IN-LB	Inch-Pound Units
SI	International System of Units

Strut-and-Tie Method Guidelines for ACI 318-19—Guide

Reported by Joint ACI-ASCE Committee 445

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

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Reported by Joint ACI-ASCE Committee 445

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Josef Hegger
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Karin Reissen
Udo Wiens
Konrad Zilch

*Subcommittee 445-A Members who Developed this Guide
†Chair of Subcommittee 445-A

Additional Subcommittee 445-A Members not noted above:

Sergio Brena
I-Kuang Fang
Katrin Habel
Matthew Huizinga
Carin Roberts-Wollmann
Rafael Alves de Souza
Bozidar Stojadinovic
Nancy Larson Verney
Fernando Yanez

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Strut-and-tie models (STMs) were first used at the end of the nineteenth century as a concrete design method. The method was added to ACI 318 in 2002 as Appendix A. In 2014, STM provisions were moved into the main body of the code as Chapter 23, Strut-and-Tie Method. This document focuses on the ACI 318-19 implementation of strut-and-tie modeling. The main objectives of this document are to: 1) explain the intent and application of ACI 318 STM provisions; 2) provide additional design guidance for the STM based on other design codes, specifications, and committee documents; and 3) present design recommendations from recent research publications. This document provides practical guidance to the structural design community.

Keywords: D-regions; design; disturbed regions; model; node; strut; tie.

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CHAPTER 1—INTRODUCTION

1.1—Background

While the origins of strut-and-tie models date back to the end of the nineteenth century (Ritter 1899; Considère 1902; Mörsch 1909), the strut-and-tie design method was not formally introduced into ACI 318 until 2002. Up until the 2014 version of ACI 318, strut-and-tie model (STM) provisions were included in Appendix A of ACI 318. With the reorganization of ACI 318 in 2014, STM provisions were moved into the main body of the code as Chapter 23 in part to recognize the importance of this method in structural design practice. Subsequently, significant changes to the STM provisions occurred in ACI 318-19. Chapter 23 was renamed to "Strut-and-Tie Method." The abbreviation of STM only stands for strut-and-tie model.

In an effort to provide information on the use of strut-and-tie models in structural design, explanatory notes are included with the ACI 318 provisions. Additionally, two ACI special publications—ACI SP-208 and ACI SP-273—were developed by Subcommittee A, Strut & Tie, of Joint ACI-ASCE Committee 445, Shear and Torsion, in which the application of STM was illustrated through various design examples. Nevertheless, there is a need to provide additional guidance on the use of STM techniques.

1.2—Objectives

This document focuses on the ACI 318-19 implementation of strut-and-tie modeling. The main objectives of this document are to: 1) explain the intent and application of ACI 318 STM provisions; 2) provide additional design guidance for the STM based on other design codes, specifications, and committee documents; and 3) present design recommendations from recent research publications. This document is intended to provide practical guidance to the structural design community.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

This section defines notations used in this guide.

A_1 = loaded area for consideration of bearing strength, in.^{2} (mm^2)
A_2 = area of the lower base of the largest frustum of a pyramid, cone, or tapered wedge contained wholly within the support and having its upper base eqa l to the loaded area. The sides of the pyramid, cone, or tapered wedge should be sloped one vertical to two horizontal, in.^{2} (mm^2)
A_b = area of an individual bar or wire, in.^{2} (mm^2)
A_{core} = cross-sectional area of a member measured to the outside edges of transverse reinforcement, in.^{2} (mm^2)
A_{cs} = cross-sectional area at one end of a strut in a strut-and-tie model, taken perpendicular to the axis of the strut, in.^{2} (mm^2)
A_{cv} = gross area of concrete section bounded by web thickness and length of section in the direction of shear force considered in the case of walls, and gross area of concrete section in the case of diaphragms. Gross area is total area of the defined section minus area of any openings, in.^{2} (mm^2)
A_g = gross area of concrete section, in.^{2} (mm^2)
A_{nz} = area of a face of a nodal zone or a section through a nodal zone, in.^{2} (mm^2)
A_{ps} = area of prestressing reinforcement in flexural tension zone, in.^{2} (mm^2)
A_s = area of nonprestressed longitudinal tension reinforcement, in.^{2} (mm^2)
A_s' = area of compression reinforcement, in.^{2} (mm^2)
A_{tp} = area of prestressing reinforcement in a tie, in.^{2} (mm^2)
A_{ts} = area of nonprestressed reinforcement in a tie, in.^{2} (mm^2)
A_v = area of shear reinforcement within spacing s, in.^{2} (mm^2)
A_{vd} = total area of reinforcement in each group of diagonal bars in a diagonally reinforced coupling beam, in.^{2} (mm^2)
$A_{v,min}$ = minimum area of shear reinforcement within spacing s, in.^{2} (mm^2)
a = shear span to near support, in. (mm)
b = shear span to far support, in. (mm)
b_s = effective width of strut, in. (mm)
b_w = web width or wall thickness, in. (mm)
C = compression force acting on a nodal zone, lb (N)
D = effect of service dead load
d = distance from extreme compression fiber to centroid of longitudinal tension reinforcement, in. (mm)
d' = distance from extreme compression fiber to centroid of longitudinal compression reinforcement, in. (mm)
E = effect of horizontal and vertical earthquake-induced forces
E_c = modulus of elasticity of concrete, psi (MPa)
E_s = modulus of elasticity of reinforcement and structural steel, psi (MPa)
F_n = nominal strength of a strut, tie, or nodal zone, lb (N)
F_{nn} = nominal strength at face of a nodal zone, lb (N)
F_{ns} = nominal strength of a strut, lb (N)
F_{nt} = nominal strength of a tie, lb (N)
F_u = factored force acting in a strut, tie, or nodal zone in a strut-and-tie model, lb (N)
f_c = compressive stress in concrete, psi (MPa)
f_c' = specified compressive strength of concrete, psi (MPa)
f_{ce} = effective compressive strength of concrete in a strut or a nodal zone, psi (MPa)
f_{pu} = specified tensile strength of prestressing reinforcement, psi (MPa)
f_{py} = specified yield strength of prestressing reinforcement, psi (MPa)
f_r = modulus of rupture of concrete, psi (MPa)
f_s = calculated tensile stress in reinforcement at service loads, psi (MPa)
f_s' = stress in compression reinforcement under factored loads, psi (MPa)
f_{se} = effective stress in prestressing reinforcement (after allowance for all prestress losses), psi (MPa)
f_{si} = stress in the i-th layer of surface reinforcement, psi (MPa)
f_y = specified yield strength of reinforcement, psi (MPa)
f_{yt} = specified yield strength of transverse reinforcement, psi (MPa)
h = overall thickness or height of member, in. (mm)
I = moment of inertia of section about centroidal axis, in.^{4} (mm^4)
I_{cr} = moment of inertia of cracked section transformed to concrete, in.^{4} (mm^4)
I_e = effective moment of inertia for computation of deflection, in.^{4} (mm^4)
I_g = moment of inertia of gross concrete section about centroidal axis, neglecting reinforcement, in.^{4} (mm^4)
L = effect of service live load
ℓ = span length of beam or one-way slab; clear projection of cantilever, in. (mm)
ℓ_{anc} = length along which anchorage of a tie should occur, in. (mm)
ℓ_b = width of bearing, in. (mm)
ℓ_c = segment length of curved reinforcement, in. (mm)
ℓ_d = development length in tension of deformed bar, deformed wire, plain and deformed welded wire reinforcement, or pretensioned strand, in. (mm)
ℓ_{dc} = development length in compression of deformed bar and deformed wire, in. (mm)
ℓ_{dh} = development length in tension of deformed bar or deformed wire with a standard hook, measured from critical section to outside end of hook (straight embedment length between critical section and start of hook [point of tangency] plus inside radius of bend and one bar diameter), in. (mm)
ℓ_{dt} = development length in tension of headed deformed bar, measured from the critical section to the bearing face of the head, in. (mm)

ℓ_n = length of clear span measured face-to-face of supports, in. (mm)
ℓ_s = effective length of node, in. (mm)
N_u = factored axial force normal to cross section; to be taken as positive for compression and negative for tension, lb (N)
R = reaction, lb (N)
r_b = bend radius at the inside of a bar, in. (mm)
s = center-to-center spacing of items, such as longitudinal reinforcement, transverse reinforcement, prestressing tendons, or wires, in. (mm)
s_i = center-to-center spacing of reinforcement in the i-th layer adjacent to the surface of the member, in. (mm)
T = tension force acting on a nodal zone, lb (N)
W = effect of wind load
w_a = effective height of concrete compressive stress region, used to dimension nodal zone, in.
w_c = density (unit weight) of normalweight concrete or equilibrium density of lightweight concrete, lb/ft^3 (kg/m^3)
w_s = width of a strut perpendicular to the axis of the strut and in the plane of the strut-and-tie model, in. (mm)
w_t = effective height of concrete concentric with a tie, used to dimension nodal zone, in.
$w_{t,max}$ = maximum effective height of concrete concentric with a tie, in. (mm)
w_u = factored load per unit length of beam or one-way slab, lb/in. (kg/m)
α = angle defining the orientation of reinforcement
α_i = angle between the axis of a strut and the bars in the i-th layer of reinforcement crossing that strut
β_1 = factor relating depth of equivalent rectangular compressive stress block to depth of neutral axis
β_c = confinement modification factor for struts and nodes in a strut-and-tie model
β_n = factor to account for the effect of the anchorage of ties on the effective compressive strength of a nodal zone
β_s = factor to account for the effect of cracking and confining reinforcement on the effective compressive strength of the concrete in a strut
Δf_p = increase in stress in prestressing reinforcement due to factored loads, psi (MPa)
ε_1 = principal tensile strain in cracked concrete due to factored loads, in./in. (mm/mm)
θ = angle between axis of strut, compression diagonal, or compression field and the tension chord of the member
θ_c = the smaller of the two angles between the strut (or the resultant of two or more struts) and ties extending from a curved-bar node
θ_{cr} = angle of diagonal cracking relative to the longitudinal axis of a member
θ_v = difference between angle of diagonal cracking and compression
λ = modification factor reflecting the reduced mechanical properties of lightweight concrete, all relative to normalweight concrete of the same compressive strength
λ_s = factor used to modify shear strength based on the effects of member depth, commonly referred to as the size effect factor
ν = Poisson's ratio (may be assumed to be 0.17 for concrete with f_c' up to 10,000 psi [69 MPa])
ϕ = strength reduction factor

2.2—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

B-region—portion of a member in which it is reasonable to assume that strains due to flexure vary linearly through the section.

cover, concrete—distance between the outermost surface of embedded reinforcement and the closest outer surface of the concrete.

D-region—portion of a member within approximately a distance h of a force discontinuity or a geometric discontinuity, where nonlinear strain distributions occur.

discontinuity—abrupt change in geometry or loading.

effective depth of section—distance measured from extreme compression fiber to centroid of longitudinal tension reinforcement.

headed deformed bars—deformed bars with heads attached at one or both ends.

nodal zone—volume of concrete around a node that is assumed to transfer strut-and-tie forces through the node.

node—point in a strut-and-tie model where the axes of the struts, ties, and concentrated forces acting on the joint intersect.

node, curved bar—the bend region of a continuous reinforcing bar (or bars).

strength, design—nominal strength multiplied by a strength reduction factor ϕ.

strength, nominal—strength of a member or cross section calculated in accordance with provisions and assumptions of the strength design method before application of any strength reduction factors.

strength, required—strength of a member or cross section required to resist factored loads or related internal moments and forces in such combinations as required by codes.

strut, bottle-shaped—strut that is wider at midlength than at its ends.

strut, boundary—strut located along the boundary of a member or discontinuity region.

strut, interior—strut not located along the boundary of a member or discontinuity region.

strut-and-tie model—framework or truss model of a structural member or of a D-region in such a member made up of struts and ties connected at nodes, capable of transferring the factored loads to the supports or to adjacent B-regions.

CHAPTER 3—OVERVIEW OF THE STRUT-AND-TIE MODEL DESIGN PROCEDURE

3.1—Introduction

The strut-and-tie method is an approach to evaluate or design structural concrete by simplifying complex states of stress within a structural member into simple load paths. These load paths are idealized as two-dimensional or three-dimensional networks of straight, pin-connected, axially loaded elements that link all applied loads with supports or with adjacent portions of the structure, such as shown in Fig. 3.1. The arrangement of struts, ties, and nodes is collectively known as a strut-and-tie model (STM) and resembles a truss or framework within the body of the member.

The process of approximating the load path in a structure, or portion thereof, entails visualizing the flow of forces from the applied loads to the reactions while maintaining equilibrium of all forces. External and internal equilibrium conditions should be satisfied. The strut-and-tie method complies with the lower-bound theorem of plasticity (Baker et al. 1956; Nielsen 19[illegible]; Thürlimann et al. 19[illegible])—the concept that a structure can resist a set of applied loads as long as there is at least one stress distribution that satisfies equilibrium without violating the yield condition. Accordingly, the STM should achieve equilibrium with the applied loads without exceeding the capacity of any model component (strut, tie, or node). Thus, for design purposes, the internal force in each element of the STM is limited to that element's design strength as prescribed by the corresponding ACI 318 strut-and-tie modeling provisions. The nominal strength of each strut, tie, or node is based on the material strength as well as the geometry and other characteristics of the STM that should fall within the bounds defined by the code provisions. Strut or overall member dimensions may be controlled by sectional shear force limits. These provisions and limits are described in Chapter 4.

The strut-and-tie method is most useful when applied to regions of a structure near localized changes in geometry or applications of external loads. In these instances, the stress and strain distributions may be complex with nonlinear variation over the cross section. Because these regions are defined by the presence of one or more *discontinuities*, they are denoted D-regions, sometimes referred to as disturbed regions. Common examples include corbels, non-slender or deep beams, anchorage zones for post-tensioned tendons, and regions near openings in structural walls. In addition to these regions of complex load paths, the strut-and-tie method can be used to model simpler stress states or load paths, including those with a linear variation of strain over the cross section. B-regions, sometimes referred to as beam regions, are those portions of the structure where the assumption that plane sections remain plane is reasonable, and Bernoulli's classical beam theory is appropriate to approximate the actual behavior. Because simplified methods for the design of B-regions are available, strut-and-tie modeling is most commonly applied to the D-regions of members.

One additional consideration of the strut-and-tie method is compatibility. In the strut-and-tie method, load paths are

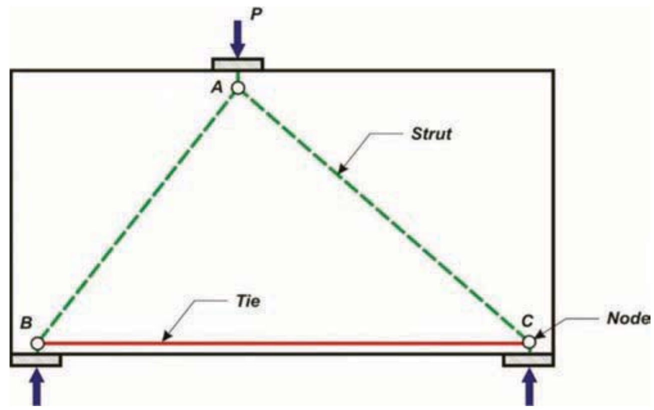

Fig. 3.1—Basic elements of a strut-and-tie model for a deep beam.

discretized into struts and ties connected at nodes, where these elements are assigned finite dimensions. The method is based on the assumption that struts carry compressive stresses, while the areas immediately adjacent to, but outside of, the strut boundaries are considered unstressed. A similar scenario exists with both ties and nodes. This simplification of the load paths leads to apparent strain discontinuities at element boundaries. These discontinuities are permissible: kinematic compatibility is not required to satisfy the lower-bound theorem of plasticity, on which the method is based. Nonetheless, compatibility considerations can be addressed by aligning the STM elements with the linear-elastic stress field to improve efficiency and service-load performance as described in Section 5.3.

3.2—Overview of the strut-and-tie method

An overview of the general strut-and-tie method for modeling and design of a structural concrete member is provided in this section. The process can be adapted to a wide variety of structure and model types. Some of the concepts described will be used later in this chapter to illustrate the application of the method through the development of an example STM. These are the basic steps of model development for each load case:

1. Determine all applied loads and reactions. This step may need to be repeated to suit the geometric layout of the STM in later steps.

2. Identify portions of a structure where the use of the strut-and-tie method may be necessary, including regions near load or geometric discontinuities. These regions are called D-regions and are discussed in more detail in Section 3.3.2.

3 Calculate all forces that should be transferred at the boundaries of the region modeled and the locations where these forces are expected to act on the STM.

4. Determine if minimum distributed reinforcement is warranted in accordance with ACI 318-19 Section 23.5. Use of distributed reinforcement may influence the allowable strut strength (Step 10).

5. Check that the member dimensions are adequate to satisfy any applicable sectional shear force limits such as those prescribed in ACI 318-19 Sections 23.4.4 or 9.9.2.

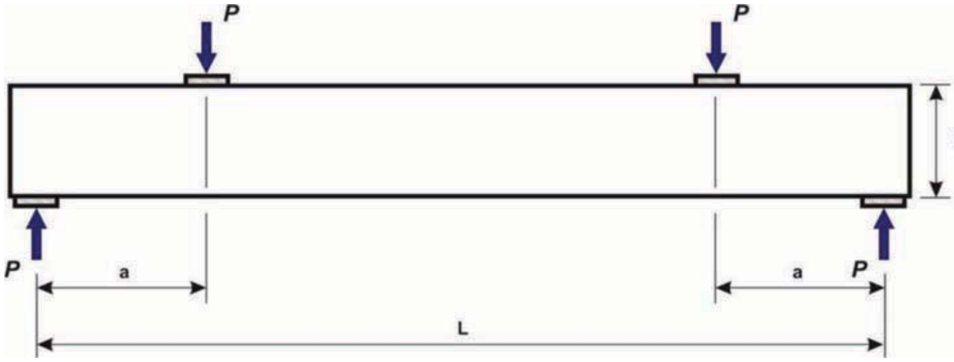

Fig. 3.3.1—Elevation view of example structure with actions.

6. Develop an STM consisting of struts and ties intersecting at nodes that is based on the flow of forces through the region to either supports or adjacent B-regions. Model development should include consideration of possible effects of cracking. In some situations, especially in more complex configurations, a linear-elastic finite element analysis (FEA) can be helpful, but not required, for establishing load paths based on principal stress trajectories. Three-dimensional effects should also be considered.

7. Calculate the internal force effects for each element within the STM to achieve equilibrium with the forces applied at the boundaries of the region modeled.

8. Determine a configuration of reinforcement, prestressed or nonprestressed, to resist all tie forces from the STM. Often, ties are sized first, as they can affect the sizes of nodes and struts and may necessitate modification of the model geometry. This process is discussed in Chapter 4.

9. Determine the geometry of the nodes and struts based on the overall model layout and the configuration of the ties chosen in the previous step. This process is discussed in Chapter 4.

10. Calculate the design strength of each strut and node by considering the relevant effectiveness factors and compare these capacities to the factored load demands at each node/strut interface.

11. Consider revisions to the STM configuration, member dimensions, or specified concrete strength as necessary to satisfy the strut or nodal strength requirements. The arrangement of reinforcement should be consistent with the geometric layout of the model. A suitable configuration of longitudinal or confinement reinforcement to enhance the strength of struts and nodes may also be considered. Recheck the design strength of all ties, struts, and nodes relative to factored forces after revising the STM.

12. Determine a configuration for additional distributed reinforcement to address serviceability and ductility considerations, such as that required by ACI 318-19 Section 23.5.1, as well as other requirements that apply to specific member types (for example, corbels). Such distributed reinforcement, if provided in sufficient quantity at appropriate locations, may increase the efficiency factor of interior struts, enhance the deformation capacity of the member, and help control crack widths in struts. These latter benefits are discussed in detail in Chapter 6 of this guide.

13. Ensure adequate anchorage of all ties. Reinforcement used as ties should be properly anchored to achieve the tie force relative to the geometric layout of each node, in accordance with Section 23.8 and Chapter 25 of ACI 318-19. Adequate anchorage of the distributed reinforcement should also be achieved.

3.3—Conceptual example

3.3.1 *Introduction*—This section presents an introductory discussion of the strut-and-tie method based on a conceptual example, which is presented to introduce and illustrate general strut-and tie modeling concepts. Subsequent chapters include details of STM application. The example structure consists of a simply-supported beam shown in Fig. 3.3.1. The self-weight is neglected for simplicity in this conceptual example.

In general, several load combinations may need to be investigated for any given member or structure and each may require a different geometric configuration of the STM to maintain static equilibrium at the nodes. Further, the presence of movable gravity loads or reversing lateral loads may necessitate the use of a different STM for each load pattern or combination. Given the simplicity of this example structure, a single load case is sufficient for discussion.

3.3.2 *Identification of B- and D-regions*—After the applied loads and corresponding reactions are determined, the structure is divided into B-regions and D-regions. The B-regions can be designed and detailed with cross-sectional strength methods described in Chapter 22 of ACI 318-19. The use of an STM as described in Chapter 23 of ACI 318-19 is also allowed in these regions. In the D-regions, conventional beam theory from Chapter 22 of ACI 318-19 that assumes a linear variation of strains over the cross section is not a reasonable basis for design. Instead, STMs are used to represent idealized load paths in these D-regions.

Based on St. Venant's principle, D-regions are normally identified as regions occurring within one cross-sectional dimension *h* of a geometric or load discontinuity. A commonly adopted value of *h* is the cross-sectional dimension perpendicular to the axis of bending. The actual length of the segment selected for analysis can be expanded to larger regions if desired or if required to ensure the adequate

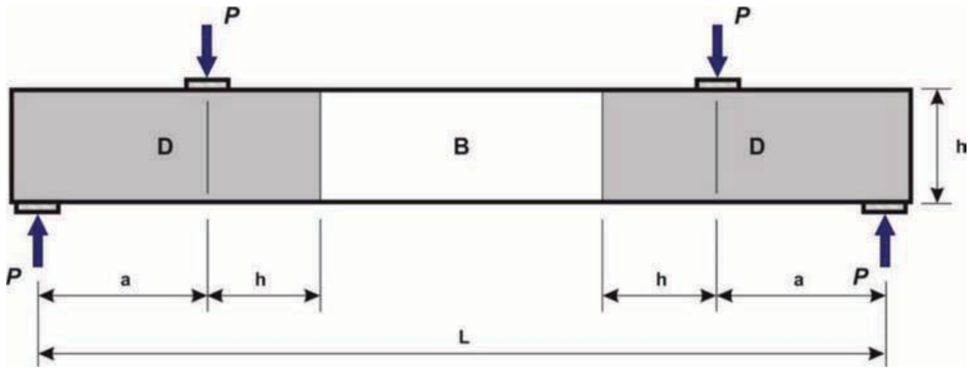

Fig. 3.3.2a—B- and D-regions of example structure.

transition of the load path from the D-region to adjacent B-regions.

For the example beam, two D-regions resulting from loading discontinuities are determined as illustrated in Fig. 3.3.2a. Each of these two shaded D-regions represents the overlapping discontinuity zones that result from the applied load and the reaction force near each end of the beam. A single B-region occupies the remaining portion of the beam. Due to the symmetry of the beam and this load case, strut-and-tie modeling will be discussed only for the D-region at the left end of the beam.

ACI 318-19 contains additional guidance on the determination of D-regions for the common types of geometric or loading discontinuities depicted in Fig. 3.3.2b, along with the forces acting on the D-region boundaries. The geometric discontinuities in Fig. 3.3.2b(a) are so named because the disturbance arises from an abrupt change in the geometric shape of a member. Loading discontinuities shown in the left three cases in Fig. 3.3.2b(b) arise due to the presence of a localized application of load, including support reactions or applied concentrated loads, as is the case in this example. A corbel, as shown at right in Fig. 3.3.2b(b), is influenced by both geometric and loading discontinuities.

3.3.3 *Boundary forces and basic strut-and-tie model*—The forces acting on each of the boundaries of each D-region are determined next. Figure 3.3.3 indicates the internal sectional load effects (shear force V and bending moment M) computed at the D-region boundary within the beam, as well as how these load effects are resolved into forces acting on the selected STM. These forces should be equilibrated by the load path defined by the model.

This simple direct-strut model represents an intuitive flow of forces in the D-region. Struts are indicated as thick, dashed lines (green); ties are thick, solid lines (red). The lower chord provides tension resistance whereas the upper chord and the diagonal Strut AJ are in compression. The depth of the lower chord is determined by the practical location of tension reinforcement and by the dimensions of nodes described later. The depth of the upper chord is at first estimated; this could be done by employing the equivalent rectangular compressive stress distribution used in B-region design. The diagonal that frames into Node C carries no force because there is no shear force V on the model boundary. Likewise, the vertical CJ carries no force. These zero-force members (indicated

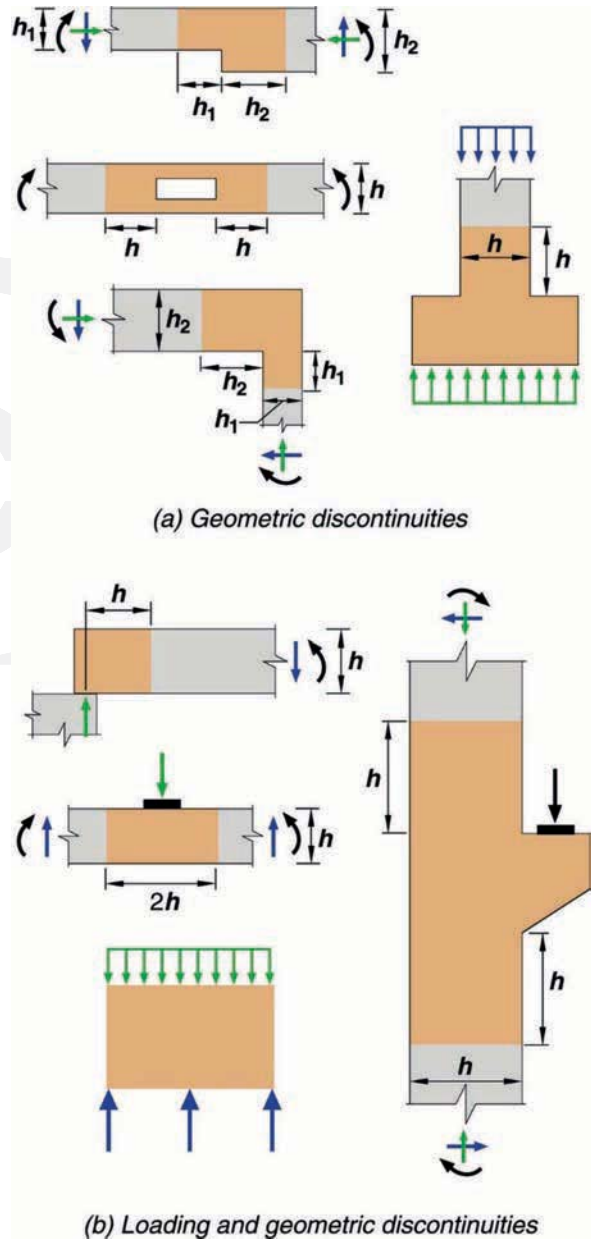

Fig. 3.3.2b—Types of D-regions (ACI 318-19 Fig. R23.1).

with thin, dotted lines and labeled 0) are often not explicitly included in the STM. However, they would become necessary to transmit forces if the loading was changed to