The Strut-and-Tie Model:
Visualizing Load Paths

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The strut-and-tie model of Article 5.6.3 of the *AASHTO LRFD Bridge Design Specifications* provides an alternate to traditional models for proportioning reinforcing steel within structural concrete components at strength and extreme event limit states. Traditional sectional models are based on the assumption that the reinforcement required at a particular section depends only on the section force effects of moment, shear, and torsion. These sectional models do not consider the interaction between these force effects. For control of cracking under service loads, the magnitude of principal tensile stresses can be checked using the principles of Mohr's Circle.

According to the *LRFD Specifications*, the strut-and-tie model may be applied to proportioning reinforcement in any component or parts of a component, but must be applied where nonlinear strain distributions exist. Such nonlinear distributions typically exist in deep pile caps and pier caps and, in general, anywhere applied loads or support reactions are less than two member depths apart. In such circumstances, linear strain distributions cannot develop.

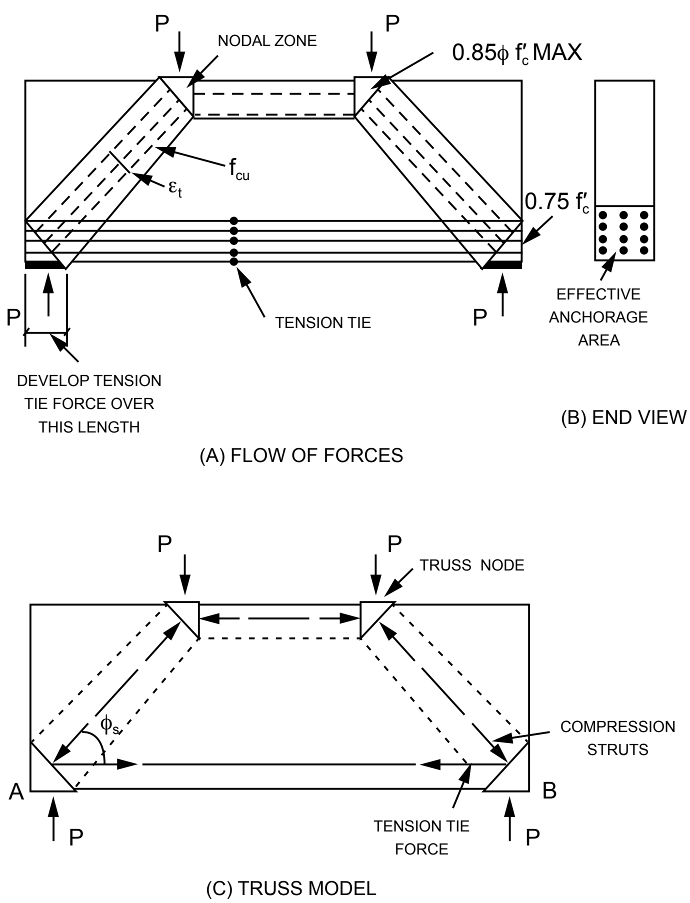

Figure C5.6.3.2-1 from the AASHTO LRFD Bridge Design Specifications.

In the application of the strut-and-tie model, rather than determine force effects at individual sections along the component, load paths carrying the applied loads to the support reactions are visualized within the component. These load paths are assumed to be straight lines that form a truss within the component. At the limit after significant cracking, the initially curved compressive-stress trajectories do indeed become straight lines, called struts. The straight tension load paths, called ties, represent the steel reinforcement, either prestressed or nonprestressed.

Many different load paths and thus strut-and-tie models are viable for a particular component, just as many solutions exist to any design problem. The more inefficient visualized load paths will require more reinforcement. The most efficient load paths are relatively self evident.

A simple, classical strut-and-tie model of a deep beam is shown in Figure C5.6.3.2-1 of the LRFD Specifications. In the case of the beam shown in the figure, each of the applied loads and nearest support reactions are less than two member depths apart. Many example strut-and-tie models representing more realistic bridge components are included in the final report for National Cooperative Highway Research Program (NCHRP) Project 20-7, Task 217, *Verification and Implementation of Strut-and-Tie Model in LRFD Bridge Design Specifications* by Modjeski & Masters. This valuable resource is available for free download at the Transportation Research Board website, http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=1232. Design examples are also given in the Portland Cement Association publication EB231 titled *AASHTO LRFD Strut-and-Tie Model Design Examples*.

After the load paths of the applied loads to the support reactions are visualized in the model, the actual load paths must be realized in the component. The size of the compression strut defined in LRFD Article 5.6.3.3.2 must be of sufficient cross-sectional area to carry the compression force without exceeding the limiting compressive stress of LRFD Article 5.6.3.3.3.

Steel reinforcement must be provided within the tension ties to carry tension force when the steel is at yield. Further, the steel must be sufficiently anchored to carry the tie force along its entire length.

The nodes at which the struts and ties meet must also satisfy compression-stress limits specified in LRFD Article 5.6.3.5.

Finally, an orthogonal grid of reinforcement must be provided near the faces of the components to control the significant cracking expected at the limit when the struts and ties are realized.

The strut-and-tie model is a powerful tool for strength load cases when conventional methods of strength of materials are no longer valid. It harkens back to when the structural engineer first learns to analyze a simple truss. By visualizing the members of the truss, the struts and ties, the designer achieves a better understanding of the mechanisms that allow complex structures to safely carry loads.