Part 1

Introduction

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Part 1: Introduction

1 Historical remarks

The last fifteen years has brought a major breakthrough in design methods for concrete structures which reflected in the terminology used. The term "structural concrete" was proposed as a unifying term for all kinds of applications of concrete and steel in order to overcome the traditional divisions between reinforced concrete, prestressed concrete and partially prestressed concrete and even externally prestressed concrete or unreinforced concrete. These differentiations were identified as artificial, leading to confusion in codes and in teaching as well as to unnecessary restrictions in practice, as pointed out at the IABSE Colloquium "Structural Concrete" April 1991 in Stuttgart [IABSE (1991 a, b)]. Shortly thereafter the American Concrete Institute renamed the ACI 318 code accordingly.

The limitations of purely empirical design procedures has been increasingly realized, driving the demand for the development of clear design models. The theory of plasticity was applied to the design of members under shear and torsion, especially by Thürlimann (1975, 1983) and Nielsen (1978, 1984) and their co-workers. This also formed the basis for strut-and-tie models after the works of Schlaich et al. (1987, 2001). Strut-and-tie models are a valuable design tool used since the beginning of reinforced concrete design, as demonstrated by the use of truss models for the shear design e.g. by Ritter (1899), Mörsch (1909, 1912,1922), Rausch (1938, 1953) and others. This is especially true for discontinuity regions (D-regions), which have been poorly addressed in codes, even though improper design and detailing of D-regions led to structural damages including some failures [Breen (1991), Podolny (1985)]. The development of strut-and-tie models has brought the unique chance toward gaining consistency in the design concept covering D-regions and B-regions with similar models. Furthermore, the application of strut-and-tie models emphasizes the essential role of detailing in design. All this was pointed out in the State-of-the-Art Report on shear by the ASCE-ACI Committee 445 (1998).

The Appendix A of ACI 318-2002 consequently reflects this international development in research and thus is in line with some codes like the CEB-FIP Model Codes 1990, EC 2, Canadian Code and AASHTO, as well as the recent FIP Recommendations (1999) and the new German code DIN 1045-1 (2001-07).

2 Dimensioning procedures according to the present codes

The principles for the design are clearly defined in most codes, and they address the whole structure and not only sections when defining the requirements and principles for the design. Contrary to the principles, however, the dimensioning procedures and the checking procedures focus on sections, and separate checks are carried out for the different actions, such as moments and shear forces. In addition, the detailing rules given finally in codes are meant to ensure the overall safety of the structure.

The danger of a sectional design approach is that the overall flow of forces may be overlooked and that critical regions are not covered. Especially the regions with discontinuities due to the loading or/and the geometry, the D-regions, are not dimensioned but left to be covered by detailing rules, apart from some special cases (e.g. frame corners or corbels). All these considerations triggered discussions at the IABSE Colloquium "Structural Concrete" in 1991 and to the conclusions published thereafter [IABSE (1991 a, b)]. The demand for developing clear models, like strut-and-tie models, was expressed by Schlaich (1991) and Breen (1991). Most of these ideas were taken up by the FIP Commission 3 "Practical Design", chaired by Julio Appleton, and one of its Working Groups developed the FIP Recommendations "Practical design of structural concrete" published in 1999 by *fib*. These recommendations are fully based on strut-and-tie models and show the direction for future developments. However, most codes still keep to the traditional concepts and only added a new chapter or appendix without integrating the new concept throughout the code. One exception is the case of the shear design where a truss model has been used for steel contribution for many years.

3 Aim and contents of this Special Publication

The implementation of strut-and-tie models in ACI 318-2002 with Appendix A is an important step in direction towards a more consistent design concept. Even more, it is a major achievement for the engineers in practice and should trigger efforts to apply strut-and-tie models in daily practice. Therefore, the main objective of this Special Publication is to show with design examples the application of strut-and-tie models according to the Appendix A of ACI 318-2002.

This Special Publication contains five parts. After the introduction (Part 1), Part 2 gives an insight into the development of Appendix A of ACI 318-2002 and of the discussions in ACI Committee 318 E "Shear and Torsion". The scope and aim of the Appendix A is described and extensive explanations are given in addition to those already presented in the Commentary of Appendix A.

Part 3 presents a summary of important tests, which justify the use of strut-and-tie models for the design of structural concrete. Among the tests are the classical examples for D-regions like deep beams, corbels and dapped beam ends.

Part 4 forms the major part of this Special Publication presenting nine different examples designed with strut-and-tie models using Appendix A of ACI 318-2002. Most of these examples were taken from practice:

- The Example 1 (deep beam), Example 2 (dapped beam end) and Example 3 (double corbel and corbel at column) are classical D-regions, which have been designed with strut-and-tie models since long, and for which even tests were carried out, as described in Part 3.
- The Example 5 (beam with indirect supports) and Example 6 (prestessed beam) deal with well known D-regions of beams, which so far have mostly been dealt with in codes by rules for the shear design.
- The Examples 7 (pier table) and Example 9 (pile cap) deal with D-regions of 3D-structures, for the design which most codes give only rare information.

Some examples were selected to demonstrate the potential of strut-and-tie models to solve uncommon design problems, such as like Example 4 (deep beam with opening) and Example 8 (high wall with two openings).

All examples show the approach of finding a model, which is the first and an important step in a design with strut-and-tie models. The examples also point out where problems in dimensioning or in detailing and anchoring the reinforcement occur and how the design could be improved.

Part 5 gives a summary and discusses some issues which are either common for all examples or turned up in several examples. After a brief review of the procedures for finding a model, the uniqueness of a model is discussed and why different models may be selected by several engineers. The other issue addresses the transition between D- and B-regions of beams and is of general importance for many examples, because many D-regions are part of a larger structure and have to be "cut out" of it, i.e. the correct actions and forces have to be applied at the border of the D-region. Finally in Part 5 the importance of detailing is pointed out as it was demonstrated in several examples.

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Part 2

Derivation of strut-and-tie models for the 2002 ACI Code

James G. MacGregor

Synopsis

This paper documents the decisions made by ACI Committee 318 to introduce strut-and-tie models into the 2002 ACI Code. Sections 3 and 4 of this paper review code statements concerning the layout of strut-and-tie models for design. The format and values of the effective compression strength of struts are presented in Sec. 5. The first step was to derive an effective compression strength which gave the same cross-sectional area and strength using Appendix A as required by another code for the same concrete strength and same unfactored loads. The final selection of design values of the effective compression strength considered test results, design values from the literature, values from other codes, and ACI Code design strengths for similar stress situations. A similar derivation of the effective compression strengths of nodal zones is summarized in Sec. 6 of the paper. The description of the geometry of nodal zones in code language proved difficult. The design of ties is described in Sec. 7 of this paper and requirements for nominal reinforcement are in Sec. 8. Nominal reinforcement is provided to add ductility, to improve the possibility of redistribution of internal forces, and to control cracks at service loads.

James G. MacGregor received a B.Sc. in Civil Engineering from the University of Alberta, Canada in 1956, and a Ph.D. from the University of Illinois in 1960. He joined the Department of Civil Engineering at the University of Alberta in 1960, employed there until 1993. Dr. MacGregor serves on ACI technical committees on shear and torsion, columns, and the ACI Code committee. He chaired Canadian code committees on reinforced concrete design, and structural design. In 1992-93 he was president of ACI. Dr. MacGregor is an Honorary Member of ACI, a Fellow of the Royal Society of Canada, and a Fellow of the Canadian Academy of Engineering. In 1998 he received an honorary Doctor of Engineering degree from Lakehead University, and in 1999, an honorary Doctor of Science degree from the University of Alberta.

1 Introduction

The 2002 ACI Code (2002) includes a new Appendix A, "*Strut-and-Tie Models*" and changes to a number of code sections to allow the use of strut-and-tie models (STM) in design. In developing Appendix A, concepts were drawn from the AASHTO LRFD Specification (1998), the CEB/FIP Model Code (1993) as interpreted in the FIP Recommendations (1999), and the Canadian concrete design code, CSA A23.3-94 (1994). Research reports [ACI Committee 445 (1997)] also provided some of the basis for the appendix This paper, in combination with the ACI 318 Commentary for Appendix A [ACI (2002)] explains the decisions and assumptions made in the development of Appendix A.

2 Research significance

This paper documents major decisions made in the development of Appendix A, "*Strut-and-Tie Models*" in the 2002 ACI Code.

3 What are strut-and-tie models?

3.1 B-Regions and D-Regions

Concrete structures can be divided into beam-like regions where the assumption of the straight line strain distribution of flexure theory applies, and disturbed regions, adjacent to abrupt changes in loading at concentrated loads and reactions; or adjacent to abrupt changes in geometry such as holes or changes in cross section. In the latter regions the strain distributions are not linear. These different portions are referred to *B-regions* and *D-regions*, respectively.

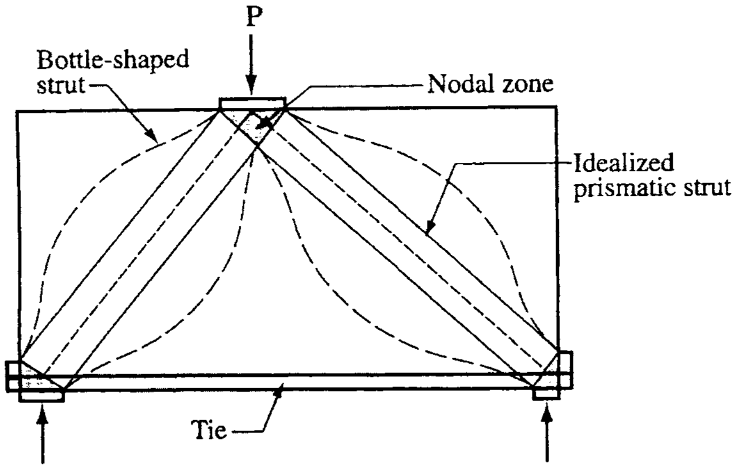

Fig. 1: A strut-and-tie model for a deep beam.

The traditional theory of flexure for reinforced concrete, and the traditional ($V_c + V_s$) design approach for shear apply in B-regions. In D-regions, on the other hand, a major portion of the load is transferred directly to the supports by in-plane compressive forces in the concrete and tensile forces in reinforcement and a different design approach is needed. D-regions may be modeled using hypothetical trusses consisting of concrete *struts* stressed in compression, steel *ties* stressed in tension, joined together at joints referred to as *nodes*. These trusses are referred to as *strut-and-tie models* (STM's).The strut and tie model of a single span deep beam shown in Fig. 1 is composed of two inclined struts, and a horizontal tie joined together at three nodes [ACI 318 (2002)]. The nodes are enclosed within *nodal zones* which transfer forces from the struts to the ties and reactions. Strut-and-tie models are assumed to fail due to yielding of the ties, crushing of the struts, failure of the nodal zones connecting the struts and ties, or anchorage failure of the ties. The struts and the nodal zones are assumed to reach their capacities when the compressive stresses acting on the ends of the struts or on the faces of the nodal zones, reach the appropriate *effective compressive strength*, f_{cu}.

De St. Venant's principle and elastic stress analyses suggest that the localized effect of a concentrated load or a geometric discontinuity will die out *about* one member depth away from the load or discontinuity. For this reason, D-regions are assumed to extend *approximately* one member depth from the load or discontinuity. The words "about" and "approximately" are emphasized here because the extent of D-regions can vary from case to case (see ACI Sec. A.1.).

If two D-regions each of length d or less, come together and touch or overlap, they are considered in Appendix A to act as a combined D-region. For a shear span in a deep beam the combined D-region has a depth of d and a length up to 2d one way or two ways from the disturbance. This establishes the smallest angle between a strut and a tie attached to one end of the strut as arctan (d / 2d) = 26.5°, rounded off to 25° (see ACI Sec. A.2.5.)

Figure 2, reproduced from "*Prestressed Concrete Structures*" [Collins and Mitchell (1991)], compares the experimental shear strengths of simply supported beams with various shear-span-to-depth ratios, a/d, from 1 to 7. B-region behavior controlled the strengths of beams with a/d greater than 2.5 as shown by the approximately horizontal line to the right of a/d = 2.5. D-region behavior controlled the strengths of beams with a/d ratios less than about 2.5 as shown by the steeply sloping line to the left of a/d = 2.5 in Fig. 2.

ACI Committee 318 limited the maximum lengths of isolated D-regions to d, and to 2d for overlapping D-regions. Strut-and-tie models can also be used in the design of B-regions [Marti (1985)]. However, the V_c term in the traditional ACI shear strength equation is not included.

Two-dimensional strut-and-tie models are used to represent planar structures such as deep beams, corbels and joints. Three-dimensional strut-and-tie models are used for structures such as pile caps for two or more rows of piles.