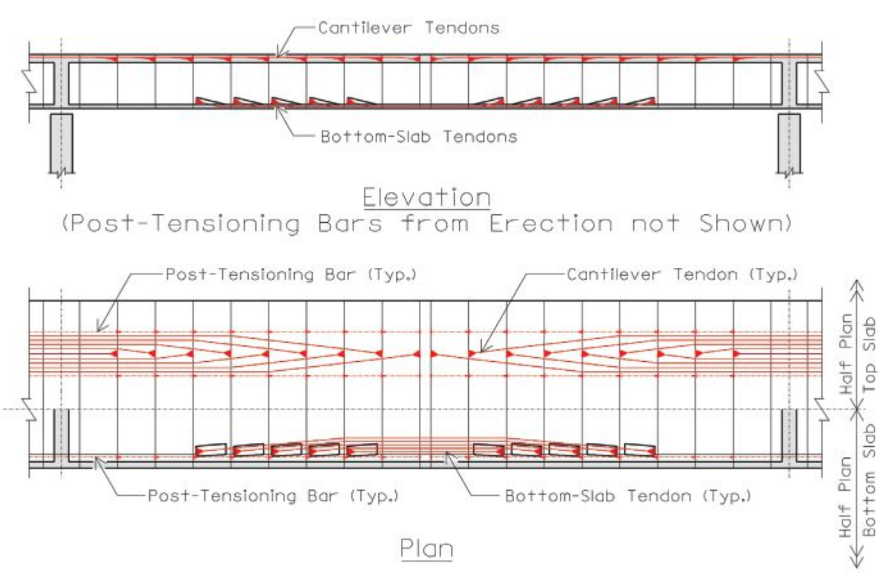

Figure 2. Typical post-tensioning layout for a constant-depth, balanced-cantilever bridge.

Balanced-Cantilever Layout

For balanced-cantilever bridges, in addition to the cantilever tendons, the design can use a single tendon type (for example, bottom slab internal), or there can be two tendon types (bottom slab and draped external), each supplying a different amount of compression per strand. For those bridges using a single tendon type, the number of strands can be estimated using the same equation used for span-by-span bridges (Eq. [2]). For bridges using two tendon types, the number of strands selected for each tendon type needs to satisfy the general equation (Eq. [1]).

For constant-depth bridges, draped- and bottom-slab tendons have approximately the same efficiency. Draped tendons can be used, and they have the benefit of reducing web shear. Using draped tendons also reduces the number of bottom-slab tendons required, and their maximum extents are typically 40% to 50% of the span length and centered on midspan for internal spans. However, many constant-depth, balanced-cantilever bridges exclusively use bottom-slab tendons. When only bottom-slab tendons are used, more tendons are required. The maximum extent for these bottom-slab tendons is typically 65% to 75% of the span length, and the tendons are centered on midspan for internal spans. For end spans, at least some bottom-slab tendons anchor in the end diaphragm and the maximum extent of the tendons is approximately 60% to 65% of the span length from the end of the unit. It is important to ensure that the precise placement of the continuity tendons adequately controls stresses and provides the required strength for the design moment diagrams, including creep redistribution, live load, and the kinematic moment from temperature gradients.

Figures 2 and **3** present a post-tensioning layout for a constant-depth, balanced-cantilever bridge. This layout is for

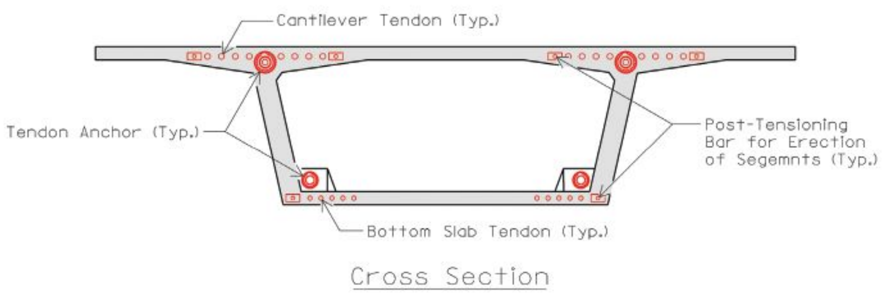

Figure 3. Typical cross section of post-tensioning layout for a constant-depth, balanced-cantilever bridge.

precast concrete segments and bottom-slab continuity tendons only; no draped tendons are used. The following items about this layout are noteworthy:

- There are post-tensioning bars that anchor at every typical segment joint for the epoxy-squeeze technique applied after each segment is erected. Subsequent lengths of the bars are coupled near the segment joints. This layout shows internal bars that become permanent parts of the bridge. It is also possible to use temporary bars that are removed after erection of the cantilever.
- Cantilever tendons anchor at each typical segment joint and are tensioned after the erection of a pair of segments (one on each end of the cantilevers). This arrangement provides the total number of required tendons over the pier. The number of tendons decreases gradually away from the pier, roughly matching the negative moment diagram.
- Bottom-slab tendons anchor in typical segments to provide the number of required tendons at midspan. The number of tendons decreases gradually away from midspan, roughly matching the positive moment diagram.

For variable-depth bridges, draped tendons are typically more efficient than bottom-slab tendons. Therefore, it makes sense to use the maximum number of draped strands that can reasonably be anchored in the pier and end diaphragms. Note that the radius of the intrados curve results in radial forces acting downward on the bottom slab. These forces result in bottom-slab bending and tendon pullout effects. These forces and their effects become larger as the radius of the curve decreases away from midspan. Therefore, it makes sense to limit the extent of bottom-slab tendons to approximately 50% of the span length centered on midspan for internal spans, assuming draped tendons are also present. (Also, as discussed in the Summer 2025 issue of *ASPIRE*, bottom-slab tendons become less efficient as they get longer.) If draped tendons are not being used, the extent of bottom-slab tendons should be increased to 60% to 65% of the span length; however, designing for the tendon radial forces becomes more challenging. **Figures 4** and **5** show a variable-depth, balanced-cantilever post-tensioning layout. This layout is for cast-in-place (CIP) segments with bottom-slab and draped continuity tendons. The following are items to note about this layout:

- For CIP balanced-cantilever construction, segments are typically cast in an alternating fashion, one segment at a time. Cantilever tendons are tensioned after the casting of each segment. To accommodate this sequence, a staggered layout is used, with two anchors at each web per segment. The layout provides for the total number of required tendons over the pier. The number of tendons decreases gradually away from the pier, roughly matching the negative moment diagram. An epoxy adhesive is not applied at the joints for CIP construction; therefore, post-tensioning bars are typically not used.
- The bottom-slab tendon layout is similar to that for a precast concrete bridge. Given the length of typical CIP segments, two tendons per web typically anchor in each segment. When developing this type of layout, consideration must be given to allow access for tensioning jacks between the anchor blocks and the deviation diaphragm.
- The draped tendon layout for balanced-cantilever construction is similar to that for span-by-span bridges.

Experience has shown that it is better to anchor a minimum number of bottom-slab tendons at any longitudinal location to avoid excessive general-zone effects. Therefore, it is common to locate a single anchor block next to each web (two blocks per cell) at any longitudinal location. Longitudinally, the blocks are typically spaced every 8 to 10 ft (depending on segment lengths), resulting in many longitudinal anchor locations spread along the span, as can be seen in Fig. 2 and 4.

Transverse Post-Tensioning

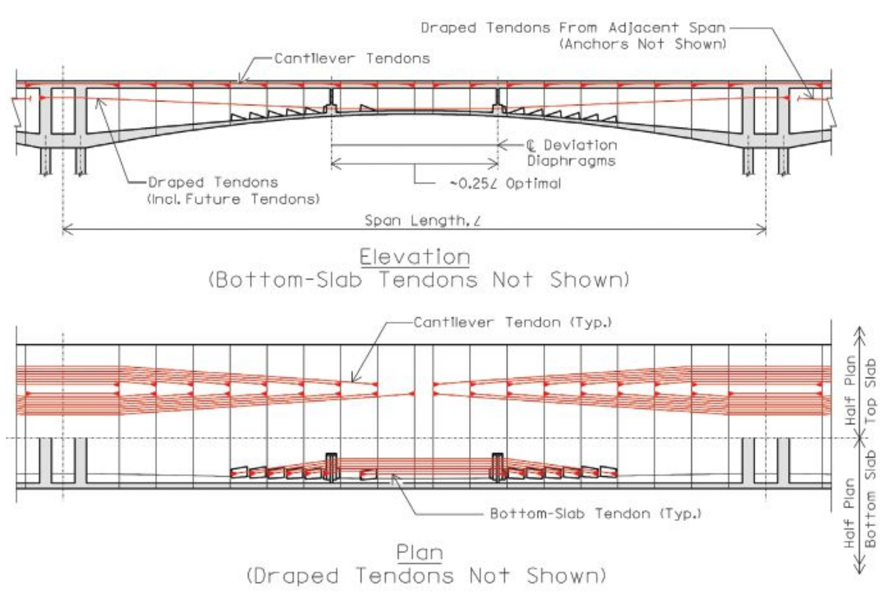

Figure 4. Typical post-tensioning layout for a variable-depth, balanced-cantilever bridge.

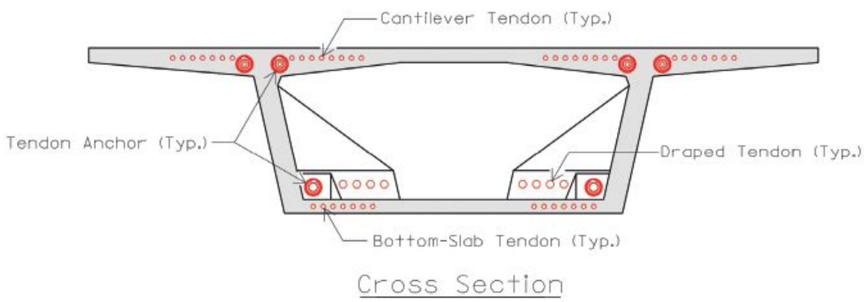

Figure 5. Typical cross section of post-tensioning layout for a variable-depth, balanced-cantilever bridge.

Layouts

To determine the preliminary amount of transverse post-tensioning, simple cantilever wing calculations can be used. Because the cantilever wing is statically determinate, the moment demand at the root of the cantilever wing can be calculated with simple hand calculations and the use of Homberg charts for live loads.[2] As noted in the Spring 2025 issue of *ASPIRE*, a cantilever wing length of approximately 42% of the interior transverse span is optimal for balancing transverse demands. Therefore, for wing lengths equal to or greater than 42% of the interior span, using the cantilever wing for preliminary calculations will produce a good estimate. For cross sections with cantilever wing lengths less than 42% of the interior span, a theoretical cantilever wing that is 42% of the internal span can be constructed using similar thicknesses as the actual wing. Simple cantilever calculations using the notional wing typically produce a good estimate for the amount of required transverse post-tensioning.

Controlling tensile stresses at the service limit state usually governs the transverse design. For transverse design, the AASHTO LRFD specifications specify the Service I limit state, which has a load factor of 1.0 for live load, for checking both tension and compression stresses. Typically, temperature gradients are not considered for transverse design of concrete box girders. (However, some owners specify a small linear gradient.) Therefore, the design moment for transverse design is as follows:

$$M_{Design} = M_{DC} + M_{DW} + M_{CR} + M_{SH} + M_{LL}$$

Note that M_{CR} and M_{SH} are zero for the cantilever wing.

Using the design moments, the governing tension stresses for design σ_{Design} can be calculated by applying classical beam theory. The moments are usually tabulated for a unit strip, and the stresses are calculated based on section properties for a unit strip. Because there are no secondary moments in the statically determinate cantilever wing, the stresses from post-tensioning can be calculated using the full axial force, the primary moment, and the section properties for a unit strip. This is usually done for a single strand, and the amount of post-tensioning can be calculated as

$$n = \frac{-\left(\sigma_{Design} - \sigma_{LIMIT}\right)}{\sigma_{PT}}$$

This equation provides the required amount of post-tensioning in terms of the number of strands per foot longitudinally. The result can easily be converted to the number of tendons required per foot.

Four-strand tendons in flat ducts are typically used for transverse tendons. The flat ducts allow for the maximum eccentricity for all strands in the tendon. The profile for a transverse tendon typically runs as high as possible over the webs, and the clear cover and the reinforcing steel mat above the tendon need to be considered. Usually, the longitudinal reinforcing bars are the top bar in the mat, and the transverse bars are the bottom bar in the mat. This arrangement allows the transverse tendon duct to fit between the transverse bars and be higher than if the opposite reinforcing bar arrangement were used. The profile also runs low across the interior transverse spans, although it is often not as low as possible. At the haunch points, the positive and negative live-load moments are both significant, although smaller than over the webs and at midspan. Therefore, the transverse tendons typically do not run high or low; rather, they run near the center of the top slab. **Figure 6** presents a profile for a transverse tendon.

For concrete segmental bridges, an integral number of tendons must be placed in each segment. This requirement can result in more post-tensioning than required being supplied. A small additional amount above that required usually is not an important issue. For some designs where the additional amount is larger, four-strand and three-strand tendons can be alternated.

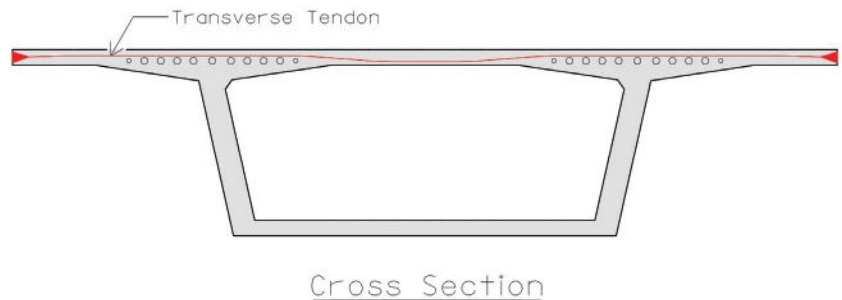

Figure 6. Typical cross section showing the transverse tendon profile.

Summary

This article presents a methodology for a quick and simple means of developing post-tensioning layouts. The layouts can be advanced into final design for a complete check of stresses at all joints (or span tenth points if the structure is not a segmental bridge), as well as strength verification. Experience with this methodology has shown that it produces good quality, preliminary post-tensioning layouts that need only minimal changes for the final design.

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2024. *AASHTO LRFD Bridge Design Specifications*. 10th ed. Washington, DC: AASHTO.
2. Homberg, Hellmut. 1968. *Fahrbahnplatten mit veränderlicher Dicke*. Berlin, Germany: Springer-Verlag.