Strut-and-Tie Modeling for Bridge Design

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This article, which follows up on a Spring 2020 *ASPIRE*® article on the use of strut-and-tie modeling (STM) for existing pier assessments, provides further thoughts on the use of STM for bridge design. Beginning with interim revisions to the seventh edition of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* and continuing to the current ninth edition,[1] there has been a heightened need to understand and apply STM principles to the design of concrete structures. Article 5.1 of the AASHTO LRFD specifications states,

> The provisions of this Section characterize regions of concrete structures by their behavior as B- (beam or Bernoulli) Regions or D- (disturbed or discontinuity) Regions, as defined in Article 5.2. The characterization of regions into B-Regions and D-Regions is discussed in Article 5.5.1.

Whereas Article 5.2 provides a definition, Article 5.5.1.2.1 provides a clear picture of what constitutes a D-region:

> D-Regions shall be taken to encompass locations with abrupt changes in geometry or concentrated forces. Based upon St. Venant's principle, D-Regions may be assumed to span one member depth on either side of the discontinuity in geometry or force.

The simply supported beam shown in **Fig. 1** illustrates this concept. On either side of each concentrated load or geometric discontinuity, a D-region exists. Considering a typical pier cap or footing, which is loaded primarily by point loads and includes cap-to-column and footing-to-column joints, nearly the entire pier cap and footing, including connections to the columns, will be classified as a D-region. This is illustrated for a typical pier in **Fig. 2**.

For this pier, extending out a distance equal to the depth of the pier cap *D* from each beam line results in the entire cap being defined as a D-region. Similarly, extending from the cap downward and from the footing upward by a distance *W*, the regions at each end of the columns are also defined as D-regions. For the footing, every line of piles is like a beam reaction and the entire footing becomes a D-region as well.

The characterization of this pier as containing primarily D-regions represents a change in approach for most engineers. The design process for bridge piers has nearly always involved a frame analysis considering vertical and lateral loads, the creation of shear and moment envelopes for various load combinations, and the design of elements using conventional methods. Because STM procedures require the creation of a truss or truss-like model, and each load case might require a unique truss, adoption of the new AASHTO requirements has been slow and inconsistent. In several recent projects, our team has employed STM approaches for the design of single- and multicolumn piers, and some of our approaches are highlighted in this article.

For the single-column pier shown in **Fig. 3**, design of the cap is the focus. The cap design is driven by the selection of the angle between the top tension tie and the compression strut. Selection of the column nodal locations is somewhat arbitrary, but it is always prudent to use a model with a direct and logical flow of forces. Simple trigonometry provides the force in the top tension tie and the compression strut as a multiple of the exterior beam reaction. The intent of this model is to determine the magnitude of the tie force and thus the quantity of tension steel needed for the design. The transverse steel must simply meet the minimum reinforcement requirements of AASHTO LRFD Article 5.8.2.6, Crack Control Reinforcement. Sketches showing the relationship between the transverse stirrups and longitudinal cap side-face reinforcement to the distribution reinforcement required by AASHTO are shown as an inset in Fig. 3, which has been adapted from the AASHTO LRFD specifications.[1] A preliminary estimate of the cap depth can be obtained by solving AASHTO LRFD specifications Eq. (C5.8.2.2-1) for the cap depth *d*.

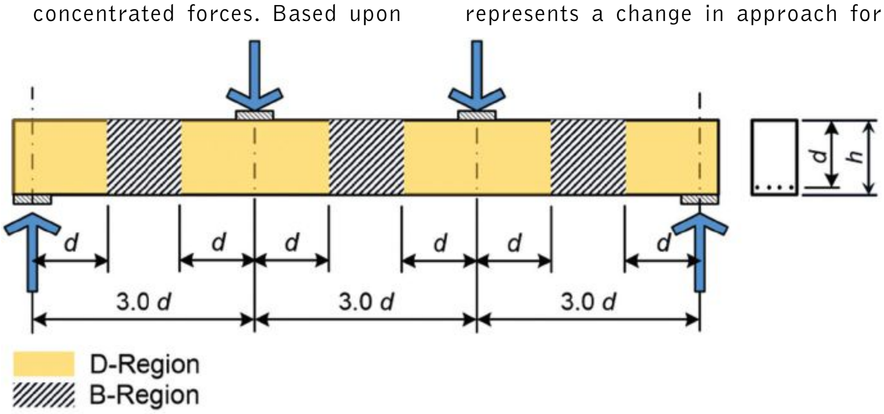

Figure 1. Definition of D-regions for a simply supported beam. Figure: Michael Baker International.

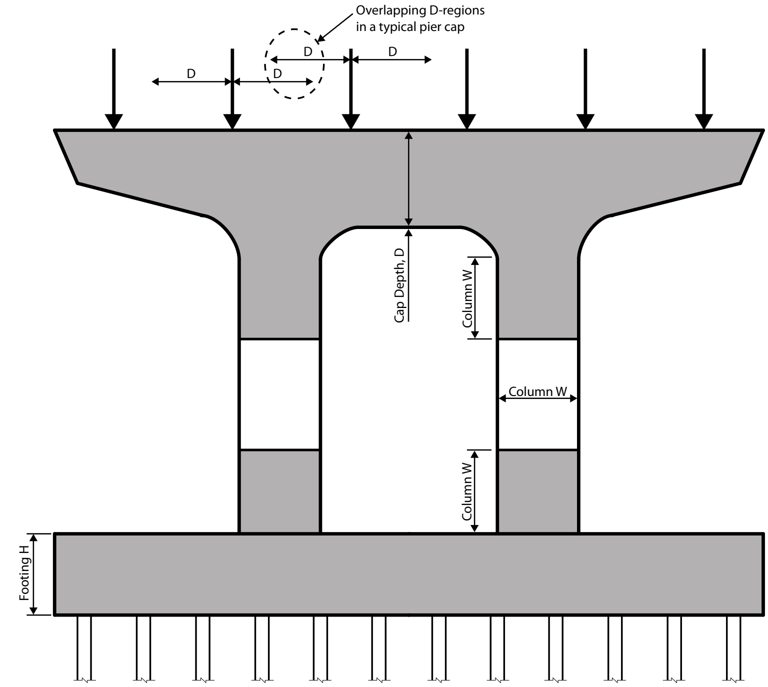

Figure 2. Definition of D-regions (shaded areas) for a pier cap in a typical framed pier. Figure: Michael Baker International.

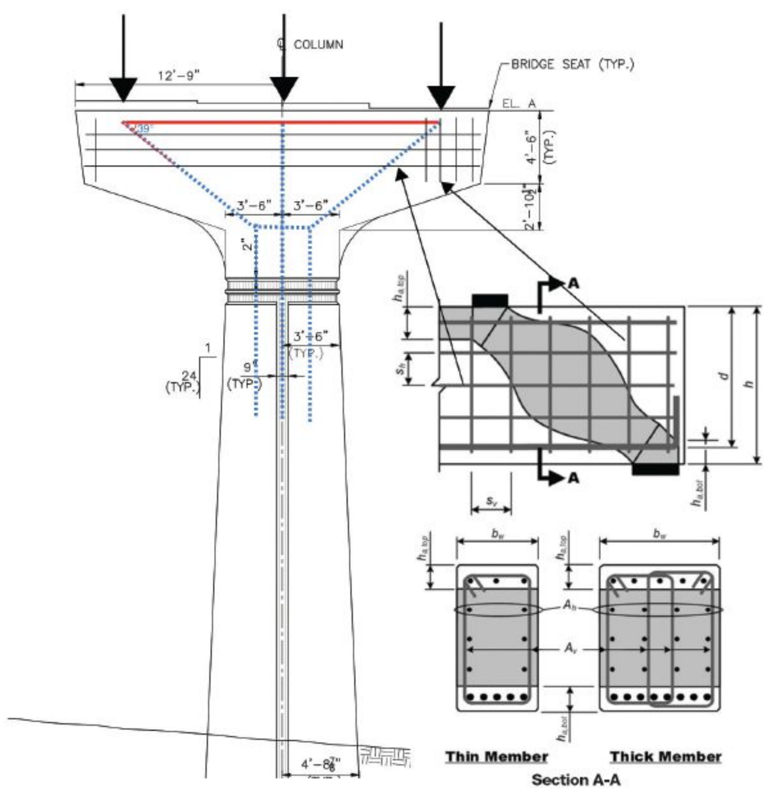

Figure 3. Strut-and-tie model for a hammerhead pier cap with inset illustrating the generalized concept of the strut and reinforcement details. Figure: Michael Baker International.

In the case of unbalanced beam reactions, which is common for pier caps, a variation of this model would also include a moment connection between the column and cap. Although this nuance would have no bearing on the top tie forces, it is a complication worth exploring. Transferring moment between the cap and column, or between the column and footing, can be a challenge. For additional guidance on this subject, the reader is referred to a complete design example (specifically, design example 3) in the manual for an STM course offered by the National Highway Institute.[2] In that example, a frame is analyzed for a critical load combination using traditional two-dimensional frame analysis tools. At *d* below the cap (that is, the transition between the B- and D-regions), a free body section is cut and an STM model of the cap and a portion of the columns is developed and solved (**Fig. 4**). The column axial load and bending moment at *d* below the cap have been resolved into tension and compression forces, and the shear in the column is shown as a horizontal reaction. The complete STM solution can be used for what would have typically been the shear and moment design of the cap, design of the top of the column, and any special considerations for joint design.

In efforts to automate the analysis of pier caps using the STM method, various approaches have been explored to couple the traditional frame model used for global pier analysis and the STM needed for the design of the cap as well as the cap-to-column joints.

Figure 5 presents an example of an STM model for a three-column pier cap. An approach has been developed and refined in which various load cases can be applied in a model where the web diagonals are assigned compression-only capability, shown in the top part of Fig. 5. As various loads are placed on the cap, the analysis software adjusts the model in an iterative way to only allow compression in the diagonals.

There are some sensitivities to this approach. Providing six points of vertical support to the cap, two at each column-to-cap connection, and analyzing the model that way with a general purpose finite element analysis program makes the cap indeterminate, and thus the member sizes become important. This approach also does not reflect the flexibility associated with the connected columns. Because the members in an STM model are truly notional (that is, not physical), they are only intended to provide a force path, and it is difficult to assign a rational member size. Instead, a more rational approach is an STM model with only two supports in a "cap-only" model and statically equivalent nodal loads applied to complete the force transfer to the columns, shown in the bottom part of Fig. 5. Attempts to link the STM model to the frame model using rigid links and constraints have only been partially successful, again owing to the indeterminate nature of the truss portion of the model.

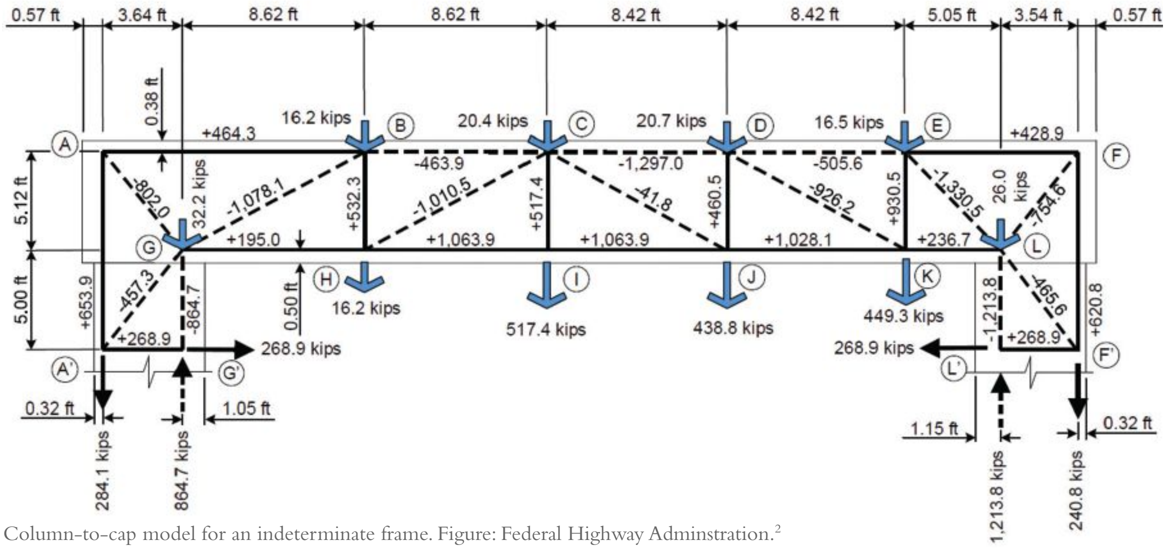

Figure 4. Column-to-cap model for an indeterminate frame. Figure: Federal Highway Adminstration.[2]

Conclusion

For preliminary engineering of all piers, and for final design of a single-column pier, the STM approach is a quick and accurate tool for pier cap design. Though the selection of node locations is somewhat arbitrary, simply sketching a model will quickly identify a logical flow of forces. Once the preliminary geometry has been established, the governing forces are quickly determined and the sizing of pier caps for service and strength limit states is easily achieved.

For more complex piers, fully automated solutions that couple STM and frame analysis have not yet been found. However, the process can be semiautomated to include a conventional frame analysis to determine the STM boundary forces and a separate model for the force flow in the cap itself. The challenges of STM deployment are met with practical solutions. Given the time involved in building and checking such models, it is strongly recommended that engineers not focus on the thousands of load cases that come from commercial software packages; instead, engineers should step back and again think about the design and what is critical. They will find that no more than a handful of loads and load combinations govern the design. This limited number of critical load cases is easily managed with the approaches highlighted in this article.

References

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2. Federal Highway Administration (FHWA) National Highway Institute (NHI). 2017. *NHI Course No. 130126: Strut-and-Tie Modeling (STM) for Concrete Structures*. FHWA-NHI-17-071. https://www.fhwa.dot.gov/bridge/concrete/nhi17071.pdf.

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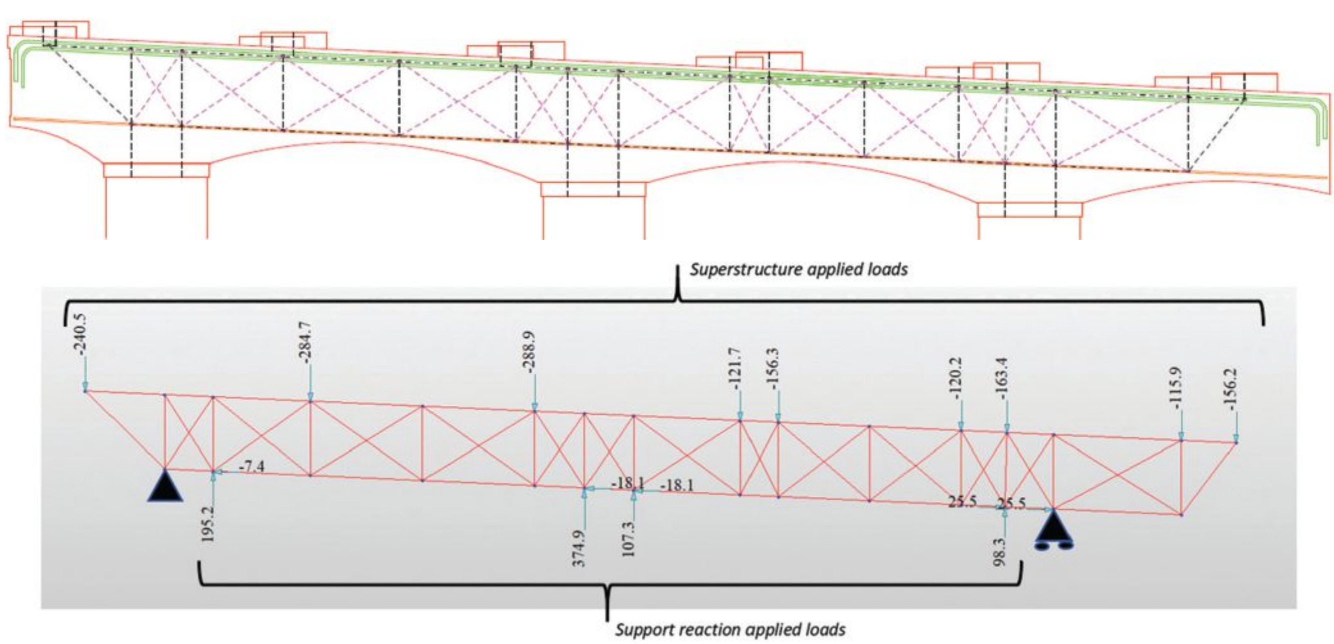

Figure 5. Strut-and-tie models for a multicolumn pier cap. Top: Indeterminate model in a general purpose finite element analysis program. Bottom: The same pier cap model with equivalent nodal loads applied at the columns results in a statically determinate model. Figure: Michael Baker International.