# Strut-and-Tie Modeling: What, When, Why, and How

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Strut-and-tie modeling (STM) is a technique that is commonly used to reduce complex states of stress in reinforced and prestressed concrete structures into a simplified truss model. STMs are made up of elements loaded uniaxially in tension (referred to as *ties*) or compression (referred to as *struts*). The intersection points of the struts and ties are called *nodes*. This simplified truss model can then be analyzed using basic statics such as the method of sections or joints. The STM method is based on the lower-bound (that is, conservative) theorem of plasticity, which ensures a safe structure. Another unique aspect of STM analysis with respect to traditional sectional analysis is that it has a unified approach that considers all force effects (moment, shear, axial) simultaneously.

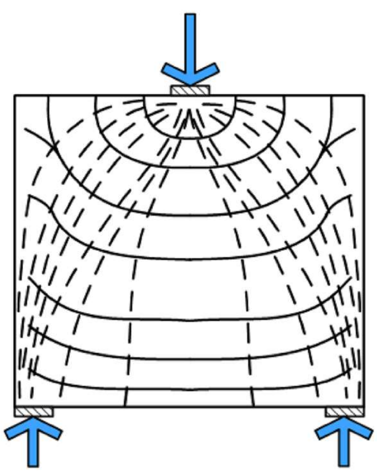

Figure 1. Complex stress trajectories within concrete element. Note: dashed lines = compression; solid lines = tension. All Figures: Federal Highway Administration.

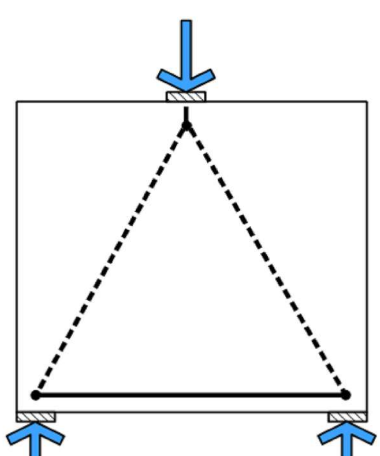

Figure 2. Strut-and-tie model. Note: dashed lines = compression; solid lines = tension.

Figures 1 and 2 show a concrete element with a complex stress profile and how STM can simplify these stresses into a truss model, respectively.

## When to Use STM?

The American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* classify regions within structural concrete elements into two distinct categories: B-regions or D-regions. B-regions (beam or Bernouli) are regions within the element that have linear strain profiles, to which the principles of linear-elastic beam theory apply and for which traditional sectional design is appropriate.

D-regions (disturbed or discontinuity), are regions that include concentrated loads or geometric discontinuities with strain profiles that are complex and nonlinear and therefore not appropriate for traditional sectional design. D-regions require analysis methods that can address these nonlinear strain profiles. Analysis using STM can address the stress complexities in a D-regions with a representative internal truss model that replicates the region's internal load transfer.

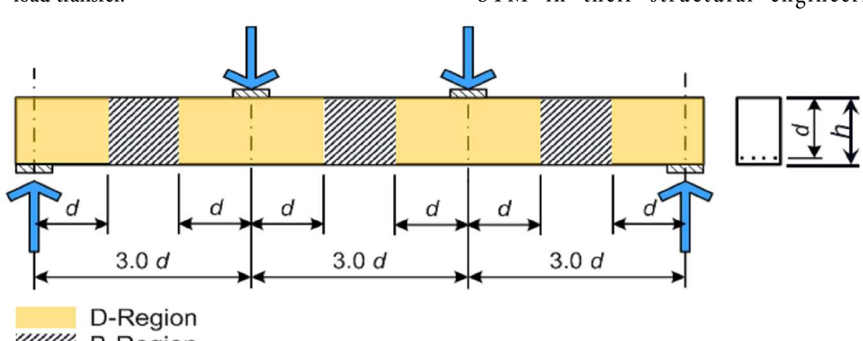


Figure 3. B- and D-regions of an example concrete beam.

Figure 3 is an example of a concrete member's B- and D-regions. The AASHTO LRFD specifications include guidance on determining the extent of each region. For the element shown in Fig. 3, only the D-regions require an analysis, such as STM, that can address their nonlinear strain profiles.

## Why Use STM?

STM provides designers with an easy-to-use analysis tool for D-regions that would otherwise require a more complex analysis, such as finite element analysis. Improperly designed D-region can result in in-service cracking issues. The AASHTO LRFD specifications have design limits and detailing requirements to limit problematic D-region cracking. It should be noted that using sectional design for D-regions can lead to structural elements that are substantially underdesigned.

A secondary benefit of STM is that it requires the designer to visualize and understand the internal load paths and stress fields, which, in turn, along with the STM design provisions, promote good overall element sizing and reinforcement detailing.

## How to Learn More?

One of the most significant hurdles in using the STM technique is the lack of available guidance for bridge practitioners and, more specifically, guidance that follows the provisions in the AASHTO LRFD specifications. Furthermore, very few U.S. colleges include STM in their structural engineering curriculum, which has compounded the need for guidance. To address this gap, the Federal Highway Administration (FHWA) has developed new STM training and design examples that follow the provisions in the 8th edition of the AASHTO LRFD specifications. The FHWA training course and guidance are based on the 8th edition because AASHTO has made significant changes to the STM provisions and substantially reorganized Section 5: Concrete Structures, resulting in many changes to this section's content and article numbering.

Four comprehensive design examples are available on the FHWA bridge website (https://www.fhwa.dot.gov/bridge/concrete/nhi17071.pdf). These design examples progress in complexity and include a simply supported beam, a cantilever bent cap, an inverted-tee straddle bent, and a three-dimensional model of a drilled-shaft footing. These design examples were selected to cover as many "real-life" STM bridge scenarios as possible. These design examples are a very valuable resource within the bridge design community (Fig. 4).

The training is a one-and-a-half-day, instructor-led course delivered through the National Highway Institute (NHI). This training course will be available in the very near future. For more information, visit the NHI website (https://www.nhi.fhwa.dot.gov/home.aspx) and search for course number 130126.

## Acknowledgment

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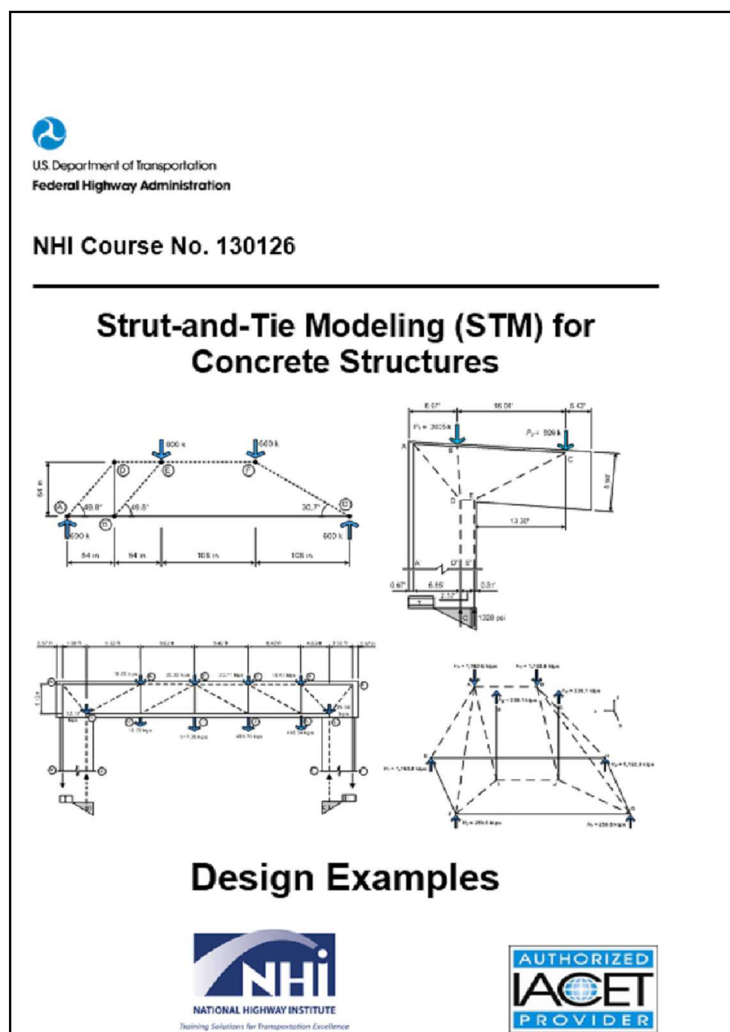
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Design Examples

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Figure 4. Cover of *Strut-and-Tie Modeling (STM) for Concrete Structures.*