Structural Design Based on Strut-and-Tie Modeling

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Structural design and detailing of reinforced and prestressed concrete members and structures requires a thorough understanding of load transfer mechanisms. Since its introduction in the late 19th and early 20th centuries,[1,2] strut-and-tie modeling (STM) has enabled structural designers to appropriately visualize the transfer of loads from their points of application down to structural foundations. This explicit visualization then helps guide the associated structural detailing based on key load transfer mechanisms. In the United States, the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* has included STM design provisions since 1994. To illustrate the power of STM, this article discusses an integral superstructure and substructure connection and how STM provides insights on load transfer.

Options for Modeling Load Transfer

Figure 1 shows three lines of prestressed concrete U-beams rigidly connected to an integral straddle bent. For the sake of simplicity, let us assume symmetrical loading in forward and back spans that frame into the straddle cap and all loads are vertical. Live and dead loadings on the deck result in substantial beam reactions that need to be transferred to the cap and through the cap to the columns. Where beam lines 1, 2, and 3 frame into the straddle cap, the loads (U-beam reactions) need to be transferred to the cap in a realistic manner. To envision this transfer of vertical loads to the cap at beam line 2, the designer has three options:

Option 1: Apply beam reaction at nodes A and B

Option 2: Apply beam reaction at nodes C and D

Option 3: Apply beam reaction at nodes A, B, C, and D

It must be emphasized that the detailing of the end of the U-beam must be consistent with the assumed transfer of loads into the cap, as noted in the following discussion.

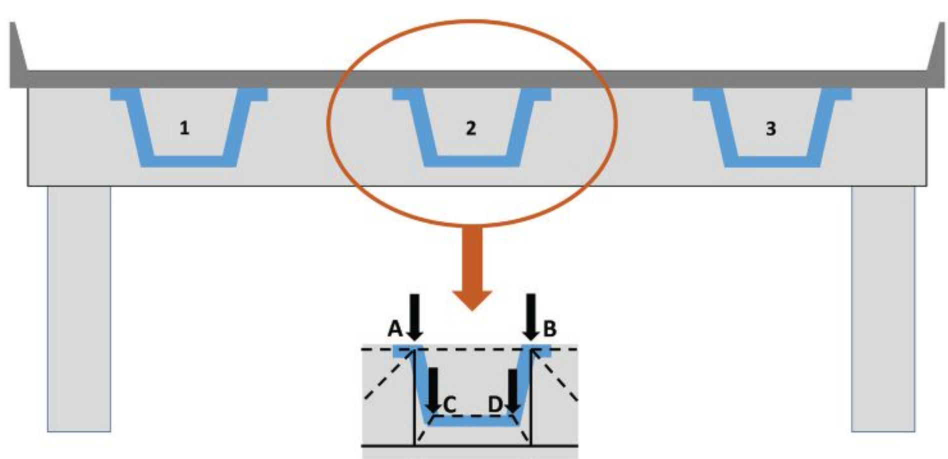
Option 1—Reaction Applied at Nodes A and B

The reaction for beam 2 is divided in half and applied at nodes A and B. Because no loads are being applied at nodes C and D, the demand for the hanger reinforcement (ties AE and BF) is zero. This load transfer mechanism calls for the U-beam design and detailing to be consistent with the assumed load application to the straddle cap. Therefore, a substantial quantity of hanger reinforcement must be provided within the prestressed concrete U-beam at or within the immediate vicinity of its connection to the straddle cap. Picking up the entire reaction with stirrups placed within the U-beam webs at the face of the cap presents a substantial challenge for detailing because the hanger reinforcement provided must be centered on the vertical tie envisioned within the end region of the U-beam. Structural detailing of the U-beam-to-straddle-cap connection must accommodate the assumed load transfer mechanism, which is hard to accomplish with standard details that involve anchorage of U-beam reinforcement into the straddle cap and continuity post-tensioning passing through the cap, in addition to providing a substantial amount of hanger reinforcement within the U-beams. The required detailing renders this option impractical in most situations, and the effectiveness of such a load transfer mechanism is questionable.

Option 2—Reaction Applied at Nodes C and D

For this option, the reaction for beam 2 is again divided in half but is applied at nodes C and D. This concept for load application assumes that the inclined webs of beam 2 are supported directly beneath the bottom flange; therefore, the support reaction introduces compression into the webs of the U-beam. This assumption is overly conservative in most common structural connection details. Hanger reinforcement sufficient to transfer 100% of the beam reaction must be provided within the cap where the superstructure meets

Figure 1. Strut-and-tie modeling (STM) for integral superstructure-to-substructure connection for U-beams framing into a straddle cap. Figure: Dr. Oguzhan Bayrak.



the substructure. Furthermore, the reinforcement needs to be centered on ties AE and BF. To resist the two forces from the beam reaction (notably, in this case, the beam reaction is presumed to be significant), a substantial quantity of hanger reinforcement must be provided in the cap where the bottoms of the slanted webs of the U-beam intersect the straddle cap. Although this assumption is conservative, it may result in an excessive amount of hanger reinforcement in the cap; detailing of this reinforcement may present constructability challenges.

Option 3—Reaction Applied at Nodes A, B, C, and D

For this option, the reaction for beam 2 is divided into four equal vertical loads and applied at nodes A, B, C, and D. With this assumed load application, 25% of the beam reaction would transfer to each of the diagonal compression struts framing into nodes A and B, with the remaining vertical load going into struts CE and DF. A compression strut is also required between C and D. The vertical components of the forces in struts CE and DF need to be picked up by ties AE and BF. Option 3 results in a more practical quantity of hanger reinforcement that is easier to detail and construct than either of the other options with half the force in the tie reinforcement in the U-beam as for Option 1. It is also worth noting that the compressive forces in struts CE and DF influence the tie-force distribution along the length of the longitudinal tie at the bottom of the cap. With respect to U-beam design, one-fourth of the total beam reaction must be carried by the stirrups within each web of the U-beam, such that load application at the top nodes A and B can be justified. As required in the AASHTO LRFD specifications, the sectional shear design of the U-beams must be done using provisions based on simplified Modified Compression Field Theory (MCFT) (AASHTO LRFD specifications article 5.7.3).[3] The quantity of stirrups required in the U-beam, on the basis of MCFT design, is typically sufficient to satisfy the application of one-half of the beam's reaction to the top nodes (A and B). Furthermore, the skin reinforcing bar detailing of the webs and extension of those bars into the cap, along with the roughened surfaces of the webs of the precast concrete U-beam, all help justify dividing the beam reaction among the four nodes. In my view, and in most structural details I have seen to date, this balanced approach constitutes a good structural engineering solution.

Once the load transfer model for the U-beam-to-straddle-cap connection is selected for beam 2, this model can be repeated for the other U-beam-to-straddle-cap connections. The complete truss visualized in the straddle cap can then be used to transfer the loads into the columns and subsequently into the foundations.

Conclusion

The superstructure-to-substructure connection discussed in this article illustrates the decision-making process in STM. As can be observed in the example, STM drives a designer to consider the implications of model selection, construction methods, and details. In structural engineering, we do not get something for nothing. We must reconcile how loads are transferred from their points of application into the concrete component, then from one element to the next, and eventually to the foundations. In my view, the fact that STM stimulates structural designers to think through the load path is the most important attribute of this technique. As we aspire to design concrete bridges to last no less than a century, STM plays a role in the design of unique structures, critical bridge components, and the bridge infrastructure that will serve our communities.

References

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2. Mörsch, E. 1902. *Der Eisenbetonbau, seine Theorie und Anwendung* (Reinforced Concrete: Theory and Application). Stuttgart, Germany: K. Witter.
3. American Association of State Highway and Transportation Officials (AASHTO). 2017. *AASHTO LRFD Bridge Design Specifications*, 8th ed. Washington, DC: AASHTO.