Research Study to Inform Strut-and-Tie Design and Guidance

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Benjamin Z. Dymond, https://orcid.org/0000-0002-4752-3445</td><td>8. Performing Organization Report No.
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The goal of the project summarized in this report was to research and develop criteria for updating and improving the ADOT Bridge Design Guidelines with respect to the strut-and-tie methodology defined in the AASHTO LRFD Bridge Design Specifications. To accomplish this goal, the existing literature was reviewed and bridge engineers in Arizona and at U.S. State Departments of Transportation were surveyed to establish how they use the strut-and-tie method in practice. These practices were compared with ADOT practices, and new design scenarios were identified for guidance development. These scenarios were comprehensively analyzed, and five in-depth design examples were developed, including examples related to a hammerhead bent cap, post-tensioned straddle bent cap, post-tensioned box girder end diaphragm, long pier cap, and construction joint. The example problems illustrate workflow, provide detailed calculations, and offer guidance for common points of confusion. Dissemination of the design examples and recommended guidance to the bridge engineering design community occurred via a classroom-style workshop.</td></tr>
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Acronyms and Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ADOT	Arizona Department of Transportation
AzSCE	American Society of Civil Engineers Arizona Section
BDG	Bridge Design Guidelines
B-Region	Beam or Bernoulli Region
BTC	Bridge Technical Committee
CFR	Code of Federal Regulations
CJ	Construction Joint
COBS	Committee on Bridges and Structures
DOT	Department of Transportation
D-Region	Discontinuity Region
Ed.	Edition
FHWA	Federal Highway Administration
LRFD	Load and Resistance Factor Design
PT	Post-Tensioned
Q	Question
STM	Strut-and-Tie Method
TAC	Technical Advisory Committee
Tech Memo	Technical Memorandum

Introduction

Current ADOT Practice

At the time of this project, the Arizona Department of Transportation (ADOT) required bridge engineers to comply with the 9th Edition (Ed.) of the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications (2020). A key change to AASHTO LRFD (2020) Article 5.5.1 was an expanded definition of a discontinuity region (D-region), using the following mandatory language:

> *"D-Regions shall be taken to encompass locations with abrupt changes in geometry or concentrated forces…"*

In addition, AASHTO LRFD (2020) Article 5.5.1.2.3 requires designers to use the strut-and-tie method (STM) from Article 5.8.2 for the design of D-regions. While the ADOT Bridge Design Guidelines (BDG) (2023) contains guidance related to the STM, including a worked example of a hammerhead pier and of a post-tensioned (PT) anchorage zone, this portion of the BDG had not been updated since approximately 2010. Thus, an opportunity existed to improve ADOT bridge design methods by incorporating the latest guidance and recommendations related to the STM.

Need for the Project

The STM is the preferred procedure for the design of reinforced concrete D-regions. In addition, the method provides fundamental insight into the internal flow of forces in regions containing complex stress states. Given the state of current ADOT practice, there was a need to update the ADOT BDG STM information to include the latest state of practice as well as provide more guidance to designers regarding when and where the STM is most advantageous. Fulfilling this need addresses common misconceptions, elevates the STM from an afterthought to the primary methodology that should be considered in relevant situations, and can result in better overall details, designs, and serviceability performance of reinforced concrete bridge elements.

Objectives

Given the need for this project, the objectives were to:

I. Identify the state of practice related to using the STM to design D-regions in reinforced concrete bridge elements in both private bridge engineering and state department of transportation (DOT) design practices.
II. Identify existing and new bridge design scenarios that benefit from the STM.
III. Develop examples of the identified STM design scenarios to update existing ADOT guidance and provide more direction to designers regarding when and where the STM is most advantageous.
IV. Implement the design example results by including them in an updated appendix to the ADOT BDG, proposing changes to Section 5 of the ADOT BDG, and hosting a design workshop for ADOT bridge engineers focused on the state of practice related to the STM.

Background

The STM is an approach for designing structural concrete where complex compressive and tensile stress fields are idealized as an analytical truss comprised of struts and ties, respectively, which meet at nodes. The capacity of the truss is assumed to be a lower-bound representation of the capacity of the member. Thus, the structure can adequately carry the loading if the capacities of the struts, ties, and nodes are not exceeded, and if the truss model satisfies equilibrium. Figure 1 shows a deep beam with tensile and compressive stress fields overlaid by an idealized strut-and-tie load path.

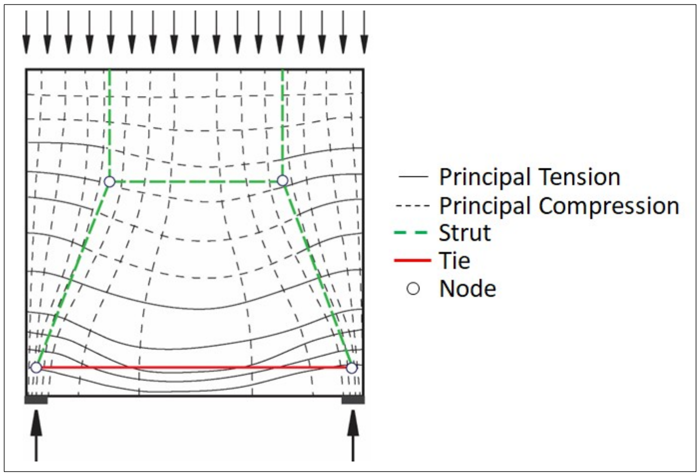

Figure 1. Loaded deep beam with principal stress fields and related strut-and-tie load path.

To illustrate the application of the STM, consider the dapped end of a beam in Figure 2 (self-weight not included for simplicity). Figure 2(a) shows the support reaction and cross-sectional forces. The sectional forces are shown approximately one member depth from the dap—the limits of a Bernoulli beam region (B-region). A B-region is where Bernoulli's *plane sections remain plane* beam theory is valid, and assumptions used to derive the beam's cross-sectional internal forces and resistance are appropriate. The STM is most often used for reinforced concrete design within a D-region, in which beam theory is not valid. Examples of D-regions are those near supports and the points of application of concentrated loads. A D-region is typically assumed to extend one member depth away from the discontinuity in either direction. For this example, the sectional forces are resolved into equivalent concentrated loads and equilibrated with the support reactions through the load path shown in Figure 2(b). Based on the truss forces in the struts (green dashes) and ties (red), it is possible to proportion the steel reinforcement and ensure the capacity of the discrete nodal regions. The anchorage of the tie reinforcement is also an extremely important consideration.

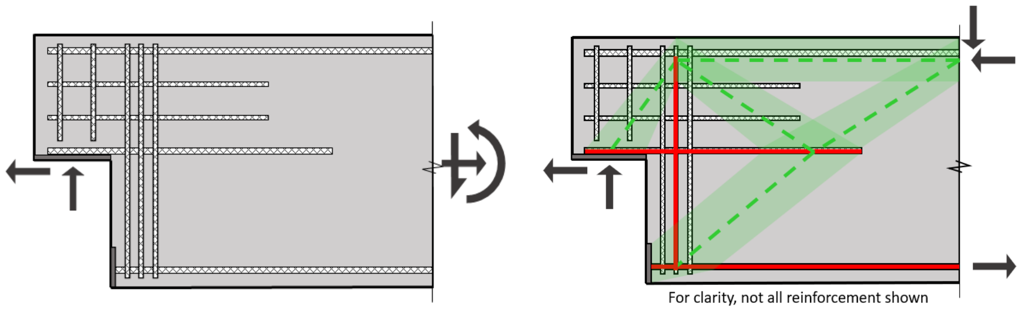

Figure 2. D-region beam with dapped end
(a) equilibrated with sectional forces and (b) equivalent load path.

The STM was originally conceived at the beginning of the 20th century by Ritter (1899) and Mörsch (1909) as a means of proportioning steel reinforcement in reinforced concrete beams. Their method was further refined by others as a means for the rational design of all reinforced concrete structures—notably by Leonhardt (1965), Marti (1985), Collins and Mitchell (1986), and Schlaich et al. (1987). In 1990, 1994, and 2002, STM code provisions were adopted into the European standard (CEB-FIP Model Code 1990), AASHTO LRFD Bridge Design Specifications (1994), and the American Concrete Institute (ACI) Building Code Requirements for Structural Concrete (2002), respectively. Since their initial adoption, STM provisions have been further calibrated against comprehensive experimental studies and analytical databases—notably by Kuchma et al. (2008), Tuchscherer et al. (2014), and Reineck and Todisco (2014).

A powerful benefit of the STM is its application as a tool for assessing the load path through reinforcement details. A PT anchorage in the box girder cross section shown in Figure 3 is presented to illustrate this benefit. Given the orientation of the web and location of the strand anchor, the web forces cannot equilibrate with the strand forces through the concrete alone, resulting in the potential crack shown. A strut-and-tie model immediately and intuitively provides insight into a load path for this condition and offers a rational means for specifying the hanger steel needed to satisfy equilibrium, as shown in Figure 4.

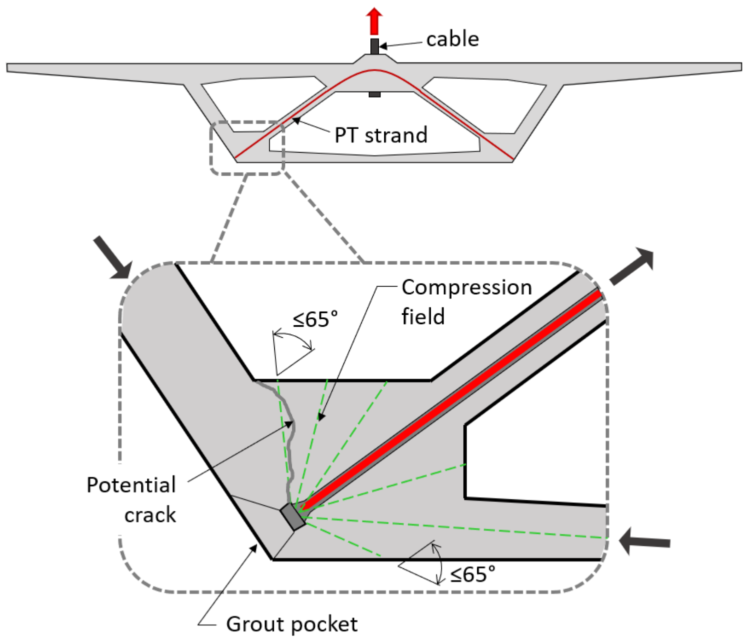

Figure 3. Example PT anchorage in a box girder cross section.

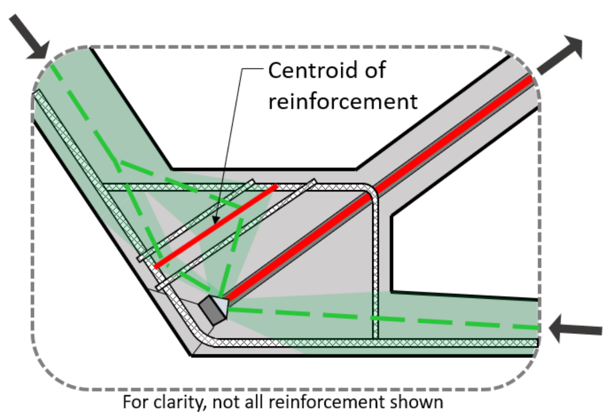

Figure 4. The strut-and-tie model used to determine hanger reinforcement at PT anchorage.

In general, strut-and-tie code provisions allow the designer to select any load path, which is one of the strengths of this procedure; the designer has flexibility to select the path for transferring loads—provided equilibrium and ductility are properly considered.

However, this flexibility also becomes one of the STM's weaknesses, or, at least, a point of confusion. While any load path is valid, some paths are better than others. For example, load paths that closely match the elastic distribution of stress often result in less cracking and better overall serviceability performance (Tuchscherer and Kettelkamp 2018).

In addition, because the AASHTO LRFD Bridge Design Specifications are legally required by the Code of Federal Regulations (CFR), it is easy for designers to become distracted by the prescriptive and/or mandatory nature of the code content, its framework, and its language. The prescriptive language needed to communicate code requirements can overshadow the strengths and advantages of the STM.

Furthermore, the intent of a code is not to teach designers textbook-level material; thus, there are areas of the code that users may perceive as lacking in detail. The STM is a first-principled design method, and it can be used to easily identify a valid load path in a structure. Engineers who use the method should have confidence in their designs; however, in practice, this may not be the case.

Scope of Work

This project began in the fall of 2023 and concluded in the summer of 2025. The following tasks were used to accomplish the project scope of work:

Task 1. Project Kick-Off and Refinement of Work Plan. The purpose of this task was to refine the details of the work plan and ensure agreement with stakeholders on the project goals, details, scope of work, schedule, and deliverables.

Task 2. Identify State of Practice. The purpose of this task was to document the current state of knowledge and practice related to the STM. This was done via a literature review, survey responses from 11 consulting bridge engineering firms in Arizona, and survey responses from 31 State DOTs.

Task 3. Compare State of Practice with ADOT Practice. The purpose of this task was to synthesize, compare, and contrast the data collected from Task 2 and compare the responses to those from the ADOT bridge group. The overarching goal of this effort was to identify the optimal design scenarios or structure types that benefit from a strut-and-tie analysis and design.

Task 4. Identify New Scenarios that Benefit from the STM. The purpose of this task was to identify new or current design scenarios and structure types that would most benefit from implementation of the STM based on the information collected from Tasks 2 and 3. Completion of Task 4 resulted in ADOT consensus on the design examples to be developed during Task 5.

Task 5. Develop Guidance and Examples. The purpose of this task was to develop detailed design examples from the scenarios identified during Task 4. This task resulted in five in-depth design examples completed using the STM. Furthermore, guidance associated with successful implementation of the STM for design of reinforced concrete D-regions was proposed for incorporation into the ADOT BDG.

Task 6. Final Products. The purpose of this task was to synthesize the results so they may easily be implemented by the Arizona bridge engineering community. Effort in this task resulted in a final report and final presentation to ADOT.

Task 7. Implementation of Recommendations. The purpose of this task was to encourage the implementation of the results of this project. This was accomplished via a one-day classroom-style workshop on the STM with ADOT bridge design engineers. Learning objectives for this workshop included: (i) identify when the STM is applicable, (ii) apply the STM to the design of a D-region in a practical example, (iii) develop the best truss model to carry loading, (iv) identify how strut-and-tie detailing requirements affect constructability, and (v) create a take-home list of the most useful, existing resources that are already published. Portions of the workshop were pre-recorded, and these recordings are available from ADOT.

Recommendations

Overview

Existing and relevant STM guidance for the design of reinforced concrete bridge structures was identified and recommended in this project. Subsequently, five in-depth calculation-based design examples using the STM were developed after identifying areas of need for new guidance; the five STM examples were for a hammerhead bent cap, PT straddle bent cap, PT box girder end diaphragm, long pier cap, and construction joint (CJ). Finally, a one-day classroom-style workshop on the STM was given to ADOT bridge design engineers during the summer of 2025 to disseminate the design examples.

Existing Relevant Guidance

Several existing documents provide relevant detailed guidance on the application of the STM; these documents were considered relevant if they met the following three criteria: (i) referenced the 8th or 9th Ed. of the AASHTO LRFD, (ii) endorsed by the Federal Highway Administration (FHWA) or a state DOT, and (iii) included a discussion of why design decisions using the STM were made. For detailed discussion of many of the engineering decisions that occur when applying the STM, refer to the following relevant guidance published by the FHWA.

- Colorito, A. B., K. E. Wilson, O. Bayrak, and F. M. Russo. 2017. *Strut-and-Tie Modeling (STM) for Concrete Structures, Design Examples*. Report No. FHWA-NHI-17-071. Vienna, VA: National Highway Institute, FHWA.

The following relevant sources discuss the underlying fundamental principles of the STM, which are sparse in existing textbook-style guidance.

- Schlaich, J., K. Schäfer, and M. Jennewein. 1987. "Towards a Consistent Design of Structural Concrete." *PCI Journal*. Prestressed Concrete Institute, Chicago, IL, Vol. 32, No. 3, May–June 1987, pp. 74–151.
- Joint ACI-ASCE Committee 445. 2021. *Strut-and-Tie Method Guidelines for ACI 318-19 – Guide (ACI PRC-445.2-21)*. American Concrete Institute, Farmington Hills, MI.

The AASHTO LRFD 9th Ed. provisions for the STM specifically refer to and are based on the following relevant publications.

- Birrcher, D.B., R. G. Tuchscherer, M. R. Huizinga, O. Bayrak, S. L. Wood, and J. O. Jirsa. 2009. *Strength and Serviceability Design of Reinforced Concrete Deep Beams*. Report No. FHWA/TX-09/0-5253-1. Texas Department of Transportation.
- Williams, C., D. Deschenes, and O. Bayrak. 2012. *Strut-and-Tie Model Design Examples for Bridges: Final Report*. FHWA/TX-12/5-5253-01-1. Texas Department of Transportation.
- Larson, N., E. F. Gómez, D. Garber, O. Bayrak, and W. Ghannoum. 2013. *Strength and Serviceability Design of Reinforced Concrete Inverted-T Beams*. FHWA/TX-13/0-6416-1. Texas Department of Transportation.

Guidance from This Study

Design Examples

Based on the existing relevant guidance, the needs of Arizona bridge design practitioners, and the needs of state DOTs, five in-depth calculation-based design examples using the STM were developed for different types of structures where minimal guidance currently exists. The scope and structure type for each of these examples was agreed upon by the research team and ADOT bridge group. Within Technical Memorandum Five (Tech Memo 5) of this project (NAU 2025e), a section that summarized the existing STM and five new examples of the STM (listed below) were completed for inclusion in the ADOT BDG.

- **Overview and Background for the STM Examples**—This overview provides engineers with background information needed to assist in their use of ADOT's STM guidance. The information is intended to supplement and not repeat or replace existing and available guidance.
- **Example 1—Hammerhead Pier Cap**. This bridge element is commonly used in Arizona. An example illustrating the application of the AASHTO LRFD STM to the design of a hammerhead pier cap does not exist in the literature. The purpose of this example is to fill this void.

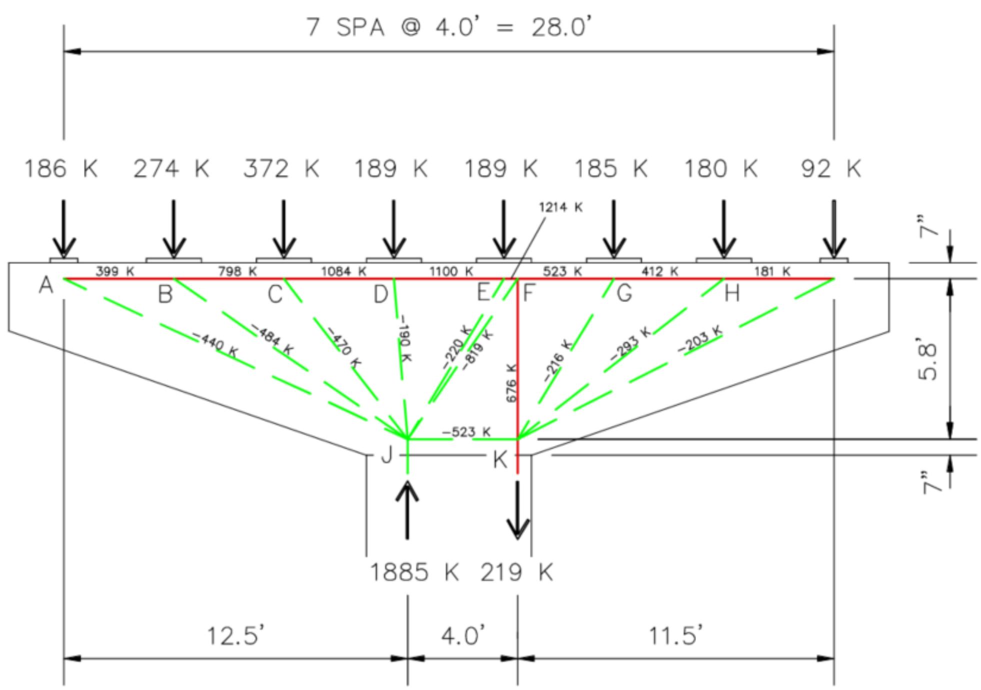

Figure 5. Strut-and-tie model for hammerhead pier cap example.

- **Example 2—PT Straddle Bent Cap**. This bridge element is less commonly used, except in situations with restrictions on clearance and location of foundation elements. A widely accepted strut-and-tie example that includes prestressing does not exist in the literature. The purpose of this example is to fill this void.

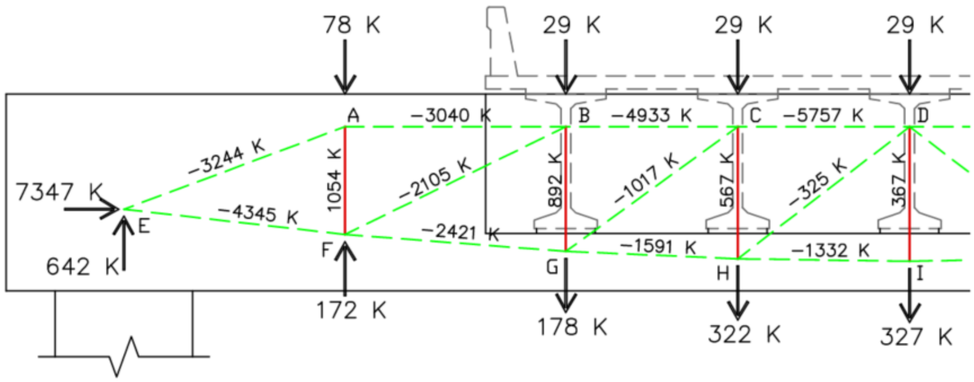

Figure 6. Strut-and-tie model for PT straddle bent cap example.

- **Example 3—PT Box Girder End Diaphragm**. PT box girders are commonly used bridge types in Arizona. A widely accepted strut-and-tie example that includes prestressing does not exist in the literature. The purpose of this example is to fill this void. In addition, this structure type clearly demonstrates the development of a strut-and-tie model, or load path, between the post-tensioning and sectional forces.

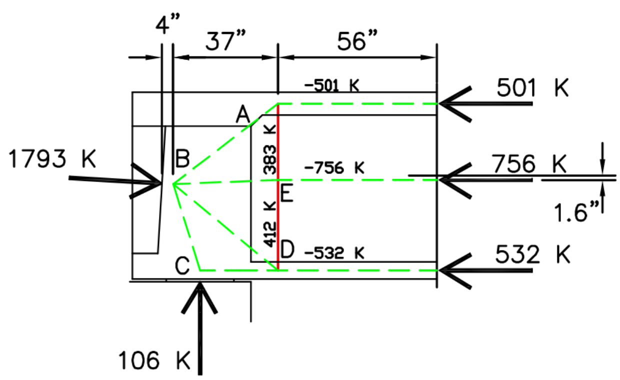

Figure 7. Strut-and-tie model for PT box girder end diaphragm example.

- **Example 4—Long Pier Cap**. This example addresses several of the serviceability concerns and deepens the discussion of the serviceability behavior of elements designed using the STM.

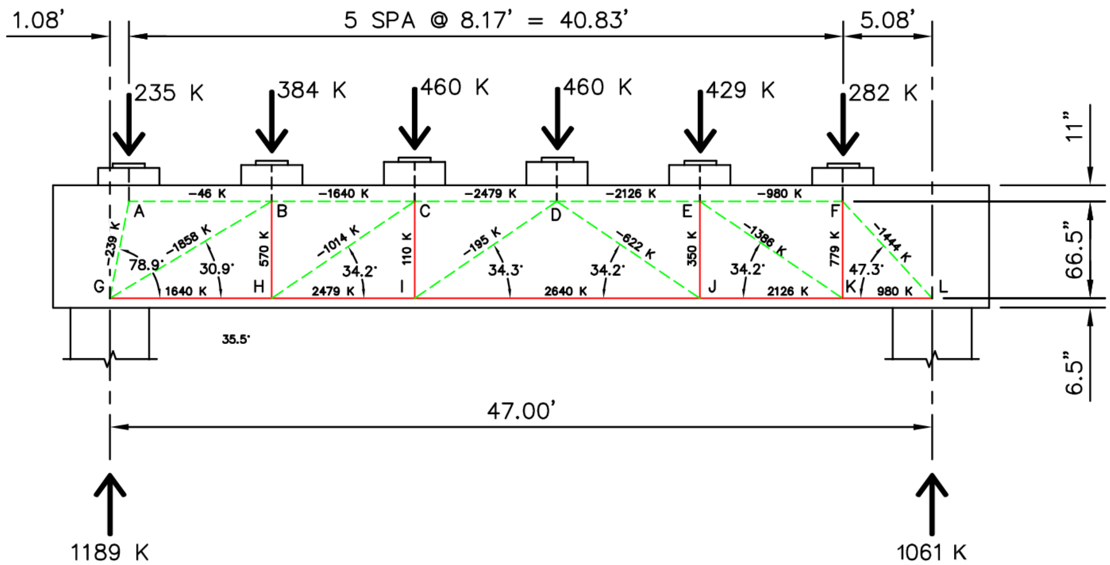

Figure 8. Strut-and-tie model for long pier cap diaphragm example.

- **Example 5—Construction Joint**. A CJ in a pier cap or abutment is frequently encountered when a bridge is widened. The purpose of this example is to illustrate the implications to the STM when developing a strut-and-tie model across a CJ. This example also discusses the considerations associated with the transfer of interface shear and the relationship between interface shear and the STM.

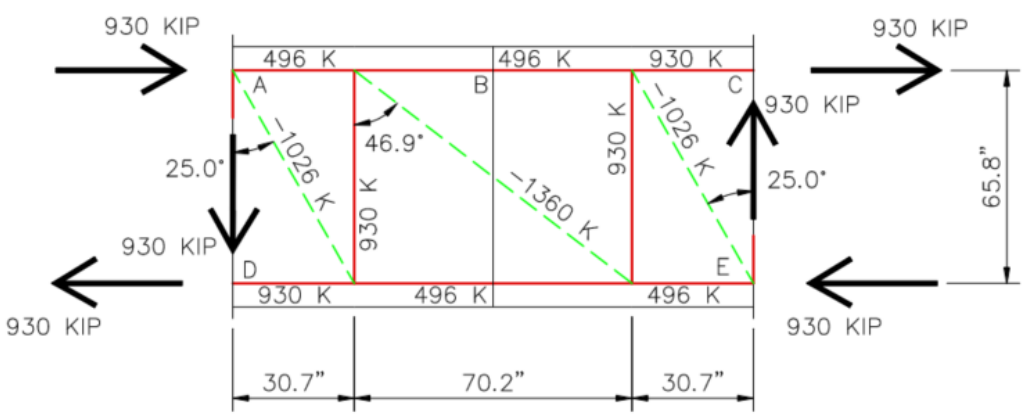

Figure 9. Strut-and-tie model for CJ example.

Proposed Changes to the ADOT Bridge Design Guidelines

After developing the five design examples, the best practices and key information points related to the STM were identified and clearly summarized. This concise, critical information was proposed as a new section of the BDG, entitled "5.8 Design of D-Regions." These proposed changes were developed based on common areas of confusion among designers and key guidance identified within each of the example problems.

Implementation Plan

Example Problem Publication

The five design examples were published in Tech Memo 5 (NAU 2025e), which provided ADOT with updated guidance for designers regarding when and where the STM is most advantageous. Furthermore, the five in-depth STM design example problems were implemented for use by practicing engineers after publishing them in an updated appendix to the ADOT BDG.

Proposed Content to be Added to Section 5 of the ADOT Bridge Design Guidelines

Tech Memo 5 (NAU 2025e) outlined the content proposed for addition to Section 5 of the ADOT BDG. Specifically, inclusion of a new section entitled "5.8 Design of D-Regions" was recommended, and Tech Memo 5 included proposed language for each subsection implemented in the ADOT BDG. The addition of this section to the BDG aligned ADOT STM design guidance with Section 5: Concrete Structures in the AASHTO LRFD Bridge Design Specifications (2020).

Workshop on the STM

The guidance and design examples from this project were deployed to train ADOT bridge design engineers via a one-day classroom-style workshop during the summer of 2025. The workshop was conducted in person, but clear and concise pre-recorded videos of key content and discussions related to the STM were made available to the bridge engineering design community and published in association with this final report (NAU 2025a). The learning objectives of the workshop were to:

- Identify when the STM is applicable—why do designers need to use the STM?
- Apply the STM to the design of a reinforced concrete D-region.
- Identify the most important factors when considering the STM.
- Develop the best strut-and-tie truss model to carry given loads.
- Identify how detailing requirements affect constructability.
- List the most useful resources that are already available and published.

Findings

Objective I

Identify the state of practice related to using the STM to design D-regions in reinforced concrete bridge elements in both the private structural engineering and state DOT design practices.

Findings associated with Objective I resulted from the work published in Tech Memo 2 (NAU 2025b). The following key findings were identified based on a review of the existing literature:

- The 8th Ed. of the AASHTO LRFD Bridge Design Specifications directly references nine sources for guidance when completing design with the STM.
- An additional four fundamental references that provide examples and guidance associated with the STM have been published by the ACI and FHWA.
- Two supplemental documents were referenced by both ADOT and other state DOTs that provide examples and guidance associated with the STM.

The following key findings were identified based on results from a survey of state DOTs and Arizona bridge engineering consultants. A total of 34 state DOT bridge designers, employed by 31 unique DOTs, and 15 bridge consultants, employed by 11 unique firms in Arizona, responded to the survey.

- 62 percent of DOT respondents indicated that they do not require consultants to design certain bridge elements using the STM. (Survey Question (Q) 1a).
- 50 percent of DOT respondents indicated that the STM is implemented in their bridge design process by referencing AASHTO. (Survey Q1b).
- 73 percent of respondents use the 9th Ed. of the AASHTO LRFD Bridge Design Specifications for bridge analysis and design. (Survey Q2).
- The most common scenarios or elements where the STM is used are with caps, deep beams, and PT anchorage. (Survey Q3). These design scenarios were also where design processes diverged from typical workflows. (Survey Q7).
- The STM is most used because of its accuracy (51 percent of respondents) or because it is required by the code (37 percent of respondents). (Survey Q4). Furthermore, the STM most benefits bridge design, processes, or workflows due to its accuracy. (Survey Q8).
- AASHTO provisions lack guidance when attempting to define model geometry for the STM. (Survey Q5).
- The most-used STM resources are those published by the FHWA. (Survey Q6).

Common scenarios where the STM is being used for design during ADOT projects included the following:

- PT anchorage zones
- Pier caps
- Hammerhead piers on spread footings
- Pier caps with an inverted tee-shaped cross section
- Straddle bent caps

Objective II

Identify existing and new bridge design scenarios that benefit from the STM.

Findings associated with Objective II resulted from the work published in Tech Memo 3 (NAU 2025c) and Tech Memo 4 (NAU 2025d). Based on a comparison between current practices and ADOT practices, along with discussions with the ADOT technical advisory committee (TAC), four primary needs related to implementing the STM that would benefit from further guidance and details were identified:

- Need to promote the accuracy and benefits of the STM.
- Need for developmental guidance for the STM.
- Need for more FHWA guidance documents for the STM.
- Need for a software or workflow example of the STM.

An overview and background chapter about the STM, along with five new examples of the STM (listed below), were proposed for inclusion in the ADOT BDG after discussion with the ADOT TAC:

0. Overview and Background for the STM Examples
1. Hammerhead Pier Cap
2. PT Straddle Bent Cap
3. PT Box Girder End Diaphragm
4. Long Pier Cap
5. Construction Joint

Objective III

Develop examples of the identified STM design scenarios to update existing ADOT guidance and provide more guidance to designers regarding when and where the STM is most advantageous.

Findings associated with Objective III resulted from the work published in Tech Memo 5 (NAU 2025e). Five in-depth calculation-based design examples using the STM were developed after identifying areas of need for new guidance; the five STM examples were for a hammerhead bent cap, PT straddle bent cap, PT box girder end diaphragm, long pier cap, and CJ. Tech Memo 5 also outlined the content proposed for a new section of the ADOT BDG entitled “5.8: Design of D-Regions,” which also included proposed language for each subsection.

Objective IV

Implement the design example results by including them in an updated appendix to the ADOT BDG, proposing changes to Section 5 of the ADOT BDG, and hosting a design workshop focused on the state of practice related to the STM for ADOT bridge engineers.

Objective IV was accomplished through the publication of Tech Memo 5 (NAU 2025e) and deployment of an all-day in-person workshop. Tech Memo 5 (NAU 2025e) contains five example designs. An overview of these examples is discussed above in the section titled: *Recommendations*. Also, proposed changes to the ADOT BDG are included in Tech Memo 5 (NAU 2025e) and an overview of these changes are similarly discussed above in the section titled: *Recommendations*. Finally, the guidance and design examples from this project were deployed to train ADOT bridge design engineers via a one-day classroom-style workshop during summer 2025, as discussed above in the subsection titled *Implementation Plan*.

Methods

Three methods were used in this study. To collect state of practice data related to the STM for Tech Memo 2 (NAU 2025b), the research team:

1. Conducted a literature review.
2. Distributed a nine-question Qualtrics© survey to the AASHTO Committee on Bridges and Structures (COBS) and the American Society of Civil Engineers Arizona Section (AzSCE) Bridge Technical Committee (BTC).

To identify areas in need of new guidance related to the STM, and thus identify the structure types highlighted in the five in-depth calculation-based design examples, the research team also:

3. Held discussions with the ADOT TAC.

Refer to Tech Memo 2 (NAU 2025b) through Tech Memo 5 (NAU 2025e) for additional details.

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