A PROFESSOR'S PERSPECTIVE

SIMPLICITY AND TRANSPARENCY IN STRUCTURAL DESIGN

Strut-and-tie method

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The 2016 Interim Revisions to the 7th edition of American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* place a greater emphasis on delineating disturbed regions (D-regions) of reinforced concrete members from the beam regions (B-regions). Whereas the use of legacy design methods is appropriate in B-regions, the AASHTO LRFD specifications recommend the use of the strut-and-tie method (STM) in D-regions as an alternative with a strong physical basis to the more prescriptive or empirical legacy methods.

To the extent it relates to STM, and in an effort to emphasize the importance of simplicity and transparency in structural design, in this article I will focus on the structural design of reinforced concrete beams. In broad terms, the design of reinforced concrete beams can be accomplished either by following the rules of legacy design methods or by using STM. Legacy design methods, such as sectional design methods, have long been used in designing reinforced concrete beams.

In such designs, axial load, shear force and bending moment diagrams are drawn first. Following the development of these diagrams, critical sections along the length of a beam are identified. By using the forces present at critical sections, those sections are designed to have sufficient axial, flexural and shear strength to meet the appropriate code requirements. In addition, all postulated failure modes have to be considered and the member has to be detailed so as to preclude all failure modes such as reinforcing bar anchorage failure and bearing failure.

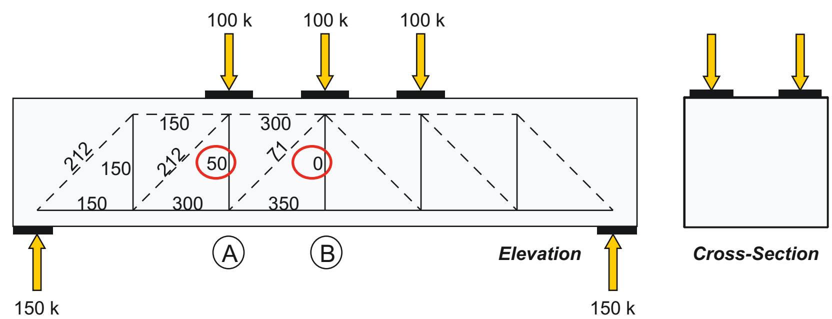

Figure 1. Longitudinal strut-and-tie model of a rectangular beam with compression chord loading. All Figures: Oguzhan Bayrak.

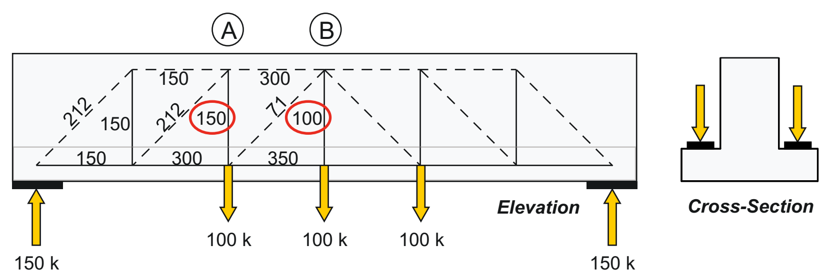

Figure 2. Longitudinal strut-and-tie model of a inverted-tee beam with tension chord loading.

Alternatively, and especially in D-regions, a designer may use STM in designing and detailing a reinforced concrete member. The use of STM allows a designer to simplify internal stress paths by using a simple truss model. In this way, a designer can proportion the longitudinal and transverse reinforcement and ensure that the specified compressive strength of concrete is sufficient and that reinforcing bar anchorage requirements are met.

To illustrate the simplicity and transparency of STM, let us use the design of an inverted-tee beam as an example. For brevity, I will focus on hanger reinforcement design rather than all aspects of the structural design of an inverted tee. Figure 1 includes an STM model for a rectangular beam that is loaded on its compression chord, and Figure 2 is an STM model for a ledge-loaded inverted-tee beam.

Since both beams are of equal length and the design loads act at the same locations along the beam length, both beams have identical bending moment and shear force diagrams. The flexural and shear designs resulting from these diagrams would be identical, except for the fact that if legacy design methods are used in design, a separate check for the hanger reinforcement becomes necessary and additional web reinforcement must be provided in the vicinity of loads applied at the beam ledges.

The use of STM makes this process much more transparent. The vertical tie forces at sections A and B are significantly higher in a truss loaded at its tension chord (Fig. 1 and 2). The 100-kip additional vertical tie forces at sections A and B clearly show that the loads applied at the tension chord have to be transferred up to the compression chord of the beam before they are transferred into the supports. Therefore, using STM, an additional step for the design of hanger reinforcement is not necessary.

Perhaps more importantly, the truss models shown in both figures clearly demonstrate the identical nature of the demand on flexural tension reinforcement and diagonal struts, for both loading scenarios. The transparency of the load-transfer mechanism evident in the truss models render STM to be a powerful design technique.

Historically, D-regions have been designed with empirical methods that require the use of a long list of design checks. The hanger reinforcement design in an inverted-tee beam, as discussed previously, is one such example. Additional checks to complete an inverted-tee design, by using legacy design methods, include ledge punching check, shear-friction check, and bearing stress check, and others as articulated in the beam ledge design provisions of the AASHTO LRFD specifications. As recognized by the specifications, if an inverted-tee beam is designed by using STM, additional checks are not necessary. The use of a cross-sectional truss model, as shown in Fig. 3, in addition to the longitudinal truss model shown in Fig. 2, is sufficient.

In conclusion, the greater level of transparency and the reduced level of empiricism offered by STM render this technique an excellent alternative in structural design. A designer who can visualize the load paths between the loads and the supports is less likely to skip a design step and more likely to develop a greater level of confidence in his/her design. In my view, as we move towards further improving our design codes, reducing empiricism and increasing transparency should be taken as important objectives. The recent improvements made to the STM provisions of AASHTO LRFD specifications are aimed at accomplishing these goals. In my upcoming articles, I will explain how these important goals are accomplished in the improved STM provisions of our bridge design specifications.

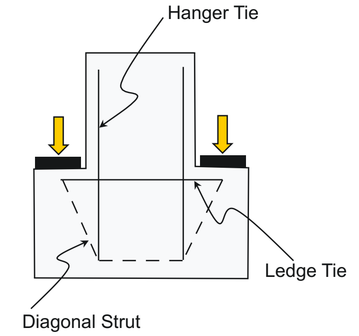

Figure 3. Cross-sectional strut-and-tie model for inverted-tee beam.