Design Examples for Strut-and-tie Models

An Application of Strat-and-tie Model to Deep Beams

A compatibility-based strut-and-tie model C-STM is proposed for analyzing deep beams and disturbed regions with particular emphasis on reinforced concrete bridge piers. In addition to the normal strut-and-tie force equilibrium requirements the model accounts for non-linear behavior through displacement compatibility using inelastic constitutive laws of cracked reinforced concrete. The model is implemented into widely used commercial structural analysis software and validated against results from previously conducted large scale experiments. A near full-scale experiment on a reinforced concrete sub-assemblage that represents cantilevered and straddle pier bents is conducted to investigate the shear-flexure performance of deep (disturbed) regions. Insights into the development of nonlinear behavior and the final collapse failure mechanism are then evaluated and accurately modeled using the C-STM. It is concluded that the proposed C-STM serves as an advanced method of analysis that can predict with suitable accuracy the force-deformation response of both D- and B- regions, deep beams, and beam-columns. This provides engineers with a supplementary analysis tool that can be used to assess the nonlinear behavior of bridge piers with stocky members and/or large disturbed regions.

Stringer-Panel Models in Structural Concrete

This enlightening textbook for undergraduates on civil engineering degree courses explains structural design from its mechanical principles, showing the speed and simplicity of effective design from first principles. This text presents good approximate solutions to complex design problems, such as “Wembley-Arch” type structures, the design of thin-walled structures, and long-
span box girder bridges. Other more code-based textbooks concentrate on relatively simple member design, and avoid some of the most interesting design problems because code compliant solutions are complex. Yet these problems can be addressed by relatively manageable techniques. The methods outlined here enable quick, early stage, “ball-park” design solutions to be considered, and are also useful for checking finite element analysis solutions to complex problems. The conventions used in the book are in accordance with the Eurocodes, especially where they provide convenient solutions that can be easily understood by students. Many of the topics, such as composite beam design, are straight applications of Eurocodes, but with the underlying theory fully explained. The techniques are illustrated through a series of worked examples which develop in complexity, with the more advanced questions forming extended exam type questions. A comprehensive range of fully worked tutorial questions are provided at the end of each section for students to practice in preparation for closed book exams.

**Practical design of structural concrete**

Strut-and-Tie models are useful in designing reinforced concrete structures with discontinuity regions where linear stress distribution is not valid. Deep beams are typically short girders with a large point load or multiple point loads. These point loads, in conjunction with the depth and length of the members, contribute to a member with primarily discontinuity regions. ACI 318-08 Building Code Requirements for Structural Concrete provides a method for designing deep beams using either Strut-and-Tie models (STM) or Deep Beam Method (DBM). This report compares dimension requirements, concrete quantities, steel quantities, and constructability of the two methods through the design of three different deep beams. The three designs consider the same single span deep beam with varying height and loading patterns. The first design is a single span deep beam with a large point load at the center girder. The second design is the deep beam with the same large point load at a quarter point of the girder. The last design is the deep beam with half the load at the midpoint and the other half at the quarter point. These three designs allow consideration of different shear and STM model geometry and design considerations. Comparing the two different designs shows the shear or cracking control reinforcement reduces by an average 13% because the STM considers the extra shear capacity through arching action. The tension steel used for either flexure or the tension tie increases by an average of 16% from deep beam in STM design. This is due to STM taking shear force through tension in the tension reinforcement through arching action. The main advantage of the STM is the ability to decreased member depth without decreasing shear reinforcement spacing. If the member depth is not a concern in the design, the preferred method is DBM unless the designer is familiar with STMs due to the similarity of deep beam and regular beam design theory.

**Understanding Structural Engineering**

Gain Confidence in Modeling Techniques Used for Complicated Bridge Structures

Bridge structures vary considerably in form, size, complexity, and importance. The methods for their computational analysis and design range from approximate to refined analyses, and rapidly improving computer technology has made the more refined and complex methods of ana

**Strut and Tie Modeling of Deep Footings**

**Experimentally Validated Compatibility Strut and Tie Modeling of Reinforced Concrete Bridge Piers**

**A Comparison of Design Using Strut-and-tie Modeling and Deep Beam Method for Transfer Girders in Building Structures**

First published in 1984, Limit Analysis and Concrete Plasticity explains for advanced design engineers the principles of plasticity theory and its application to the design of reinforced and
prestressed concrete structures, providing a thorough understanding of the subject, rather than simply applying current design formulas. Updated and revised th

Strut-and-tie Modeling of Multistory, Partially-grouted, Concrete Masonry Shear Walls with Openings

The book covers the application of numerical methods to reinforced concrete structures. To analyze reinforced concrete structures linear elastic theories are inadequate because of cracking, bond and the nonlinear and time dependent behavior of both concrete and reinforcement. These effects have to be considered for a realistic assessment of the behavior of reinforced concrete structures with respect to ultimate limit states and serviceability limit states. The book gives a compact review of finite element and other numerical methods. The key to these methods is through a proper description of material behavior. Thus, the book summarizes the essential material properties of concrete and reinforcement and their interaction through bond. These basics are applied to different structural types such as bars, beams, strut and tie models, plates, slabs and shells. This includes prestressing of structures, cracking, nonlinear stressstrain relations, creeping, shrinkage and temperature changes. Appropriate methods are developed for each structural type. Large displacement and dynamic problems are treated as well as short-term quasi-static problems and long-term transient problems like creep and shrinkage. Most problems are illustrated by examples which are solved by the program package ConFem, based on the freely available Python programming language. The ConFem source code together with the problem data is available under open source rules at concrete-fem.com. The author aims to demonstrate the potential and the limitations of numerical methods for simulation of reinforced concrete structures, addressing students, teachers, researchers and designing and checking engineers.

Reinforced Concrete Deep Beams

This book examines the application of strut-and-tie models (STM) for the design of structural concrete. It presents state-of-the-art information, from fundamental theories to practical engineering applications, and also provides innovative solutions for many design problems that are not otherwise achievable using the traditional methods.

Computational Modelling of Concrete Structures

Computational Methods for Reinforced Concrete Structures

Bridge bents (deep beams) in the State of Texas have experienced diagonal cracking problems with increasing frequency. These field related issues, taken in combination with discrepancies that exist between design provisions for strut and tie modeling (STM), were the impetus for the funding of the current project. The overall objective of the project was to develop safe and consistent design guidelines in regard to both the strength and serviceability of deep beams. In order to accomplish this research objective and related tasks, a database of 868 deep beam tests was assembled from previous research. Inadvertently, many of the beams in this database were considerably smaller, did not contain sufficient information, or contained very little shear reinforcement. As a result, filtering criteria were used to remove 724 tests from the database. The criteria were chosen to consider only beams that represent bent caps designed in the field. In addition to the 144 tests that remained in the database, 34 tests were conducted as part of the current experimental program resulting in 178 total tests available for evaluation purposes. Two additional tests were conducted on beams without shear reinforcement, thus they did not meet the filtering criteria. However, the results from these tests provided valuable information regarding deep beam behavior. Beams that were fabricated and tested as part of the current experimental program ranged in size from, 36"x48", 21"x75", 21"x42", and 21"x23". These tests represent some of the largest deep beam shear tests ever conducted. STM details that were investigated included: (i) the influence that triaxial confinement of the load or support plate has on strength and serviceability performance; and (ii) the influence that multiple stirrup legs distributed across the
web has on strength and serviceability performance. Based on the findings of the experimental and analytical program, a new strut-and-tie modeling procedure was proposed for the design of deep beam regions. The procedure is based on an explicitly defined single-panel truss model with non-hydrostatic nodes. An important aspect of the new STM design methodology is that it was comprehensively derived based on all the stress checks that constitute an STM design. Thus, the new method considers every facet of a STM design. The newly proposed STM procedure is simple, more accurate, and more conservative in comparison with the ACI 318-08 and AASHTO LRFD (2008) STM design provisions. As such, the implementation of the new design provisions into ACI 318 and AASHTO LRFD is recommended.

Strut-and-tie Model Design Examples for Bridge

A comprehensive guide to bridge design Bridge Design - Concepts and Analysis provides a unique approach, combining the fundamentals of concept design and structural analysis of bridges in a single volume. The book discusses design solutions from the authors’ practical experience and provides insights into conceptual design with concrete, steel or composite bridge solutions as alternatives. Key features: Principal design concepts and analysis are dealt with in a unified approach. Execution methods and evolution of the static scheme during construction are dealt with for steel, concrete and composite bridges. Aesthetics and environmental integration of bridges are considered as an issue for concept design. Bridge analysis, including modelling and detail design aspects, is discussed for different bridge typologies and structural materials. Specific design verification aspects are discussed on the basis of present design rules in Eurocodes. The book is an invaluable guide for postgraduate students studying bridge design, bridge designers and structural engineers.

Reinforced and Prestressed Concrete


Structural Concrete

Strut-and-tie modeling (STM) is a versatile, lower-bound (i.e. conservative) design method for reinforced concrete structural components. Uncertainty expressed by engineers related to the implementation of existing STM code specifications as well as a growing inventory of distressed in-service bent caps exhibiting diagonal cracking was the impetus for the Texas Department of Transportation (TxDOT) to fund research project 0-5253, D-Region Strength and Serviceability Design, and the current implementation project (5-5253-01). As part of these projects, simple, accurate STM specifications were developed. This thesis acts as a guidebook for application of the proposed specifications and is intended to clarify any remaining uncertainties associated with strut-and-tie modeling. A series of five detailed design examples feature the application of the STM specifications. A brief overview of each design example is provided below. The examples are prefaced with a review of the theoretical background and fundamental design process of STM (Chapter 2). · Example 1: Five-Column Bent Cap of a Skewed Bridge - This design example serves as an introduction to the application of STM. Challenges are introduced by the bridge’s skew and complicated loading pattern. A clear procedure for defining relatively complex nodal geometries is presented. · Example 2: Cantilever Bent Cap - A strut-and-tie model is developed to represent the flow of forces around a frame corner subjected to closing loads. The design and detailing of a curved-bar node at the outside of the frame corner is described. · Example 3a: Inverted-T Straddle Bent Cap (Moment Frame) - An inverted-T straddle bent cap is modeled as a component within a moment frame. Bottom-chord (ledge) loading of the inverted-T necessitates the use of local STMs to model the flow of forces through the bent cap’s cross section. · Example 3b: Inverted-T Straddle Bent Cap (Simply Supported) - The inverted-T bent cap of Example 3a is designed as a member that is simply supported at the columns. · Example 4: Drilled-Shaft Footing - Three-dimensional STMs are developed to properly model the flow of forces through a deep drilled-shaft footing. Two
unique load cases are considered to familiarize the designer with the development of such models.

**Further Examples for the Design of Structural Concrete with Strut-and-tie Models**

**Limit Analysis and Concrete Plasticity**

Performance-Based Optimization of Structures introduces a method to bridge the gap between structural optimization theory and its practical application to structural engineering. The Performance-Based Optimization (PBO) method combines modern structural optimisation theory with performance based design concepts to produce a powerful technique for use in structural design. This book provides the latest PBO techniques for achieving optimal topologies and shapes of continuum structures with stress, displacement and mean compliance constraints. The emphasis is strongly placed on practical applications of automated PBO techniques to the strut-and-tie modelling of structural concrete, which includes reinforced and prestressed concrete structures. Basic concepts underlying the development of strut-and-tie models, design optimization procedure, and detailing of structural concrete are described in detail. Alternative approaches to topology optimization are also introduced. The book contains numerous practical design examples illustrating the nature of the load transfer mechanism of structures.

**Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary**

The research included testing six three story, half-scale masonry shear walls. Half of the walls had door openings while the other half had window openings. The configurations were selected to represent typical walls in multi-story buildings. The measured lateral strength was compared to estimations from the equations in the US masonry code and to those from an equivalent truss model and a strut-and-tie model. The results show that the U.S. masonry code equations over predicts while the equivalent truss model under predicts the lateral strength of the walls. The results further show that the strut-and-tie model is the most accurate method for lateral strength prediction and is able to account for wall openings and partial-grouting.

**Strut-and-tie Modeling of Reinforced Concrete Deep Beams**

Strut and Tie Models: Analysis and Design presents a systematic and consistent approach to the application of the STM to almost all types of members using the arbitrary distinction between a D and a B region. Strut and tie modeling provides design engineers with a flexible and intuitive option for designing structures or portions that are heavily influenced by shear forces. The book also demonstrates how strut and tie modeling and finite element methods are not mutually exclusive but rather complementary and supportive. The book’s four part treatment starts with an overview of structural analysis and strut and tie models (STM). This is quickly followed by relevant topics such as: loads and load paths through members plus case studies, and formalization of strut and tie models. Applications of STM are then explained in detail along with extracting STM through FEM. In addition, the book will include solved examples and mobile apps. Includes moment curvature analysis, interaction diagrams and reinforcement design and stress analysis for structural cross sections Includes modeling tools and computational methods for cross-sections for stress distribution and stress calculations Features many illustrations, schematics, diagrams and line drawings Includes author-developed computer-based apps to be used in conjunction with the practical applications presented in the book Covers both the Eurocodes and American Concrete Institute codes, which are two major, widely-used building design code documents in the world according to researchgate.net

**Bridge Design**
In our world of seemingly unlimited computing, numerous analytical approaches to the estimation of stress, strain, and displacement—including analytical, numerical, physical, and analog techniques—have greatly advanced the practice of engineering. Combining theory and experimentation, computer simulation has emerged as a third path for engineering.

Structural Design from First Principles

Design for Shear in Reinforced Concrete Using Strut-and-tie Models

Strut-and-tie Model Design Examples for Bridges

The sixth edition of this comprehensive textbook provides the same philosophical approach that has gained wide acceptance since the first edition was published in 1965. The strength and behavior of concrete elements are treated with the primary objective of explaining and justifying the rules and formulas of the ACI Building Code. The treatment is incorporated into the chapters in such a way that the reader may study the concepts in a logical sequence in detail or merely accept a qualitative explanation and proceed directly to the design process using the ACI Code.

Strut-and-tie Modeling (STM) for Concrete Structures

Strut-and-tie modeling has been proven to conservatively predict the strength of specialty concrete structures such as corbels, dapped ends, and deep beams with openings. The objective of this study is to determine if strut-and-tie modeling can be used to predict the strength of masonry beams with openings. To this end, a suite of 23 tests were conducted on masonry beams with openings of various sizes and locations. Test data is compared to the predictions made by the strut-and-tie models to validate that this lower-bound solution is a reasonable and conservative method for evaluating the capacity of masonry beams with openings. Results confirm that strut-and-tie modeling provides conservative predictions for the strength of masonry beams with openings. Furthermore, data indicates that beams with transverse reinforcement at the openings did not perform significantly better than the beams without transversely reinforced openings.

Structural Concrete

These Proceedings are based on the Fifth International Conference on Space Structures, organised by the University of Surrey. Produced as a 2-volume set, they contain original and innovative information on space structures from leading engineers and architects from around the world.

Automatic design of concrete structures using a strut & tie approach

This volume comprises select peer reviewed papers presented at the international conference - Advanced Research and Innovations in Civil Engineering (ARICE 2019). It brings together a wide variety of innovative topics and current developments in various branches of civil engineering. Some of the major topics covered include structural engineering, water resources engineering, transportation engineering, geotechnical engineering, environmental engineering, and remote sensing. The book also looks at emerging topics such as green building technologies, zero-energy buildings, smart materials, and intelligent transportation systems. Given its contents, the book will prove useful to students, researchers, and professionals working in the field of civil engineering.

Building Code Requirements for Structural Concrete (ACI 318M-08) and Commentary

The contents of this book have been chosen with the following main aims: to review the present
coverage of the major design codes and the CIRIA guide, and to explain the fundamental
behaviour of deep beams; to provide information on design topics which are inadequately covered
by the current codes and design manuals; and to give authoritative revi

Concrete Structures Standard

A series of five detailed design examples feature the application of state-of-the-art strut-and-tie
modeling (STM) design recommendations. This guidebook is intended to serve as a primary
reference material for designers in the application of STM to bridge components. The examples
are as follows: (Example 1) Five-Column Bent Cap of a Skewed Bridge: this design example serves
as an introduction to the application of STM. Challenges are introduced by the bridge skew and
complicated loading pattern. A clear procedure for defining nodal geometries is presented.
(Example 2) Cantilever Bent Cap: a strut-and-tie model is developed to represent the flow of forces
around a frame corner subjected to closing loads. This is accomplished, in part, through the
design and detailing of a curved-bar node at the outside of the frame corner. (Example 3a) Inverted-
T Straddle Bent Cap (Moment Frame): an inverted-T straddle bent cap is modeled as a component
within a moment frame. Bottom-chord (ledge) loading of the inverted-T necessitates the use of
local STMs to model the flow of forces through the bent cap cross section. (Example 3b) Inverted-
T Straddle Bent Cap (Simply Supported): the inverted-T bent cap of Example 3a is designed as a
simply supported member. Results for both the moment frame case and the simply supported
case are compared to illustrate the influence of boundary condition assumptions. (Example 4)
Drilled-Shaft Footing: three-dimensional STMs are developed to properly model the flow of forces
through a deep drilled-shaft footing. Two unique load cases are considered to familiarize the
designer with the development of such models.

Computational Analysis and Design of Bridge Structures

"Prepared by members of ACI Subcommittee 445-1, Strut and Tie Models, for sessions at the Fall
Convention in Phoenix, October 27 to November 1, 2002, and sponsored by Joint ACI-ASCE
Committee 445, Shear and Torsion and ACI Committee 318-E, Shear and Torsion."

Strut and Tie Models

The quality and testing of materials used in construction are covered by reference to the
appropriate ASTM standard specifications. Welding of reinforcement is covered by reference to
the appropriate AWS standard. Uses of the Code include adoption by reference in general building
codes, and earlier editions have been widely used in this manner. The Code is written in a format
that allows such reference without change to its language. Therefore, background details or
suggestions for carrying out the requirements or intent of the Code portion cannot be included.
The Commentary is provided for this purpose. Some of the considerations of the committee in
developing the Code portion are discussed within the Commentary, with emphasis given to the
explanation of new or revised provisions. Much of the research data referenced in preparing the
Code is cited for the user desiring to study individual questions in greater detail. Other documents
that provide suggestions for carrying out the requirements of the Code are also cited.

Strut-and-tie Modeling of Two-dimensional Reinforced Concrete Structural
Elements

Emphasizing a conceptual understanding of concrete design and analysis, this revised and
updated edition builds the student’s understanding by presenting design methods in an easy to
understand manner supported with the use of numerous examples and problems. Written in
intuitive, easy-to-understand language, it includes SI unit examples in all chapters, equivalent
conversion factors from US customary to SI throughout the book, and SI unit design tables. In
addition, the coverage has been completely updated to reflect the latest ACI 318–11 code.

Examples for the Design of Structural Concrete with Strut-and-tie Models
Reinforced Concrete Design

Structural concrete designers nowadays distinguish between B-regions (named after Bernoulli beam theory) and D-regions (D standing for ‘disturbed’). They are all familiar with B-regions, but less acquainted with the expertise required for D-regions. To design D-regions, the Strut-and-Tie Model (STM) is usually applied, a model laid down worldwide in structural codes of practice. The Stringer-Panel Model (SPM) recommended here is a companion method to the STM, with the advantage of being suitable for different load cases and reversed loading. This being so, the SPM is suitable for linear-elastic analyses where durability is a key consideration, but also suits structural design for contexts of cyclical seismic activity. Finally, this book sets out how structural engineers who prefer the STM can nevertheless apply the SPM to determine a proper strut-and-tie model.

Advances in Civil Engineering

This text presents the theoretical and practical aspects of analysis and design, complemented by numerous design examples.

Space Structures 5

Anchorage Zone Reinforcement for Post-tensioned Concrete Girders

Performance-Based Optimization of Structures

fib Bulletin 61 is a continuation of fib Bulletin 16 (2002). Again the bulletin’s main objective is to demonstrate the application of the FIP Recommendations “Practical Design of Structural Concrete”, and especially to illustrate the use of strut-and-tie models to design discontinuity regions (D-regions) in concrete structures. Bulletin 61 presents 14 examples, most of which are existing structures built in recent years. Although some of the presented structures can be considered to be quite important and, in some instances, complex, the chosen examples are not intended to be exceptional. The main aim is to look at specific design aspects, by selecting D-regions of the presented structures that are designed and detailed according to the proposed design principles and specifications for the use of strut-and-tie models. Two papers at the end of the bulletin deal with the role of concrete tension fields in modelling with strut-and-tie models, and summarize the experiences gained by the Working Group in applying strut-and-tie models to the examples in the bulletin. It is hoped that fib Bulletin 61 will be of interest to engineers involved in the design of concrete structures, supporting the use of more consistent design and detailing tools such as strut-and-tie models.

Predicted Strength of Masonry Beams with Openings and Varying Vertical Reinforcement Using Strut-and-tie Modeling

Strut-and-tie modeling (STM) is an experimentally proven technique to analyze and design D-regions. STM is easy to model if the truss configuration is available. The flow of forces and stresses within the beam can be visualized with STM, and an appropriate truss can be assembled to represent the stress pattern. The required reinforcement to resist the tension at different locations can be detailed from the forces in the truss members. The study presented herein analyzes and designs deep beams subjected to point loads and uniformly distributed loads. Beams with high-strength as well as normal-strength concrete were modeled in this study. The clauses from ACI 318 (2008) are followed throughout this research. Strut-and-tie technique is an iterative process. MATLAB programs were written to perform the iterative calculations. The output from the MATLAB programs includes the longitudinal reinforcement as well as shear reinforcement required to resist the applied loads on the beam. The cases considered herein
included simply supported beams subjected to single or two point loads. The loads were placed symmetrically as well as asymmetrically. The output from the MATLAB programs was verified with the software CAST. The results from MATLAB were found to be in agreement with CAST output. A comparative study between two different models proposed in literature was performed and the results were included to justify the selection of a particular model in this research. An attempt was made in this research to generate an optimum design. The design was subjected to a large number of iterations. These iterations generated an optimum truss height and, hence, the most efficient design for the given beam properties. The strut-and-tie model considered in this research requires design of shear reinforcement as well as reinforcement to resist the transverse tensile force in the bottle shaped struts. The required reinforcement to resist the two actions (shear and transverse tension) was detailed such that excessive use of bars was avoided. The detailing of the longitudinal reinforcement was performed in a manner that would ensure ease of field installation. Preference was given to straight developed bars and smaller diameter bars. Similarly, large diameter bars were avoided as shear reinforcement. Adequate space was ensured within the bars from the same layer, with adjacent layers and shear reinforcement to facilitate concreting of the section.

CEB-FIP Model Code 1990

This design code for concrete structures is the result of a complete revision to the former Model Code 1978, which was produced jointly by CEB and FIP. The 1978 Model Code has had a considerable impact on the national design codes in many countries. In particular, it has been used extensively for the harmonisation of national design codes and as basic reference for Eurocode 2. The 1990 Model Code provides comprehensive guidance to the scientific and technical developments that have occurred over the past decade in the safety, analysis and design of concrete structures. It has already influenced the codification work that is being carried out both nationally and internationally and will continue so to do.

Use of Strut-and-tie Model for Design of Discontinuous Stress Regions in Reinforced Concrete Structures