

PART VI
Appendix I
Strut-and-Tie Models

I.1 Scope and Definitions

Scope: Strut-and-Tie model is elaborated in this Appendix. Sec. I.1 introduces the basic definitions. The design procedure by Strut-and-Tie model is described in Sec. I.2. Strength of struts, ties and nodal zones are given in Sections I.3, I.4 and I.5 respectively. Definitions and clauses in the above sections are followed by clarifications as necessary.

B-region: A region of a member where the plane sections assumption of flexure theory from Sec 6.3.2.2 can be applied. In general, B-region is any portion of a member outside of a D-region.

Discontinuity: An abrupt change in loading or geometry.

Clarification for Discontinuity: It is assumed that discontinuities extend a distance h from the section where the load or change in geometry occurs. Figure 6.I.1(a) shows typical geometric discontinuities, and Figure 6.I.1(b) shows combined geometrical and loading discontinuities.

D-region: The region of a member within a distance, h , from a force discontinuity or a geometric discontinuity.

Clarification for D-region: Typical D-regions are the shaded regions in Figure 6.I.1(a) and Figure 6.I.1(b). The plane sections assumption of Sec 6.3.2.2 is not applicable in such regions. Each shear span of the beam in Figure 6.I.2(a) is a D-region.

When two D-regions overlap or meet as shown in Figure 6.I.2(b), they can be considered as a single D-region for design purposes. The maximum length-to-depth ratio of such a D-region would be approximately 2. Thus, the smallest angle between the strut and the tie in a D-region is $\arctan \frac{1}{2} = 26.5^\circ$, rounded to 25° .

When there is a B-region between the D-regions in a shear span, as shown in Figure 6.I.2(c), the strength of the shear span is governed by the strength of the B-region if the B- and D-regions have similar geometry and reinforcement, as because the shear strength of a B-region is less than the shear strength of a comparable D-region. Shear spans containing B-regions-the usual case in beam design-are designed for shear using the traditional shear design procedures from Sections 6.4.1 to 6.4.4 ignoring D-regions.

Deep Beam: See Sections 6.3.7.1 and 6.4.6.1.

Clarification for Deep Beam: See Figures 6.I.2(a), 6.I.2(b), and 6.I.3, and Sections 6.3.7 and 6.4.6.

Nodal Zone: The volume of concrete around a node assumed to transfer strut-and-tie forces through the node.

Clarification for Nodal Zone: Hydrostatic nodal zones as shown in Figure 6.I.4 were used traditionally. These were largely superseded by what are called extended nodal zones, shown in Figure 6.I.5.

A hydrostatic nodal zone has equal stresses on the loaded faces which are perpendicular to the axes of the struts and ties acting on the node. A C-C-C nodal zone is shown in Figure 6.I.4(a). If the stresses on the face of the nodal zone are the same in all three struts, the ratios of the lengths of the sides of the nodal zone, w_{n1} : w_{n2} : w_{n3} are in the same proportions as the three forces C_1 : C_2 : C_3 . The faces of a hydrostatic nodal zone are perpendicular to the axes of the struts and ties acting on the nodal zone.

As the in-plane stresses are the same in all directions, these nodal zones are called hydrostatic nodal zones. This terminology, strictly speaking, is incorrect because the in-plane stresses are not equal to the out-of-plane stresses.

A C-C-T nodal zone can be represented as a hydrostatic nodal zone if the tie is assumed to extend through the node to be anchored by a plate on the far side of the node, as shown in Figure 6.I.4(b), provided that the size of the plate results in bearing stresses that are equal to the stresses in the struts. The bearing plate on the left side of Figure 6.I.4(b) is used to represent an actual tie anchorage. The tie force can be anchored by a plate, or through development of straight or hooked bars, as shown in Figure 6.I.4(c).

Portion of a member bounded by the intersection of the effective strut width, w_s , and the effective tie width, w_t (see Sec I.4.2) is an extended nodal zone. The shaded areas in Figures 6.I.5(a) and (b) are extended nodal zones.

The reaction R equilibrates the vertical components of the forces C_1 and C_2 in the nodal zone shown in Figure 6.I.6(a). Frequently, calculations are easier if the reaction R is divided into R_1 , which equilibrates the vertical component of C_1 and R_2 , which equilibrates the vertical component of the force C_2 , as shown in Figure 6.I.6(b).

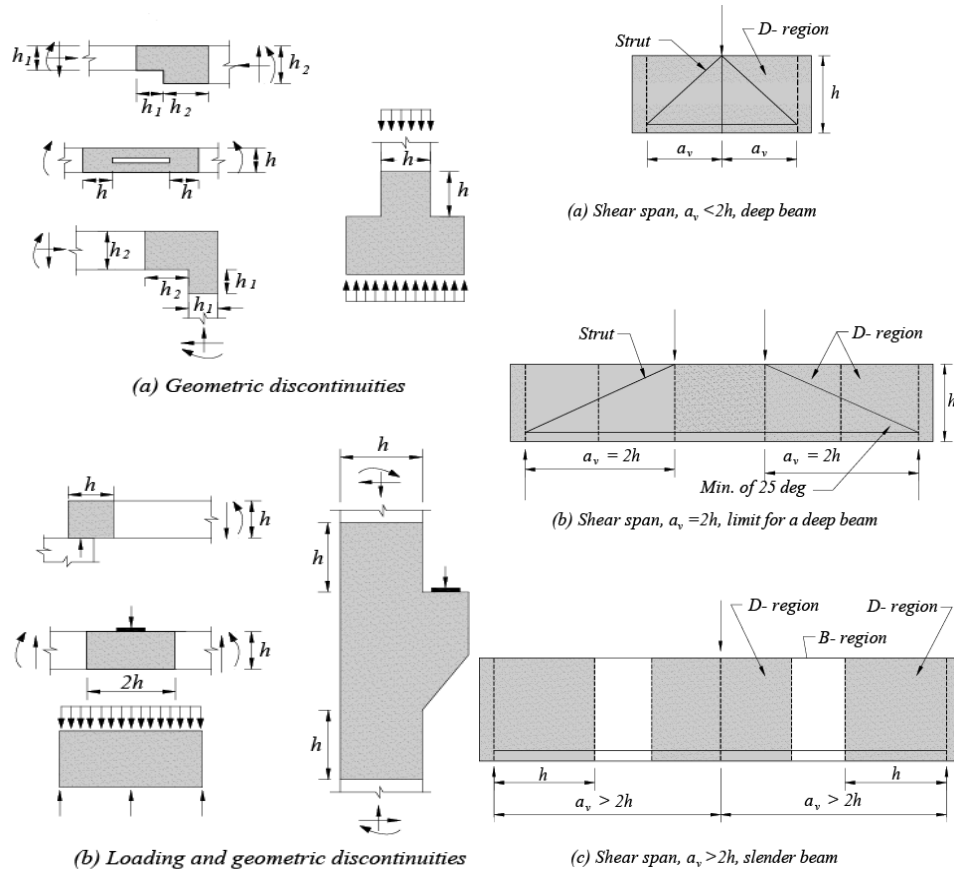


Figure 6.1.1 D-Regions and discontinuities

Figure 6.1.2 Description of deep and slender beams

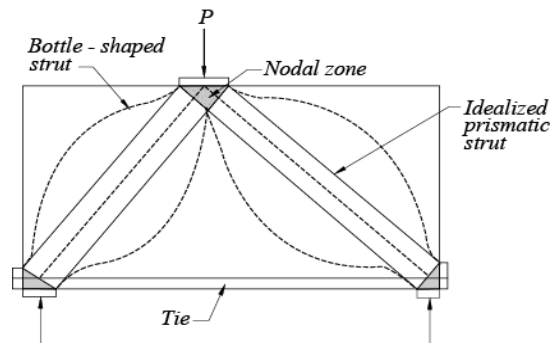


Figure 6.1.3 Description of strut-and-tie model

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

Clarification for Node: To be in equilibrium, at least three forces should act on a node in a strut-and-tie model, as shown in Figure 6.I.7. Classification of nodes is based on signs of these forces. A C-C-C node resists three compressive forces, a C-C-T node resists two compressive forces and one tensile force, and so on.

Strut: A member that is in compression in a strut-and-tie model. A strut represents the resultant of a parallel or a fan-shaped compression field.

Clarification for Strut: Struts are usually idealized in design as prismatic compression members, as shown by the straight line outlines of the struts in Figures 6.I.2 and 6.I.3. The strut is idealized as a uniformly tapered compression member, if the effective compression strength f_{ce} differs at the two ends of a strut, due either to different nodal zone strengths at the two ends, or to different bearing lengths.

Bottle-shaped Strut: A strut that is wider at mid-length than at its ends.

Clarification for Bottle-shaped Struts: A strut located in a part of a member where the width of the compressed concrete at mid-length of the strut can spread laterally is a bottle-shaped strut. The curved dashed outlines of the struts in Figure 6.I.3 and the curved solid outlines in Figure 6.I.8 approximate the boundaries of bottle-shaped struts. A split cylinder test is an example of a bottle-shaped strut. The internal lateral spread of the applied compression force in such a test leads to a transverse tension that splits the specimen.

Bottle-shaped struts are idealized either as prismatic or as uniformly tapered in design, and crack-control reinforcement from Sec I.3.3 is provided to resist the transverse tension. The amount of confining transverse reinforcement can be computed using the strut-and-tie model shown in Figure 6.I.8(b) with the struts that represent the spread of the compression force acting at a slope of 1:2 to the axis of the applied compressive force. Alternatively for f_c' not exceeding 40 MPa, Eq. (I.4) can be used. The cross-sectional area A_c of a bottle-shaped strut is taken as the smaller of the cross-sectional areas at the two ends of the strut. See Figure 6.I.8(a).

Strut-and-tie Model: A 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.

Clarification for Strut-and-tie Model: In Figure 6.I.3, the components of a strut-and-tie model of a single-span deep beam loaded with a concentrated load are identified. The thickness and width, both perpendicular to the axis of the strut or tie are designated as the cross-sectional dimensions of a strut or tie. Thickness is perpendicular to the plane of the truss model, and width is in the plane of the truss model.

Clarification for Tie. A tie is a member consisting of reinforcement or pre-stressing steel plus a portion of the surrounding concrete that is concentric with the axis of the tie. The surrounding concrete is included to define the zone in which the forces in the struts and ties are to be anchored. The concrete in a tie is not used to resist the axial force in the tie. Although not considered in design, the surrounding concrete will reduce the elongations of the tie, especially at service loads.

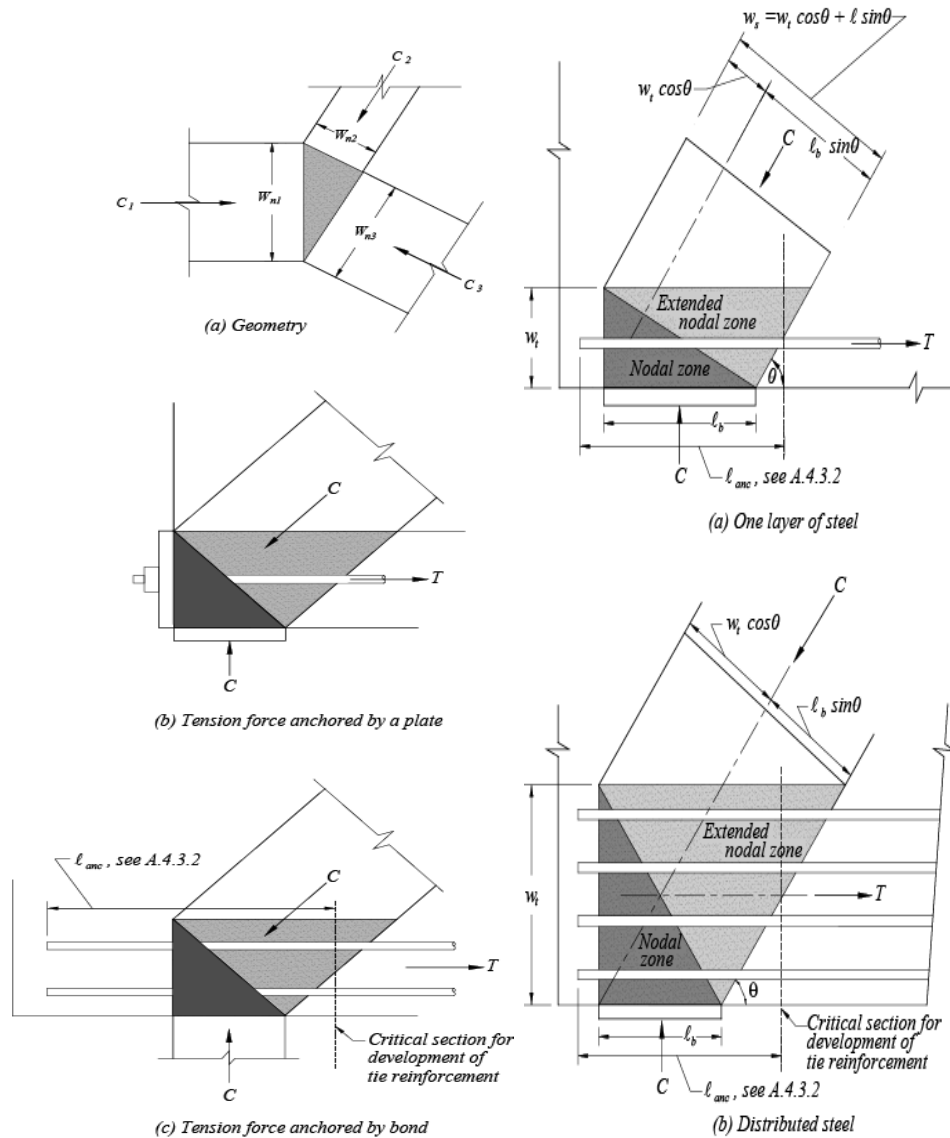


Figure 6.I.5 Extended nodal zone showing the effect of the distribution of the force

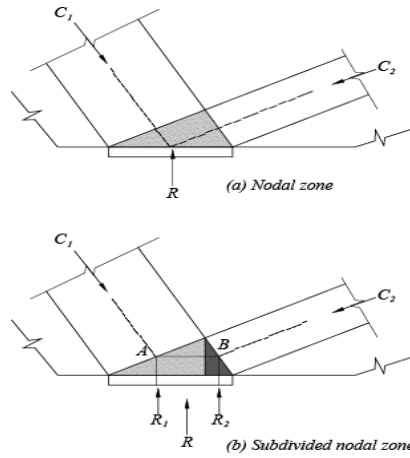


Figure 6.I.6 Subdivision of nodal zone

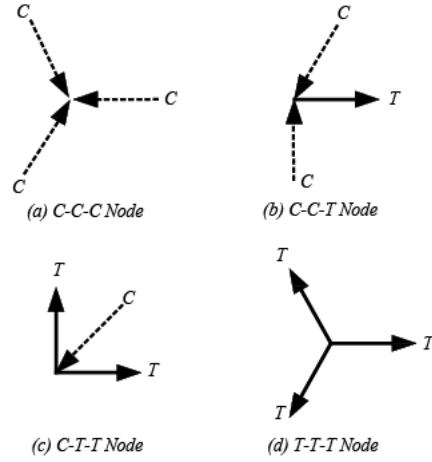


Figure 6.I.7 Classification of nodes

I.2 Design Procedure for Strut-and-Tie Model

I.2.1 It shall be allowed to design structural concrete members, or D-regions in such members, by modeling the member or region as an idealized truss. The truss model shall contain struts, ties, and nodes as defined in Sec I.1. The truss model shall be capable of transferring all factored loads to the supports or adjacent B-regions.

Clarification for Section I.2.1: The truss model described in Sec I.2.1 is what is referred to as a strut-and-tie model. Details of the use of strut-and-tie models are available in References I.1 to I.7 of Sec I.6. The design of a D-region includes the following four steps:

- First, define and isolate each D-region;
- Then, compute resultant forces on each D-region boundary;
- Then, a truss model is to be selected to transfer the resultant forces across the D-region. The axes of the struts and ties, respectively, are chosen to approximately coincide with the axes of the compression and tension fields. The forces in the struts and ties are computed.
- Finally, the effective widths of the struts and nodal zones are determined considering the forces from Step 3 and the effective concrete strengths defined in Sections I.3.2 and I.5.2, and reinforcement is provided for the ties considering the steel strengths defined in Sec I.4.1. The reinforcement should be anchored in the nodal zones.

Code requirements for serviceability should be satisfied for strut-and-tie models representing strength limit states. Deflections of deep beams or similar members can be estimated using an elastic analysis to analyze the strut-and-tie model. In addition, the crack widths in a tie can be controlled using Sec 6.3.6.4, assuming the tie is encased in a prism of concrete corresponding to the area of tie from Sec I.4.2.

I.2.2 Under the applied loads and the reactions, the strut-and-tie model shall be in equilibrium.

I.2.3 The dimensions of the struts, ties, and nodal zones shall be taken into account in determining the geometry of the truss,

Clarification for Section I.2.3: The components of the strut-and-tie model, i.e. the struts, ties, and nodal zones, all have finite widths that should be taken into account in selecting the dimensions of the truss. Figure 6.I.9(a) shows a node and the corresponding nodal zone. The vertical and horizontal forces equilibrate the force in the inclined strut. If the stresses are equal in all three struts, a hydrostatic nodal zone can be used and the widths of the struts will be in proportion to the forces in the struts.

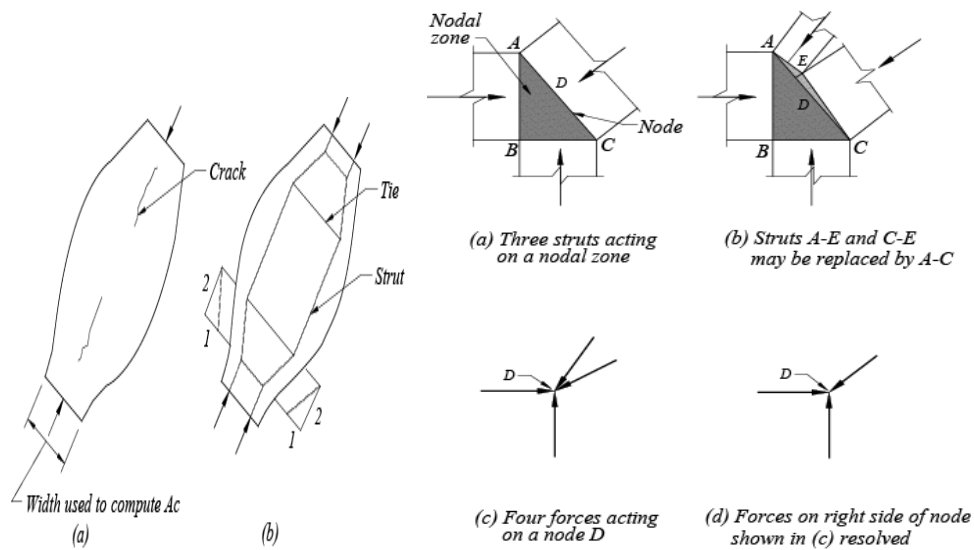


Figure 6.I.8 Bottle-shaped strut:
(a) cracking of a bottle-shaped strut; and (b) strut-and-tie model of a bottle-shaped strut

Figure 6.I.9 Resolution of forces on a nodal zone

When more than three forces act on a nodal zone in a two-dimensional structure, as shown in Figure 6.I.9(b), it is generally necessary to resolve some of the forces to end up with three intersecting forces. The strut forces acting on Faces A-E and C-E in Figure 6.I.9(b) can be replaced with one force acting on Face A-C. This force passes through the node at D.

Alternatively, the strut-and-tie model could be analyzed assuming all the strut forces acted through the node at D, as shown in Figure 6.I.9(c). In this case, the forces in the two struts on the right side of Node D can be resolved into a single force acting through Point D, as shown in Figure 6.I.9(d).

Transverse reinforcement may be required to restrain vertical splitting in the plane of the node when the width of the support in the direction perpendicular to the member is less than the width of the member. This can be modeled using a transverse strut-and-tie model.

I.2.4 Ties shall be permitted to cross struts. Struts shall cross or overlap only at nodes.

I.2.5 The angle, θ , between the axes of any strut and any tie entering a single node shall not be taken as less than 25° .

Clarification for Section I.2.5: In order to mitigate cracking and to avoid incompatibilities due to shortening of the struts and lengthening of the ties occurring in almost the same directions, the angle between the axes of struts and ties acting on a node should be large enough. This limitation on the angle prevents modeling the shear spans in slender beams using struts inclined at less than 25° from the longitudinal steel (Reference I.6 of Sec I.6).

I.2.6 Struts, ties, and nodal zones shall be designed based on

$$\phi F_n \geq F_u \quad (6.I.1)$$

Where, F_u is the factored force acting in a strut, in a tie, or on one face of a nodal zone; F_n is the nominal strength of the strut, tie, or nodal zone; and ϕ is specified in Sec 6.2.3.2.6.

Clarification for Section I.2.6: The forces in all the struts, ties, and nodal zones are computed after applying factored loads to the strut-and-tie model. If several loading cases exist, each should be investigated. The strut-and-tie model, or models, are analyzed for the loading cases and, for a given strut, tie, or nodal zone, F_u is the largest force in that element for all loading cases.

I.3 Strength of Struts

I.3.1 For a strut without longitudinal reinforcement, the nominal compressive strength, F_{ns} , shall be taken as the smaller value of

$$F_{ns} = f_{ce} A_{cs} \quad (6.I.2)$$

at the two ends of the strut, where A_{cs} is the cross-sectional area at one end of the strut, and f_{ce} is the smaller of (a) and (b):

- (a) the effective compressive strength of the concrete in the strut given in Sec I.3.2;
- (b) the effective compressive strength of the concrete in the nodal zone given in Sec I.5.2.

Clarification for Section I.3.1: The smaller dimension perpendicular to the axis of the strut at the ends of the strut is taken as the width of strut w_s used to compute A_{cs} . This strut width is illustrated in Figures 6.I.4(a), 6.I.5(a) and 6.I.5(b). The thickness of the struts may be taken as the width of the member in two-dimensional structures, such as deep beams.

I.3.2 The effective compressive strength of the concrete, f_{ce} , in a strut shall be taken as

$$f_{ce} = 0.85\beta_s f'_c \quad (6.I.3)$$

Clarification for Section I.3.2: The strength coefficient, $0.85f'_c$, in Eq. 6.I.3 represents the effective concrete strength under sustained compression, similar to that used in Equations 6.6.8 and 6.6.9.

I.3.2.1 When a strut has uniform cross-sectional area over its length, $\beta_s = 1.0$

Clarification for Section I.3.2.1: The value of β_s in Sec I.3.2.1 applies to a strut equivalent to the rectangular stress block in a compression zone in a beam or column.

I.3.2.2 For struts located such that the width of the midsection of the strut is larger than the width at the nodes (bottle-shaped struts):

- (a) With reinforcement satisfying Sec I.3.3, $\beta_s = 0.75$
- (b) Without reinforcement satisfying Sec I.3.3, $\beta_s = 0.60\lambda$

Where the value of λ is defined in Sec 6.1.8.1.

Clarification for Section I.3.2.2: The value of β_s given in Sec I.3.2.2 applies to bottle-shaped struts as shown in Figure 6.I.3. The internal lateral spread of the compression forces can lead to splitting parallel to the axis of the strut near the ends of the strut, as shown in Figure 6.I.8. Reinforcement placed to resist the splitting force restrains crack width, allows the strut to resist more axial load, and permits some redistribution of force.

The value given for β_s in Sec I.3.2.2(b) includes the correction factor, λ , for lightweight concrete because the strength of a strut without transverse reinforcement is assumed to be limited to less than the load at which longitudinal cracking develops.

I.3.2.3 For struts in tension members, or the tension flanges of members, $\beta_s = 0.40$

Clarification for Section I.3.2.3: The value given for β_s in Sec I.3.2.3 applies, for example, to compression struts in a strut-and-tie model used to design the longitudinal and transverse reinforcement of the tension flanges of beams, box girders, and walls. The low value of β_s reflects that these struts need to transfer compression across cracks in a tension zone.

I.3.2.4 For all other cases, $\beta_s = 0.60\lambda$

Clarification for Section I.3.2.4: The value given for β_s in Sec I.3.2.4 applies to strut applications not included in Sections I.3.2.1, I.3.2.2, and I.3.2.3. Examples are struts in a beam web compression field in the web of a beam where parallel diagonal cracks are likely to divide the web into inclined struts, and struts are likely to be crossed by cracks at an angle to the struts [see Figures 6.I.10(a) and (b)]. Sec I.3.2.4 gives a reasonable lower limit on β_s except for struts described in Sections I.3.2.2(b) and I.3.2.3.

I.3.3 If the specified value of β_s in Sec I.3.2.2(a) is used, the axis of the strut shall be crossed by reinforcement proportioned to resist the transverse tensile force resulting from the compression force spreading in the strut. It shall be permitted to assume the compressive force in the strut spreads at a slope of 2 longitudinal to 1 transverse to the axis of the strut.

Clarification for Section I.3.3: The reinforcement necessary from Sec I.3.3 is related to the tension force in the concrete due to the spreading of the strut, as shown in the strut-and-tie model in Figure 6.I.8(b). Sec I.3.3 allows the use of local strut-and-tie models to compute the amount of transverse reinforcement needed in a given strut. The compressive forces in the strut may be assumed to spread at a 2:1 slope, as shown in Figure 6.I.8(b). For specified concrete compressive strengths not exceeding 40 MPa, the amount of reinforcement required by Eq. 6.I.4 is deemed to satisfy Sec I.3.3.

Figure 6.I.11 shows two layers of reinforcement crossing a cracked strut. If the crack opens without shear slip along the crack, bars in layer i in the figure will cause a stress perpendicular to the strut of $\frac{A_{si}f_{si}}{b_s s_i} \sin \alpha_i$.

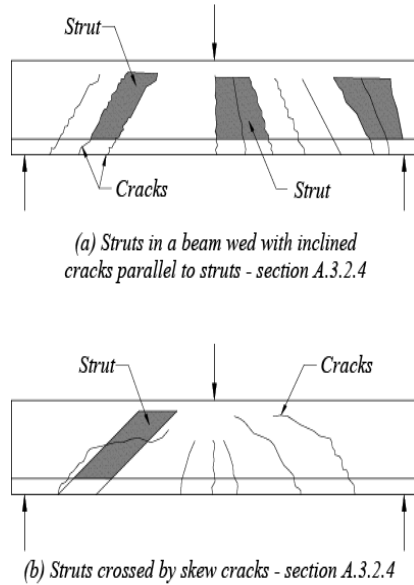


Figure 6.I.10 Types of struts

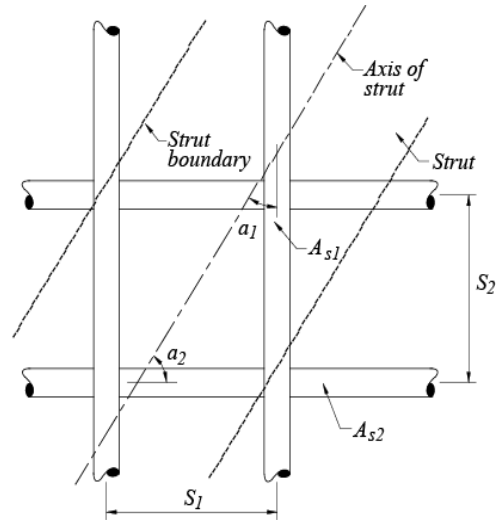


Figure 6.I.11 Reinforcement crossing a strut

Where the subscript i shall have the values of 1 and 2 for the vertical and horizontal bars, respectively, as shown in Figure 6.I.11. Eq. 6.I.4 is written in terms of a reinforcement ratio rather than a stress to simplify the calculation.

The confinement reinforcement given in Sec I.3.3 is difficult to place in three-dimensional structures (e.g. pile caps) most of the time. If this reinforcement is not provided, the value of f_{ce} given in Sec I.3.2.2(b) is used.

I.3.3.1 For f_c' not exceeding 40 MPa, the requirement of Sec I.3.3 shall be permitted to be satisfied by the axis of the strut being crossed by layers of reinforcement that satisfy Eq. 6.I.4.

$$\sum \frac{A_{si}}{b_s s_i} \sin \alpha_i \geq 0.003 \quad (6.I.4)$$

Where A_{si} is the total area of surface reinforcement at spacing s_i in the i -th layer of reinforcement crossing a strut at an angle α_i to the axis of the strut.

I.3.3.2 The reinforcement necessary in Sec I.3.3 shall be placed in either two orthogonal directions at angles α_1 and α_2 to the axis of the strut, or in one direction at an angle α to the axis of the strut. If the reinforcement is in one direction only, α shall not be less than 40° .

Clarification for Section I.3.3.2: The confinement reinforcement required to satisfy Sec I.3.3 is usually provided in the form of horizontal stirrups crossing the inclined compression strut in a corbel with a shear span-to-depth ratio less than 1.0, as shown in Figure 6.6.13 Chapter 6.

I.3.4 It shall be permitted to use an increased effective compressive strength of a strut due to confining reinforcement, if supported by tests and analyses.

Clarification for Section I.3.4: The design of tendon anchorage zones for pre-stressed concrete sometimes uses confinement to enhance the compressive strength of the struts in the local zone. Confinement of struts is discussed in References I.4 and I.8 of Sec I.6.

I.3.5 It shall be permitted to use compression reinforcement to increase the strength of a strut. Compression reinforcement shall be properly anchored, parallel to the axis of the strut, located within the strut, and enclosed in ties or spirals satisfying Sec 8.1.10 Chapter 8. In such cases, the nominal strength of a longitudinally reinforced strut is

$$F_{ns} = f_{ce} A_{cs} + A_s' f_s' \quad (6.I.5)$$

Clarification for I.3.5 - The last term in Eq. 6.I.5 gives the strength added by the reinforcement. The stress f_s' in the reinforcement in a strut at nominal strength can be obtained from the strains in the strut when the strut crushes. For Grade 40 or 60 reinforcement, f_s' can be taken as f_y .

I.4 Strength of Ties

I.4.1 The nominal strength of a tie, F_{nt} , shall be taken as

$$F_{nt} = A_{ts}f_y + A_{tp}(f_{se} + \Delta f_p) \quad (6.I.6)$$

Where $(f_{se} + \Delta f_p)$ shall not exceed f_{py} , and A_{tp} is zero for nonprestressed members.

In Eq. (I.6), it shall be permitted to take Δf_p equal to 420 MPa for bonded prestressed reinforcement, or 70 MPa for unbonded prestressed reinforcement. Other values of Δf_p shall be permitted when justified by analysis.

I.4.2 In the strut-and-tie model, the axis of the reinforcement in a tie shall coincide with the axis of the tie.

Clarification for Section I.4.2: The effective tie width w_t assumed in design can vary between the following limits, depending on the distribution of the tie reinforcement:

- (a) If the bars in the tie are in one layer, the effective tie width can be taken as the diameter of the bars in the tie plus twice the cover to the surface of the bars, as shown in Figure 6.I.5(a); and
- (b) A practical upper limit of the tie width can be taken as the width corresponding to the width in a hydrostatic nodal zone, calculated as

$$w_{t,max} = F_{nt}/(f_{ce}b_s)$$

Where f_{ce} is computed for the nodal zone in accordance with Sec I.5.2. If the tie width exceeds the value from (a), the tie reinforcement should be distributed approximately uniformly over the width and thickness of the tie, as shown in Figure 6.I.5(b).

I.4.3 Anchorage of tie reinforcement by mechanical devices, post-tensioning anchorage devices, standard hooks, or straight bar development as required by Sections I.4.3.1 to I.4.3.4 shall be ensured.

Clarification for Section I.4.3: Special attention is often required for anchorage of ties in nodal zones of corbels or in nodal zones adjacent to exterior supports of deep beams. The reinforcement in a tie should be anchored before it leaves the extended nodal zone at the point defined by the intersection of the centroid of the bars in the tie and the extensions of the outlines of either the strut or the bearing area. This length is l_{anc} . In Figure 6.I.5(a) and (b), this occurs where the outline of the extended nodal zone is crossed by the centroid of the reinforcement in the tie. Some of the anchorage may be achieved by extending the reinforcement through the nodal zone, as shown in Figure 6.I.4(c), and developing it beyond the nodal zone. If the tie is anchored using 90-degree

hooks, the hooks should be confined within the reinforcement extending into the beam from the supporting member to avoid cracking along the outside of the hooks in the support region.

In deep beams, hairpin bars spliced with the tie reinforcement can be used to anchor the tension tie forces at exterior supports, provided the beam width is large enough to accommodate such bars.

Figure 6.I.12 shows two ties anchored at a nodal zone. Development is required where the centroid of the tie crosses the outline of the extended nodal zone.

The development length of the tie reinforcement can be reduced through hooks, mechanical devices, additional confinement, or by splicing it with several layers of smaller bars.

I.4.3.1 Nodal zones shall develop the difference between the tie force on one side of the node and the tie force on the other side.

I.4.3.2 At nodal zones anchoring one tie, the tie force shall be developed at the point where the centroid of the reinforcement in a tie leaves the extended nodal zone and enters the span.

I.4.3.3 At nodal zones anchoring two or more ties, the tie force in each direction shall be developed at the point where the centroid of the reinforcement in the tie leaves the extended nodal zone.

I.4.3.4 The transverse reinforcement required by Sec I.3.3 shall be anchored in accordance with Sec 8.2.10 Chapter 8.

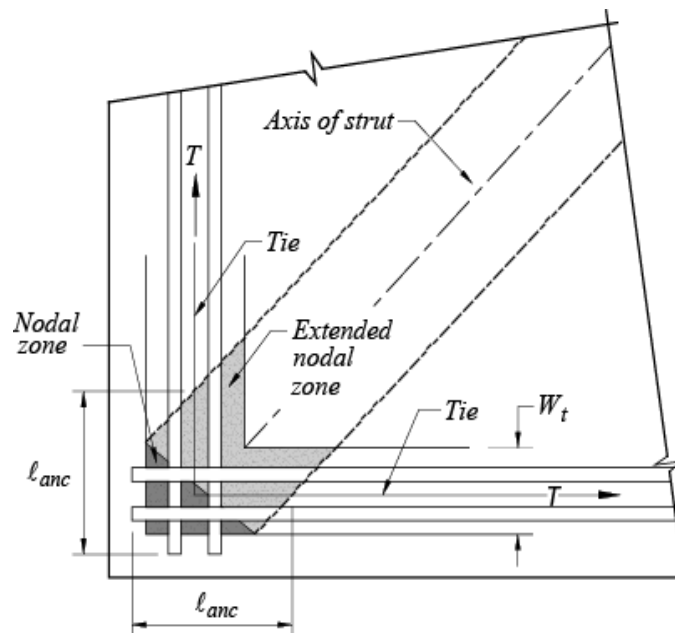


Figure 6.I.12 Extended nodal zone anchoring two ties

I.5 Strength of Nodal Zones

I.5.1 The Nominal compression strength of a nodal zone, F_{nn} , shall be

$$F_{nn} = f_{ce} A_{nz} \quad (6.1.7)$$

Where f_{ce} is the effective compressive strength of the concrete in the nodal zone as given in Sec I.5.2, and A_{nz} is the smaller of (a) and (b):

- (a) The area of the face of the nodal zone on which F_u acts, taken perpendicular to the line of action of F_u ;
- (b) The area of a section through the nodal zone, taken perpendicular to the line of action of the resultant force on the section.

Clarification for Section I.5.1: A hydrostatic nodal zone can be used, if the stresses in all the struts meeting at a node are equal. The faces of such a nodal zone are perpendicular to the axes of the struts, and the widths of the faces of the nodal zone are proportional to the forces in the struts.

Assuming the principal stresses in the struts and ties act parallel to the axes of the struts and ties, the stresses on faces perpendicular to these axes are principal stresses, and Sec I.5.1(a) is used. If, as shown in Figure 6.1.5(b), the face of a nodal zone is not perpendicular to the axis of the strut, there will be both shear stresses and normal stresses on the face of the nodal zone. Typically, these stresses are replaced by the normal (principal compression) stress acting on the cross-sectional area A_c of the strut, taken perpendicular to the axis of the strut as given in Sec I.5.1(a).

Sec I.5.1(b) requires in some cases that the stresses be checked on a section through a subdivided nodal zone. The stresses are checked on the least area section which is perpendicular to a resultant force in the nodal zone. In Figure 6.1.6(b), the vertical face which divide the nodal zone into two parts is stressed by the resultant force acting along A-B. The design of the nodal zone is governed by the critical section from Sec I.5.1(a) or Sec I.5.1(b), whichever gives the highest stress.

I.5.2 The calculated effective compressive stress, f_{ce} , on a face of a nodal zone due to the strut-and-tie forces shall not exceed the value given by

$$f_{ce} = 0.85 \beta_n f'_c \quad (6.1.8)$$

Unless confining reinforcement is provided within the nodal zone and its effect is supported by tests and analysis. The value of β_n for Eq. 6.1.8 is given in Sections I.5.2.1 to I.5.2.3.

I.5.2.1 In nodal zones bounded by struts or bearing areas, or both, $\beta_n = 1.0$

I.5.2.2 In nodal zones anchoring one tie, $\beta_n = 0.80$ or

I.5.2.3 $\beta_n = 0.80, \beta_n = 0.60$

Clarification for I.5.2 - In two-dimensional members, such as deep beams, the nodes can be classified as C-C-C if all the members intersecting at the node are in compression; as C-C-T nodes if one of the members acting on the node is in tension; and so on, as shown in Figure 6.I.7. The effective compressive strength of the nodal zone is given by Eq. 6.I.8, as modified by Section I.5.2.1 to I.5.2.3 apply to C-C-C nodes, C-C-T nodes, and C-T-T or T-T-T nodes, respectively.

The increasing degree of disruption of the nodal zones due to the incompatibility of tension strains in the ties and compression strains in the struts is reflected by the β_n values. The stress on any face of the nodal zone or on any section through the nodal zone should not exceed the value given by Eq. 6.I.8, as modified by Sections I.5.2.1 to I.5.2.3.

I.5.3 In a three-dimensional strut-and-tie model, the area of each face of a nodal zone shall not be less than that given in I.5.1, and the shape of each face of the nodal zones shall be similar to the shape of the projection of the end of the struts onto the corresponding faces of the nodal zones.

Clarification for Sections I.5.3: In order to simplify the calculations of the geometry of a three-dimensional strut-and-tie model, this description of the shape and orientation of the faces of the nodal zones is introduced.

I.6 Related References to Appendix I

- I.1. Schlaich, J.; Schäfer, K.; and Jennewein, M., "Toward a Consistent Design of Structural Concrete," PCI Journal, V. 32, No. 3, May-June 1987, pp. 74-150.
- I.2. Collins, M. P., and Mitchell, D., Prestressed Concrete Structures, Prentice Hall Inc., Englewood Cliffs, NJ, 1991, 766 pp.
- I.3. MacGregor, J. G., Reinforced Concrete: Mechanics and Design, 3rd Edition., Prentice Hall, Englewood Cliffs, NJ, 1997, 939 pp.
- I.4. FIP Recommendations, Practical Design of Structural Concrete, FIP-Commission 3, "Practical Design," Pub.: SETO, London, Sept. 1999.
- I.5. Menn, C., Prestressed Concrete Bridges, Birkhäuser, Basle, 535 pp.
- I.6. Muttoni, I.; Schwartz, J.; and Thürlimann, B., Design of Concrete Structures with Stress Fields, Birkhauser, Boston, MA, 1997, 143 pp.
- I.7. Joint ACI-ASCE Committee 445, "Recent Approaches to Shear Design of Structural Concrete (ACI 445R-99)," American Concrete Institute, Farmington Hills, MI, 1999, 55 pp.
- I.8. Bergmeister, K.; Breen, J. E.; and Jirsa, J. O., "Dimensioning of the Nodes and Development of Reinforcement," IABSE Colloquium Stuttgart 1991, International Association for Bridge and Structural Engineering, Zurich, 1991, pp. 551-556.

PART VI
Appendix J

Working Stress Design Method for Reinforced Concrete Structures

J.1 Analysis and Design - General Consideration

J.1.1 Notation

A_s	=	Area of tension reinforcement
A'_s	=	Area of compression reinforcement
A_v	=	Area of shear reinforcement perpendicular to flexural tension reinforcement within a distance s , mm ²
A_{vh}	=	Area of shear reinforcement parallel to flexural tension reinforcement within a distance s_l , mm ²
E_c	=	Modulus of elasticity of concrete, N/mm ²
E_s	=	Modulus of elasticity of reinforcement, N/mm ²
H	=	Total lateral force acting in any storey
M	=	Moment at the section acting simultaneously with P
M_n	=	Flexural moment capacity
M_r	=	Resisting moment capacity based on f'_c
N	=	Axial load normal to cross section occurring simultaneously with V , to be taken as positive for compression, negative for tension and to include effects of tension due to creep and shrinkage
P	=	Working axial load at the section
R	=	Constant, $\frac{1}{2} f_c k j$
T	=	Torsional moment at section
T_c	=	Torsional moment strength provided by concrete
T_s	=	Torsional moment strength provided by torsion reinforcement
V	=	Shear at section
V_c	=	Shear strength provided by concrete
V_s	=	Shear strength provided by shear reinforcement
V_n	=	Shear strength
a	=	Shear span, distance between concentrated load and face of support, mm