CHAPTER 9—BEAMS

CODE

9.1—Scope

9.1.1 This chapter shall apply to the design of nonprestressed and prestressed beams, including:

(a) Composite beams of concrete elements constructed in separate placements but connected so that all elements resist loads as a unit
(b) One-way joist systems in accordance with 9.8
(c) Deep beams in accordance with 9.9

9.2—General

9.2.1 *Materials*

9.2.1.1 Design properties for concrete shall be selected to be in accordance with Chapter 19.

9.2.1.2 Design properties for steel reinforcement shall be selected to be in accordance with Chapter 20.

9.2.1.3 Materials, design, and detailing requirements for embedments in concrete shall be in accordance with 20.6.

9.2.2 *Connection to other members*

9.2.2.1 For cast-in-place construction, joints shall satisfy Chapter 15.

9.2.2.2 For precast construction, connections shall satisfy the force transfer requirements of 16.2.

9.2.3 *Stability*

9.2.3.1 If a beam is not continuously laterally braced, (a) and (b) shall be satisfied:

(a) Spacing of lateral bracing shall not exceed 50 times the least width of compression flange or face.
(b) Spacing of lateral bracing shall take into account effects of eccentric loads.

9.2.3.2 In prestressed beams, buckling of thin webs and flanges shall be considered. If there is intermittent contact between prestressed reinforcement and an oversize duct, member buckling between contact points shall be considered.

COMMENTARY

R9.1—Scope

R9.1.1 Composite structural steel-concrete beams are not covered in this chapter. Design provisions for composite beams are covered in ANSI/AISC 360.

R9.2—General

R9.2.3 *Stability*

R9.2.3.1 Tests (Hansell and Winter 1959; Sant and Bletzacker 1961) have shown that laterally unbraced reinforced concrete beams, even when very deep and narrow, will not fail prematurely by lateral buckling, provided the beams are loaded without lateral eccentricity that causes torsion.

If laterally unbraced beams are loaded eccentrically or with slight inclination, stresses and deformations from such loading can become detrimental for narrow, deep beams with long unsupported lengths. Lateral supports spaced closer than 50b may be required for such loading conditions.

R9.2.3.2 In post-tensioned beams where the prestressed reinforcement has intermittent contact with an oversize duct, the beam can buckle due to the axial prestressing force, as the beam can deflect laterally while the prestressed reinforcement does not. If the prestressed reinforcement is in continuous contact with the beam being prestressed or is part of an unbonded tendon with the sheathing not excessively larger than the prestressed reinforcement, the prestressing force cannot buckle the beam.

CODE

9.2.4 *T-beam construction*

9.2.4.1 In T-beam construction, flange and web concrete shall be placed monolithically or made composite in accordance with 16.4.

9.2.4.2 Effective flange width shall be in accordance with 6.3.2.

9.2.4.3 For T-beam flanges where the primary flexural slab reinforcement is parallel to the longitudinal axis of the beam, reinforcement in the flange perpendicular to the longitudinal axis of the beam shall be in accordance with 7.5.2.3.

9.2.4.4 For torsional design according to 22.7, the overhanging flange width used to calculate A_{cp}, A_g, and p_{cp} shall be in accordance with (a) and (b):

(a) The overhanging flange width shall include that portion of slab on each side of the beam extending a distance equal to the projection of the beam above or below the slab, whichever is greater, but not greater than four times the slab thickness.

(b) The overhanging flanges shall be neglected in cases where the parameter A_{cp}^2/p_{cp} for solid sections or A_g^2/p_{cp} for hollow sections calculated for a beam with flanges is less than that calculated for the same beam ignoring the flanges.

COMMENTARY

R9.2.4 *T-beam construction*

R9.2.4.1 For monolithic or composite concrete construction, the beam includes a portion of the slab as a flange.

R9.2.4.3 Refer to R7.5.2.3.

R9.2.4.4 Two examples of the section to be considered in torsional design are provided in Fig. R9.2.4.4.

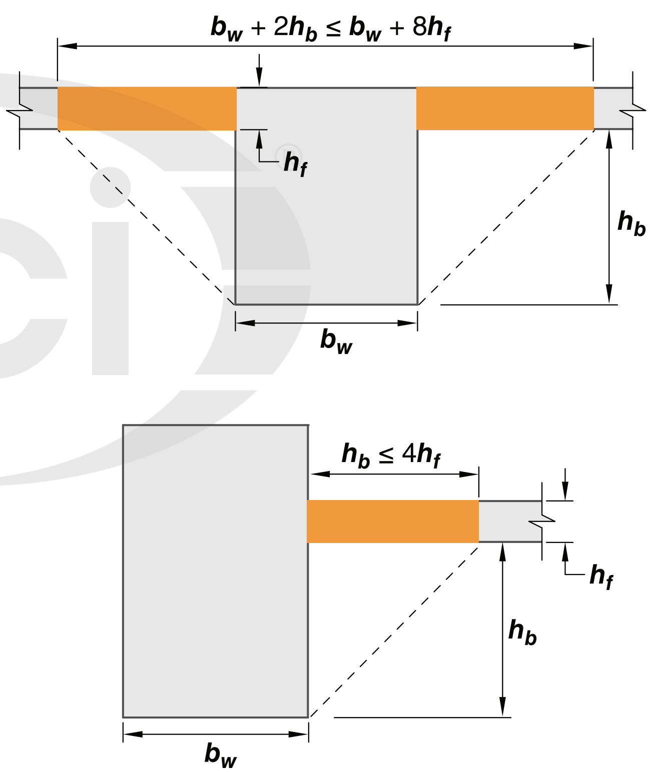

Fig. R9.2.4.4—Examples of the portion of slab to be included with the beam for torsional design.

9.3—Design limits

9.3.1 *Minimum beam depth*

9.3.1.1 For nonprestressed beams not supporting or attached to partitions or other construction likely to be damaged by large deflections, overall beam depth h shall

R9.3—Design limits

R9.3.1 *Minimum beam depth*

Minimum depths in 9.3.1.1 are independent of loading. These minimum depths are not applicable to beams with unusually heavy superimposed sustained loads. Deflections should be calculated for such situations.

R9.3.1.1 For application of this provision to composite concrete beams, refer to R9.3.2.2.

CODE

satisfy the limits in Table 9.3.1.1, unless the calculated deflection limits of 9.3.2 are satisfied.

Table 9.3.1.1—Minimum depth of nonprestressed beams

Support condition	Minimum h[1]
Simply supported	$\ell/16$
One end continuous	$\ell/18.5$
Both ends continuous	$\ell/21$
Cantilever	$\ell/8$

[1]Expressions applicable for normalweight concrete and f_y = 60,000 psi. For other cases, minimum h shall be modified in accordance with 9.3.1.1.1 through 9.3.1.1.3, as appropriate.

9.3.1.1.1 For f_y other than 60,000 psi, the expressions in Table 9.3.1.1 shall be multiplied by $(0.4 + f_y/100{,}000)$.

9.3.1.1.2 For nonprestressed beams made of lightweight concrete having w_c in the range of 90 to 115 lb/ft^3, the expressions in Table 9.3.1.1 shall be multiplied by the greater of (a) and (b):

(a) $1.65 - 0.005w_c$
(b) 1.09

9.3.1.1.3 For nonprestressed composite concrete beams made of a combination of lightweight and normalweight concrete, shored during construction, and where the lightweight concrete is in compression, the modifier of 9.3.1.1.2 shall apply.

9.3.1.2 The thickness of a concrete floor finish shall be permitted to be included in h if it is placed monolithically with the beam or if the floor finish is designed to be composite with the beam in accordance with 16.4.

9.3.2 *Calculated deflection limits*

9.3.2.1 For nonprestressed beams not satisfying 9.3.1 and for prestressed beams, immediate and time-dependent deflections shall be calculated in accordance with 24.2 and shall not exceed the limits in 24.2.2.

9.3.2.2 For nonprestressed composite concrete beams satisfying 9.3.1, deflections occurring after the member becomes composite need not be calculated. Deflections occurring before the member becomes composite shall be investigated unless the precomposite depth also satisfies 9.3.1.

COMMENTARY

R9.3.1.1.1 The modification for f_y should provide conservative results for typical reinforcement ratios and for values of f_y between 40,000 and 100,000 psi.

R9.3.1.1.2 The modification for lightweight concrete is based on the results and discussions in ACI PRC-213. No correction is given for concretes with w_c greater than 115 lb/ft^3 because the correction term would be close to unity in this range.

R9.3.2 *Calculated deflection limits*

R9.3.2.2 The limits in Table 9.3.1.1 apply to the entire depth of nonprestressed composite concrete beams shored during construction so that, after removal of temporary supports, the dead load is resisted by the full composite section. In unshored construction, the beam depth of concern depends on if the deflection being considered occurs before or after the attainment of effective composite action.

Additional deflections due to excessive creep and shrinkage caused by premature loading should be considered. This is especially important at early ages when the moisture content is high and the strength is low.

CODE

9.3.3 *Reinforcement strain limit in nonprestressed beams*

9.3.3.1 Nonprestressed beams with $P_u < 0.10f_c'A_g$ shall be tension controlled in accordance with Table 21.2.2.

COMMENTARY

R9.3.3 *Reinforcement strain limit in nonprestressed beams*

R9.3.3.1 The effect of this limitation is to restrict the reinforcement ratio in nonprestressed beams to mitigate brittle flexural behavior in case of an overload. In the 2019 Code, the previous minimum strain limit of 0.004 for nonprestressed flexural members was replaced with the requirement that beams be tension-controlled.

9.3.4 *Stress limits in prestressed beams*

9.3.4.1 Prestressed beams shall be classified as Class U, T, or C in accordance with 24.5.2.

9.3.4.2 Stresses in prestressed beams immediately after transfer and at service loads shall not exceed permissible stresses in 24.5.3 and 24.5.4.

9.4—Required strength

9.4.1 *General*

9.4.1.1 Required strength shall be calculated in accordance with the factored load combinations in Chapter 5.

9.4.1.2 Required strength shall be calculated in accordance with the analysis procedures in Chapter 6.

9.4.1.3 For prestressed beams, effects of reactions induced by prestressing shall be considered in accordance with 5.3.14.

9.4.2 *Factored moment*

9.4.2.1 For beams built integrally with supports, M_u at the support shall be permitted to be calculated at the face of support.

9.4.3 *Factored shear*

9.4.3.1 For beams built integrally with supports, V_u at the support shall be permitted to be calculated at the face of support.

9.4.3.2 Sections between the face of support and a critical section located d from the face of support for nonprestressed beams and $h/2$ from the face of support for prestressed beams shall be permitted to be designed for V_u at that critical section if (a) through (c) are satisfied:

(a) Support reaction, in direction of applied shear, introduces compression into the end region of the beam
(b) Loads are applied at or near the top surface of the beam
(c) No concentrated load occurs between the face of support and critical section

R9.4—Required strength

R9.4.3 *Factored shear*

R9.4.3.2 The closest inclined crack to the support of the beam in Fig. R9.4.3.2a will extend upward from the face of the support reaching the compression zone approximately d from the face of the support. If loads are applied to the top of the beam, the stirrups across this crack need only resist the shear force due to loads acting beyond d (right free body in Fig. R9.4.3.2a). Loads applied to the beam between the face of the support and the point d away from the face are transferred directly to the support by compression in the web above the crack. Accordingly, the Code permits design for a maximum factored shear V_u at a distance d from the

CODE

COMMENTARY

support for nonprestressed beams and at a distance $h/2$ for prestressed beams.

In Fig. R9.4.3.2b, loads are shown acting near the bottom of a beam. In this case, the critical section is taken at the face of the support. Loads acting near the support should be transferred across the inclined crack extending upward from the support face. The shear force acting on the critical section should include all loads applied below the potential inclined crack.

Typical support conditions where the shear force at a distance d from the support may be used include:

(a) Beams supported by bearing at the bottom of the beam, such as shown in Fig. R9.4.3.2(c)
(b) Beams framing monolithically into a column, as illustrated in Fig. R9.4.3.2(d)

Typical support conditions where the critical section is taken at the face of support include:

(a) Beams framing into a supporting member in tension, such as shown in Fig. R9.4.3.2(e). Shear within the connection should also be investigated and special corner reinforcement should be provided.
(b) Beams for which loads are not applied at or near the top, as shown in Fig. R9.4.3.2b.
(c) Beams loaded such that the shear at sections between the support and a distance d from the support differs radically from the shear at distance d. This commonly occurs in brackets and in beams where a concentrated load is located close to the support, as shown in Fig. R9.4.3.2(f).

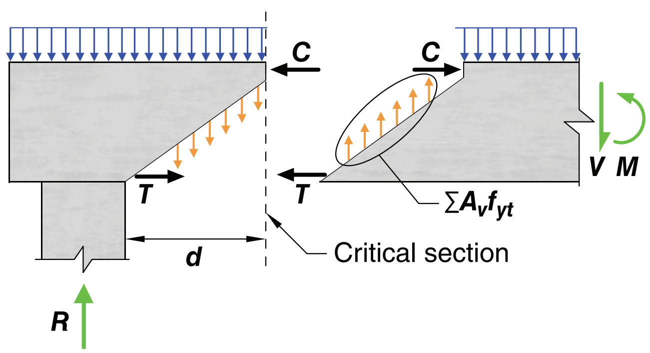

Fig. R9.4.3.2a—Free body diagrams of the end of a beam.

Beams

CODE

COMMENTARY

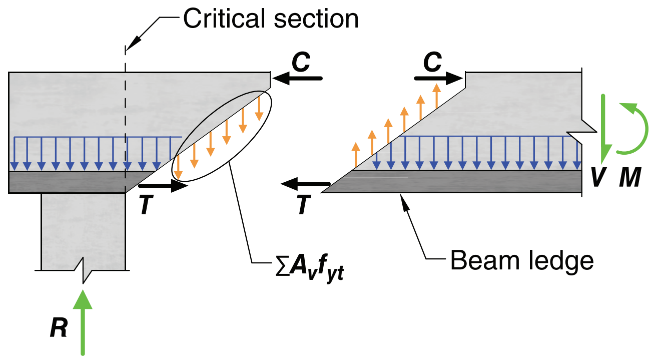

Fig. R9.4.3.2b—Location of critical section for shear in a beam loaded near bottom.

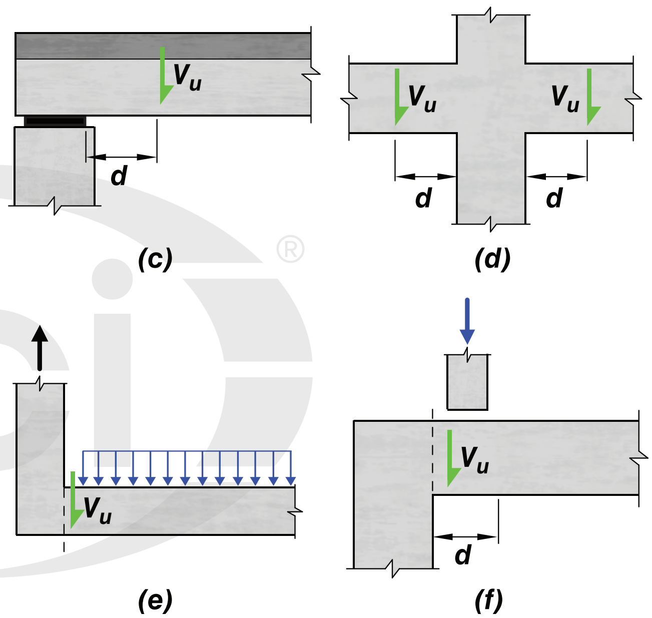

Fig. R9.4.3.2(c), (d), (e), (f)—Typical support conditions for locating factored shear force V_u.

9.4.4 *Factored torsion*

R9.4.4 *Factored torsion*

9.4.4.1 Unless determined by a more detailed analysis, it shall be permitted to take the torsional loading from a slab as uniformly distributed along the beam.

9.4.4.2 For beams built integrally with supports, T_u at the support shall be permitted to be calculated at the face of support.

9.4.4.3 Sections between the face of support and a critical section located d from the face of support for nonprestressed beams or $h/2$ from the face of support for prestressed beams shall be permitted to be designed for T_u at that critical section unless a concentrated torsional moment occurs within this distance. In that case, the critical section shall be taken at the face of the support.

R9.4.4.3 A beam framing into one side of a girder near its support causes a concentrated shear and torsional moment on the girder at that location.

CODE

9.4.4.4 It shall be permitted to reduce T_u in accordance with 22.7.3.

9.5—Design strength

9.5.1 *General*

9.5.1.1 For each applicable factored load combination, design strength at all sections shall satisfy $\phi S_n \geq U$ including (a) through (d). Interaction between load effects shall be considered.

(a) $\phi M_n \geq M_u$
(b) $\phi V_n \geq V_u$
(c) $\phi T_n \geq T_u$
(d) $\phi P_n \geq P_u$

9.5.1.2 ϕ shall be determined in accordance with 21.2.

9.5.2 *Moment*

9.5.2.1 If $P_u < 0.10 f_c' A_g$, M_n shall be calculated in accordance with 22.3.

9.5.2.2 If $P_u \geq 0.10 f_c' A_g$, M_n shall be calculated in accordance with 22.4.

9.5.2.3 For prestressed beams, external tendons shall be considered as unbonded tendons in calculating flexural strength, unless the external tendons are effectively bonded to the concrete along the entire length.

9.5.3 *Shear*

9.5.3.1 V_n shall be calculated in accordance with 22.5.

9.5.3.2 For composite concrete beams, horizontal shear strength V_{nh} shall be calculated in accordance with 16.4.

9.5.4 *Torsion*

9.5.4.1 If $T_u < \phi T_{th}$, where T_{th} is given in 22.7, it shall be permitted to neglect torsional effects. The minimum reinforcement requirements of 9.6.4 and the detailing requirements of 9.7.5 and 9.7.6.3 need not be satisfied.

9.5.4.2 T_n shall be calculated in accordance with 22.7.

9.5.4.3 Longitudinal and transverse reinforcement required for torsion shall be added to that required for the V_u, M_u, and P_u that act in combination with the torsion.

COMMENTARY

R9.5—Design strength

R9.5.1 *General*

R9.5.1.1 The general condition $\phi S_n \geq U$ indicates that all forces and moments that are relevant for a given structure need to be considered.

R9.5.2 *Moment*

R9.5.2.2 Beams resisting significant axial forces require consideration of the combined effects of axial forces and moments. These beams are not required to satisfy the provisions of Chapter 10, but are required to satisfy the requirements for ties or spirals defined in Table 22.4.2.1. For slender beams with significant axial loads, consideration should be given to slenderness effects as required for columns in 6.2.5.

R9.5.4 *Torsion*

R9.5.4.3 The requirements for torsional reinforcement and shear reinforcement are added and stirrups are provided to supply at least the total amount required. Because the

Beams 9

CODE

COMMENTARY

reinforcement area A_v for shear is defined in terms of all the legs of a given stirrup while the reinforcement area A_t for torsion is defined in terms of one leg only, the addition of transverse reinforcement area is calculated as follows:

$$\text{Total}\left(\frac{A_{v+t}}{s}\right) = \frac{A_v}{s} + 2\frac{A_t}{s} \qquad \text{(R9.5.4.3)}$$

If a stirrup group has more than two legs for shear, only legs adjacent to the sides of the beam are included in this summation because inner legs would be ineffective for resisting torsion.

Torsion causes an axial tensile force in the longitudinal reinforcement balanced by the force in the diagonal concrete compression struts. In a nonprestressed beam, the tensile force must be resisted by longitudinal reinforcement having an axial tensile strength of $A_\ell f_y$. This reinforcement is in addition to the required flexural reinforcement and is distributed uniformly inside and around the perimeter of the closed transverse reinforcement so that the resultant of $A_\ell f_y$ acts along the axis of the member.

The longitudinal reinforcement required for torsion is added at each section to the longitudinal reinforcement required for bending moment that acts concurrently with torsion. If the maximum bending moment occurs at one section, while the maximum torsional moment occurs at another, the total longitudinal reinforcement required may be less than that obtained by adding the maximum flexural reinforcement, plus the maximum torsional reinforcement. In such a case, the required longitudinal reinforcement should be evaluated at multiple locations.

9.5.4.4 For prestressed beams, the total area of longitudinal reinforcement, A_s and A_{ps}, at each section shall be designed to resist M_u at that section, plus an additional concentric longitudinal tensile force equal to $A_\ell f_y$, based on T_u at that section.

R9.5.4.4 In a prestressed beam, reinforcing bars with strength $A_\ell f_y$ may be added, or overstrength of the prestressed reinforcement can be used to resist some of the axial force $A_\ell f_y$. The stress in the prestressed reinforcement at nominal strength will be between f_{se} and f_{ps}. A portion of the $A_\ell f_y$ force can be resisted by a force of $A_{ps}\Delta f_{pt}$ in the prestressed reinforcement. The stress required to resist the bending moment can be calculated as $M_u/(\phi 0.9 d_p A_{ps})$. For pretensioned strands, the stress that can be developed near the free end of the strand can be calculated using the procedure illustrated in Fig. R25.4.8.3.

9.5.4.5 It shall be permitted to reduce the area of longitudinal torsional reinforcement in the flexural compression zone by an amount equal to $M_u/(0.9df_y)$, where M_u occurs simultaneously with T_u at that section, except that the longitudinal reinforcement area shall not be less than the minimum required in 9.6.4.

R9.5.4.5 Longitudinal tension due to torsion is offset in part by compression in the flexural compression zone, allowing a reduction in longitudinal torsional reinforcement required in the compression zone.

9.5.4.6 For solid sections with an aspect ratio $h/b_t \geq 3$, it shall be permitted to use an alternative design procedure, provided the adequacy of the procedure has been shown by analysis and substantial agreement with results of comprehensive tests. The minimum reinforcement requirements of

R9.5.4.6 An example of an alternative design that satisfies this provision can be found in Zia and Hsu (2004), which has been extensively used for design of precast, prestressed concrete spandrel beams with $h/b_t \geq 3$ and closed stirrups. The *PCI Design Handbook* (PCI MNL-120) describes

CODE

9.6.4 need not be satisfied, but the detailing requirements of 9.7.5 and 9.7.6.3 apply.

9.5.4.7 For solid precast sections with an aspect ratio $h/b_t \geq 4.5$, it shall be permitted to use an alternative design procedure and open web reinforcement, provided the adequacy of the procedure and reinforcement have been shown by analysis and substantial agreement with results of comprehensive tests. The minimum reinforcement requirements of 9.6.4 and detailing requirements of 9.7.5 and 9.7.6.3 need not be satisfied.

9.6—Reinforcement limits

9.6.1 *Minimum flexural reinforcement in nonprestressed beams*

9.6.1.1 A minimum area of flexural reinforcement, $A_{s,min}$, shall be provided at every section where tension reinforcement is required by analysis.

9.6.1.2 $A_{s,min}$ shall be the larger of (a) and (b), except as provided in 9.6.1.3. For a statically determinate beam with a flange in tension, the value of b_w shall be the smaller of b_f and $2b_w$. The value of f_y shall be limited to a maximum of 80,000 psi.

(a) $\dfrac{3\sqrt{f_c'}}{f_y}b_w d$

(b) $\dfrac{200}{f_y}b_w d$

9.6.1.3 If A_s provided at every section is at least one-third greater than A_s required by analysis, 9.6.1.1 and 9.6.1.2 need not be satisfied.

9.6.2 *Minimum flexural reinforcement in prestressed beams*

9.6.2.1 For beams with bonded prestressed reinforcement, total quantity of A_s and A_{ps} shall be adequate to develop a factored load at least 1.2 times the cracking load calculated on the basis of f_r defined in 19.2.3.

COMMENTARY

this procedure,which was experimentally verified by tests described in Klein (1986).

R9.5.4.7 Tests (Lucier et al. 2011a) demonstrate that properly designed open web reinforcement is an effective alternative to traditional closed stirrups for precast spandrels with $h/b_t \geq 4.5$. Lucier et al. (2011b) presents a design procedure that satisfies this provision for slender spandrels and describes the limited conditions to which the procedure applies.

R9.6—Reinforcement limits

R9.6.1 *Minimum flexural reinforcement in nonprestressed beams*

R9.6.1.1 This provision is intended to result in flexural strength exceeding the cracking strength by a margin. The objective is to produce a beam that will be able to sustain loading after the onset of flexural cracking, with visible cracking and deflection, thereby warning of possible overload. Beams with less reinforcement may sustain sudden failure with the onset of flexural cracking.

In practice, this provision controls reinforcement design only for beams with cross sections larger than those required for flexural strength. With a small amount of tension reinforcement required for strength, the calculated moment strength using cracked section analysis becomes less than that of the corresponding unreinforced concrete section calculated from its modulus of rupture. To prevent a sudden failure after cracking, a minimum amount of tension reinforcement is required in both positive and negative moment regions.

R9.6.1.2 If the flange of a section is in tension, the amount of tension reinforcement needed to make the strength of the reinforced section equal that of the unreinforced section is approximately twice that for a rectangular section or that of a flanged section with the flange in compression. A larger amount of minimum tension reinforcement is particularly necessary in cantilevers and other statically determinate beams where there is no possibility for redistribution of moments.

R9.6.2 *Minimum flexural reinforcement in prestressed beams*

R9.6.2.1 Minimum flexural reinforcement is required for reasons similar to those discussed in R9.6.1.1 for nonprestressed beams.

Beams 9

CODE

9.6.2.2 For beams with both flexural and shear design strength at least twice the required strength, 9.6.2.1 need not be satisfied.

9.6.2.3 For beams with unbonded tendons, the minimum area of bonded deformed longitudinal reinforcement $A_{s,min}$ shall be:

$$A_{s,min} = 0.004A_{ct} \quad (9.6.2.3)$$

where A_{ct} is the area of that part of the cross section between the flexural tension face and the centroid of the gross section.

9.6.3 *Minimum shear reinforcement*

9.6.3.1 For nonprestressed beams, minimum area of shear reinforcement, $A_{v,min}$, shall be provided in all regions where $V_u > \phi\lambda\sqrt{f_c'}b_wd$ except for the cases in Table 9.6.3.1. For these cases, at least $A_{v,min}$ shall be provided where $V_u > \phi V_c$.

Table 9.6.3.1—Cases where $A_{v,min}$ is not required if $V_u \leq \phi V_c$

Beam type	Conditions	
Shallow depth	$h \leq 10$ in.	(a)
Integral with slab	$h \leq$ greater of $2.5t_f$ or $0.5b_w$ and $h \leq 24$ in.	(b)
Constructed with steel fiber-reinforced concrete conforming to 26.4.1.6.1(a), 26.4.2.2(h), and 26.12.8.1(a) and $V_u < \phi V_c$, where V_c is computed in accordance with 22.5.5.1.4	For normalweight concrete with $f_c' <$10,000 psi and Grade 60 or Grade 80 longitudinal reinforcement: $h \leq 40$ in.	(c)
	For lightweight concrete with f_c' ≤6000 psi and Grade 60 longitudinal reinforcement: $h \leq$ 24 in.	(d)
One-way joist system	In accordance with 9.8	(e)

COMMENTARY

Abrupt flexural failure immediately after cracking does not occur when the prestressed reinforcement is unbonded (ACI PRC-423.3); therefore, this requirement does not apply to members with unbonded tendons.

R9.6.2.3 Minimum bonded reinforcement is required by the Code in beams prestressed with unbonded tendons to ensure flexural behavior at ultimate beam strength, rather than tied arch behavior, to limit crack width and spacing at service load when concrete tensile stresses exceed the modulus of rupture, and to ensure acceptable behavior at all loading stages. The minimum amount of bonded reinforcement is based on research comparing the behavior of bonded and unbonded post-tensioned beams (Mattock et al. 1971) and is independent of reinforcement f_y.

R9.6.3 *Minimum shear reinforcement*

R9.6.3.1 Shear reinforcement restrains the growth of inclined cracking so that ductility of the beam is improved and a warning of failure is provided. In an unreinforced web, the formation of inclined cracking might lead directly to failure without warning. Such reinforcement is of great value if a beam is subjected to an unexpected tensile force or overload.

The exception for beams constructed using steel fiber-reinforced concrete is intended to provide a design alternative to the use of shear reinforcement, as defined in 22.5.8.5, for beams with longitudinal flexural reinforcement in which V_u does not exceed ϕV_c, where V_c is the greater of Eq. (a) and 1.3 times Eq. (b) of Table 22.5.5.1. Chapter 26 specifies design information and compliance requirements that need to be incorporated into the construction documents when steel fiber-reinforced concrete is used for this purpose. Fiber-reinforced concrete beams with hooked or crimped steel fibers, in dosages as required by 26.4.2.2(h), have been shown through laboratory tests to exhibit shear strengths greater than $3.5\sqrt{f_c'}b_wd$ (Parra-Montesinos 2006). Shear strengths exceeding V_c can be obtained in steel fiber-reinforced concrete beams without stirrups meeting the criteria in Rows (c) and (d) of Table 9.6.3.1. A smaller depth and a concrete strength limit of 6000 psi for lightweight concrete used in steel fiber-reinforced concrete beams are specified due to limited experimental data (Shoaib et al. 2014; Zarrinpour and Chao 2017). There are no data for the use of steel fibers as shear reinforcement in concrete beams exposed to chlorides from deicing chemicals, salt, salt water, brackish water, seawater, or spray from these sources. Where steel fibers are used as shear reinforcement in corrosive environments, corrosion protection should be considered.

Joists are excluded from the minimum shear reinforcement requirement as indicated because there is a possibility of load sharing between weak and strong areas.

For repeated loading of beams, the possibility of inclined diagonal tension cracks forming at stresses smaller than

CODE / COMMENTARY

under static loading should be taken into account in design. In these instances, use of at least the minimum shear reinforcement expressed by 9.6.3.4 is recommended even though tests or calculations based on static loads show that shear reinforcement is not required.

9.6.3.2 For prestressed beams, a minimum area of shear reinforcement, $A_{v,min}$, shall be provided in all regions where $V_u > 0.5\phi V_c$ except for the cases in Table 9.6.3.1. For these cases, at least $A_{v,min}$ shall be provided where $V_u > \phi V_c$.

R9.6.3.2 Even when V_u is less than $0.5\phi V_c$, the use of some web reinforcement is recommended in all thin-web, post-tensioned members such as joists, waffle slabs, beams, and T-beams, to reinforce against tensile forces in webs resulting from local deviations from the design tendon profile and to provide a means of supporting the tendons during construction. If sufficient support is not provided, lateral wobble and local deviations from the parabolic tendon profile assumed in design may result during placement of the concrete. In such cases, deviations in the tendons tend to straighten out when tendons are stressed. This process may impose large tensile stresses in webs, and severe cracking may develop if no web reinforcement is provided. Unintended curvature of tendons, and resulting tensile stresses in webs, may be minimized by securely tying tendons to stirrups that are rigidly held in place by other elements of the reinforcement cage. The recommended maximum spacing of stirrups used for this purpose is the smaller of $1.5h$ or 4 ft. If applicable, the shear reinforcement provisions of 9.6.3 and 9.7.6.2.2 will require closer stirrup spacings.

9.6.3.3 If shown by testing that the required M_n and V_n can be developed, 9.6.3.1 and 9.6.3.2 need not be satisfied. Such tests shall simulate effects of differential settlement, creep, shrinkage, and temperature change, based on a realistic assessment of these effects occurring in service.

R9.6.3.3 When a beam is tested to demonstrate that its shear and flexural strengths are adequate, the test strengths are considered the nominal strengths V_n and M_n. Considering these strengths as nominal values ensures that if actual material strengths in the field were less than specified, or the member dimensions were in error such as to result in a reduced member strength, a satisfactory margin of safety will be retained due to the strength reduction factor ϕ.

9.6.3.4 If shear reinforcement is required and torsional effects can be neglected according to 9.5.4.1, $A_{v,min}$ shall be in accordance with Table 9.6.3.4.

Table 9.6.3.4—Required $A_{v,min}$

Beam type	$A_{v,min}/s$			
Nonprestressed and prestressed with $A_{ps}f_{se} < 0.4(A_{ps}f_{pu} + A_sf_y)$	Greater of:		$0.75\sqrt{f_c'}\dfrac{b_w}{f_{yt}}$	(a)
			$50\dfrac{b_w}{f_{yt}}$	(b)
Prestressed with $A_{ps}f_{se} \geq 0.4(A_{ps}f_{pu} + A_sf_y)$	Lesser of:	Greater of:	$0.75\sqrt{f_c'}\dfrac{b_w}{f_{yt}}$	(c)
			$50\dfrac{b_w}{f_{yt}}$	(d)
		$\dfrac{A_{ps}f_{pu}}{80f_{yt}d}\sqrt{\dfrac{d}{b_w}}$		(e)

R9.6.3.4 Tests (Roller and Russell 1990) have indicated the need to increase the minimum area of shear reinforcement as concrete strength increases to prevent sudden shear failures when inclined cracking occurs. Therefore, expressions (a) and (c) in Table 9.6.3.4 provide for a gradual increase in the minimum area of transverse reinforcement with increasing concrete strength. Expressions (b) and (d) in Table 9.6.3.4 provide for a minimum area of transverse reinforcement independent of concrete strength and govern for concrete strengths less than 4400 psi.

Tests (Olesen et al. 1967) of prestressed beams with minimum web reinforcement based on 9.6.3.4 indicate that the lesser of $A_{v,min}$ from expressions (c) and (e) is sufficient to develop ductile behavior. Expression (e) is discussed in Olesen et al. (1967).

CODE

9.6.4 *Minimum torsional reinforcement*

9.6.4.1 A minimum area of torsional reinforcement shall be provided in all regions where $T_u \geq \phi T_{th}$ in accordance with 22.7.

9.6.4.2 If torsional reinforcement is required, minimum transverse reinforcement $(A_v + 2A_t)_{min}/s$ shall be the greater of (a) and (b):

(a) $0.75\sqrt{f_c'}\dfrac{b_w}{f_{yt}}$

(b) $50\dfrac{b_w}{f_{yt}}$

9.6.4.3 If torsional reinforcement is required, minimum area of longitudinal reinforcement $A_{\ell,min}$ shall be the lesser of (a) and (b):

(a) $\dfrac{5\sqrt{f_c'}A_{cp}}{f_y} - \left(\dfrac{A_t}{s}\right)p_h\dfrac{f_{yt}}{f_y}$

(b) $\dfrac{5\sqrt{f_c'}A_{cp}}{f_y} - \left(\dfrac{25b_w}{f_{yt}}\right)p_h\dfrac{f_{yt}}{f_y}$

9.7—Reinforcement detailing

9.7.1 *General*

9.7.1.1 Concrete cover for reinforcement shall be in accordance with 20.5.1.

9.7.1.2 Development lengths of deformed and prestressed reinforcement shall be in accordance with 25.4.

9.7.1.3 Splices of deformed reinforcement shall be in accordance with 25.5.

9.7.1.4 Along development and lap splice lengths of longitudinal bars with $f_y \geq 80{,}000$ psi, transverse reinforcement shall be provided such that K_{tr} shall not be smaller than $0.5d_b$.

9.7.1.5 Bundled bars shall be in accordance with 25.6.

9.7.2 *Reinforcement spacing*

9.7.2.1 Minimum spacing s shall be in accordance with 25.2.

9.7.2.2 For nonprestressed and Class C prestressed beams, spacing of bonded longitudinal reinforcement closest to the tension face shall not exceed s given in 24.3.

COMMENTARY

R9.6.4 *Minimum torsional reinforcement*

R9.6.4.2 Although there are a limited number of tests of high-strength concrete beams in torsion, the equation for the minimum area of transverse closed stirrups has been made consistent with calculations required for minimum shear reinforcement discussed in R9.6.3.4 .

R9.6.4.3 Under combined torsion and shear, the torsional cracking moment decreases with applied shear, which leads to a reduction in torsional reinforcement required to prevent brittle failure immediately after cracking. When subjected to pure torsion, reinforced concrete beam specimens with less than 1 percent torsional reinforcement by volume have failed at first torsional cracking (MacGregor and Ghoneim 1995). Equation 9.6.4.3(a) is based on a 2:1 ratio of torsion stress to shear stress and results in a torsional reinforcement volumetric ratio of approximately 0.5 percent (Hsu 1968). Tests of prestressed concrete beams have shown that a similar amount of longitudinal reinforcement is required.

R9.7—Reinforcement detailing

R9.7.2 *Reinforcement spacing*

CODE

9.7.2.3 For nonprestressed and Class C prestressed beams with h exceeding 36 in., longitudinal skin reinforcement shall be uniformly distributed on both side faces of the beam for a distance $h/2$ from the tension face. Spacing of skin reinforcement shall not exceed s given in 24.3.2, where c_c is the clear cover from the skin reinforcement to the side face. It shall be permitted to include skin reinforcement in strength calculations if a strain compatibility analysis is made.

COMMENTARY

R9.7.2.3 For relatively deep beams, skin reinforcement should be placed near vertical faces of the tension zone to control cracking in the web (Frantz and Breen 1980; Frosch 2002), as shown in Fig. R9.7.2.3. Without skin reinforcement, the width of cracks in the web may exceed the crack widths at the level of the flexural tension reinforcement.

The size of skin reinforcement is not specified; research has indicated that the spacing rather than bar size is of primary importance (Frosch 2002). Bar sizes No. 3 to No. 5, or welded wire reinforcement with a minimum area of 0.1 in.^{2} per foot of depth, are typically provided.

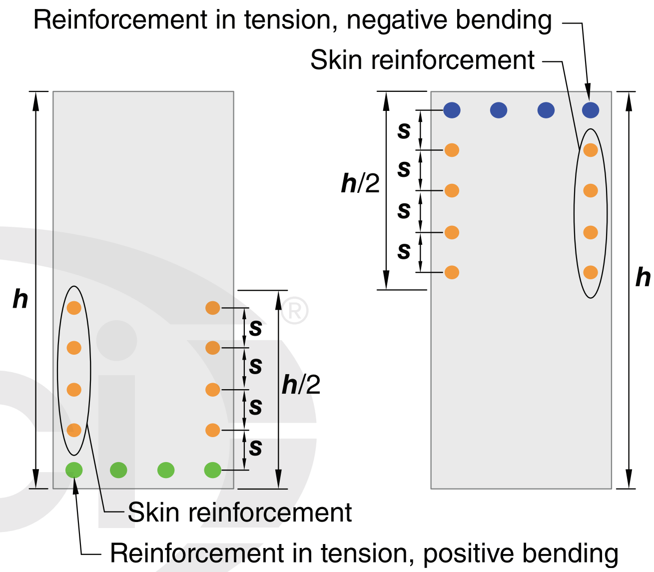

Fig. R9.7.2.3—Skin reinforcement for beams and joists with h > *36 in.*

9.7.3 *Flexural reinforcement in nonprestressed beams*

R9.7.3 *Flexural reinforcement in nonprestressed beams*

9.7.3.1 Calculated tensile or compressive force in reinforcement at each section of the beam shall be developed on each side of that section.

9.7.3.2 Critical locations for development of reinforcement are points of maximum stress and points along the span where bent or terminated tension reinforcement is no longer required to resist flexure.

R9.7.3.2 Critical sections for a typical continuous beam are indicated with a "c" for points of maximum stress or an "x" for points where bent or terminated tension reinforcement is no longer required to resist flexure (Fig. R9.7.3.2). For uniform loading, the positive reinforcement extending into the support is more likely governed by the requirements of 9.7.3.8.1 or 9.7.3.8.3 than by development length measured from a point of maximum moment or the bar cutoff point.

CODE

COMMENTARY

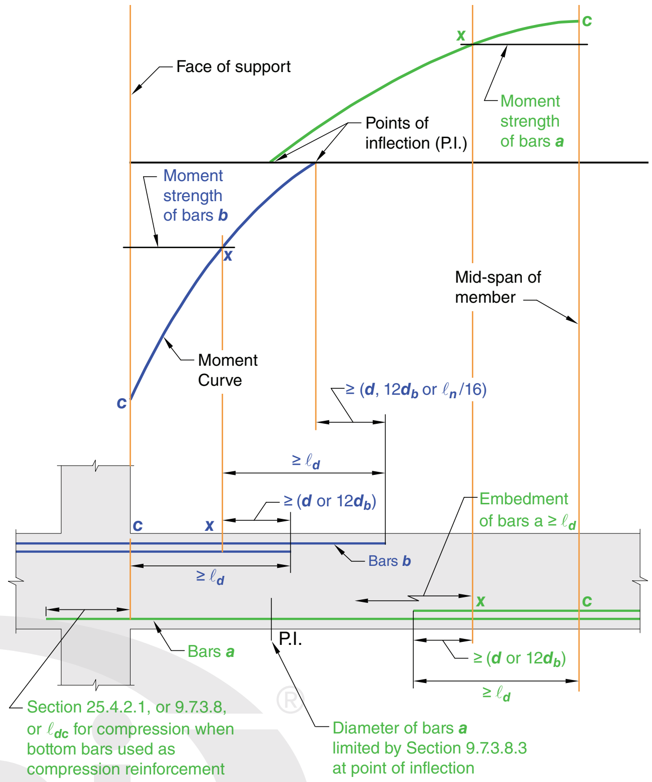

Fig. R9.7.3.2—Development of flexural reinforcement in a typical continuous beam.

9.7.3.3 Reinforcement shall extend beyond the point at which it is no longer required to resist flexure for a distance equal to the greater of d and $12d_b$, except at supports of simply-supported spans and at free ends of cantilevers.

R9.7.3.3 Moment diagrams customarily used in design are approximate; some shifting of the location of maximum moments may occur due to changes in loading, settlement of supports, lateral loads, or other causes. A diagonal tension crack in a flexural member without stirrups may shift the location of the calculated tensile stress approximately a distance d toward a point of zero moment. If stirrups are provided, this effect is less severe, although still present to some extent.

To provide for shifts in the location of maximum moments, the Code requires the extension of reinforcement a distance d or $12d_b$ beyond the point at which it is calculated to be no longer required to resist flexure, except as noted. Cutoff points of bars to meet this requirement are illustrated in Fig. R9.7.3.2. If different bar sizes are used, the extension should be in accordance with the diameter of the bar being terminated.

9.7.3.4 Continuing flexural tension reinforcement shall have an embedment length at least ℓ_d beyond the point where bent or terminated tension reinforcement is no longer required to resist flexure.

R9.7.3.4 Local peak stresses exist in the remaining bars wherever adjacent bars are cut off in tension regions. In Fig. R9.7.3.2, an "x" is used to indicate the point where terminated tension reinforcement is no longer required to resist flexure. If bars were cut off at this location (the required cutoff point is beyond location "x" in accordance with 9.7.3.3), peak stresses in the continuing reinforcement (bars b) would reach f_y at "x". Therefore, the continuing reinforcement is required to have a full ℓ_d extension as indicated.

CODE

9.7.3.5 Flexural tension reinforcement shall not be terminated in a tension zone unless (a), (b), or (c) is satisfied:

(a) $V_u \leq (2/3)\phi V_n$ at the cutoff point
(b) For No. 11 bars and smaller, continuing reinforcement provides double the area required for flexure at the cutoff point and $V_u \leq (3/4)\phi V_n$
(c) Stirrup or hoop area in excess of that required for shear and torsion is provided along each terminated bar or wire over a distance $(3/4)d$ from the cutoff point. Excess stirrup or hoop area shall be at least $60b_w s/f_{yt}$. Spacing s shall not exceed $d/(8\beta_b)$

9.7.3.6 Adequate anchorage shall be provided for tension reinforcement where reinforcement stress is not directly proportional to moment, such as in sloped, stepped, or tapered beams, or where tension reinforcement is not parallel to the compression face.

9.7.3.7 Development of tension reinforcement by bending across the web to be anchored or made continuous with reinforcement on the opposite face of beam shall be permitted.

9.7.3.8 *Termination of reinforcement*

9.7.3.8.1 At simple supports, at least one-third of the maximum positive moment reinforcement shall extend along the beam bottom into the support at least 6 in., except for precast beams where such reinforcement shall extend at least to the center of the bearing length.

9.7.3.8.2 At other supports, at least one-fourth of the maximum positive moment reinforcement shall extend along the beam bottom into the support at least 6 in. and, if the beam is part of the primary lateral-load-resisting system, shall develop f_y in tension at the face of the support.

9.7.3.8.3 At simple supports and points of inflection, d_b for positive moment tension reinforcement shall be limited such that ℓ_d for that reinforcement satisfies (a) or (b). If reinforcement terminates beyond the centerline of supports by a standard hook, head, or mechanical anchorage in accordance with 25.4.5, (a) or (b) need not be satisfied.

(a) $\ell_d \leq (1.3M_n/V_u + \ell_a)$ if end of reinforcement is confined by a compressive reaction
(b) $\ell_d \leq (M_n/V_u + \ell_a)$ if end of reinforcement is not confined by a compressive reaction

M_n is calculated assuming all reinforcement at the section is stressed to f_y, and V_u is calculated at the section. At a support, ℓ_a is the embedment length beyond the center of the

COMMENTARY

R9.7.3.5 Reduced shear strength and loss of ductility can occur where bars are cut off in a tension zone, such as in Fig. R9.7.3.2 (Ferguson and Matloob 1959). Flexural cracks tend to open at low load levels wherever any reinforcement is terminated in a tension zone. If stress in the continuing reinforcement and shear strength are each near their limiting values, diagonal tension cracking tends to develop prematurely from these flexural cracks. Diagonal cracks are less likely to form where shear stress is low (9.7.3.5(a)) or flexural reinforcement stress is low (9.7.3.5(b)). Diagonal cracks can be restrained by closely spaced stirrups (9.7.3.5(c)). These requirements are not intended to apply to tension splices that are covered by 25.5.

R9.7.3.7 A bar bent to the far face of a beam and continued there may be considered effective in satisfying 9.7.3.3 to the point where the bar crosses the mid-depth of the member.

R9.7.3.8 *Termination of reinforcement*

R9.7.3.8.1 Positive moment reinforcement is extended into the support to provide for shifting of moments due to changes in loading, settlement of supports, and lateral loads. It also enhances structural integrity.

For precast beams, tolerances and reinforcement cover should be considered to avoid bearing on plain concrete where reinforcement has been discontinued.

R9.7.3.8.2 Development of positive moment reinforcement at the support is required for beams that are part of the primary lateral-load-resisting system to provide ductility in the event of moment reversal.

R9.7.3.8.3 The diameter of positive moment tension reinforcement is limited to ensure that the bars are developed in a length short enough such that the moment capacity is greater than the applied moment over the entire length of the beam. As illustrated in the moment diagram of Fig. R9.7.3.8.3(a), the slope of the moment diagram is V_u, while the slope of moment development is M_n/ℓ_d, where M_n is the nominal flexural strength of the cross section. By sizing reinforcement such that the capacity slope M_n/ℓ_d equals or exceeds the demand slope V_u, proper development is provided. Therefore, M_n/V_u represents the available development length. Under favorable support conditions, a 30% increase for M_n/V_u is permitted when the ends of reinforcement are confined by a compressive reaction.

Beams 9

CODE

support. At a point of inflection, ℓ_a is the embedment length beyond the point of inflection limited to the greater of d and $12d_b$.

COMMENTARY

Application of this provision is illustrated in Fig. R9.7.3.8.3(b) for simple supports and in Fig. R9.7.3.8.3(c) for points of inflection.

The ℓ_a limitation at points of inflection is provided because test data are not available to show that a long end anchorage length will be effective in developing a bar that has only a short length between a point of inflection and a point of maximum stress.

CODE

COMMENTARY

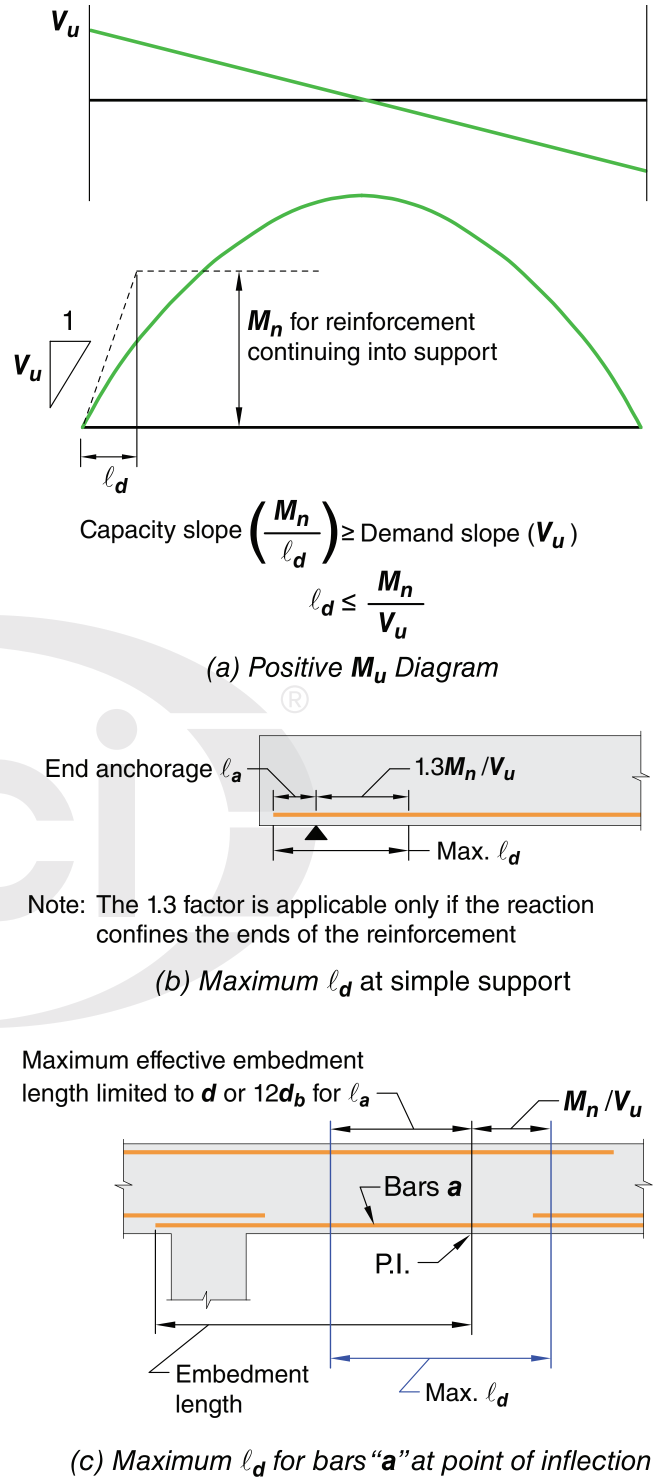

Fig. R9.7.3.8.3—Determination of maximum bar size according to 9.7.3.8.3.

9.7.3.8.4 At least one-third of the negative moment reinforcement at a support shall have an embedment length beyond the point of inflection at least the greatest of d, $12d_b$, and $\ell_n/16$.

CODE

9.7.4 *Flexural reinforcement in prestressed beams*

9.7.4.1 External tendons shall be attached to the member in a manner that maintains the specified eccentricity between the tendons and the concrete centroid through the full range of anticipated member deflections.

9.7.4.2 If nonprestressed reinforcement is required to satisfy flexural strength, the detailing requirements of 9.7.3 shall be satisfied.

9.7.4.3 *Termination of prestressed reinforcement*

9.7.4.3.1 Post-tensioned anchorage zones shall be designed and detailed in accordance with 25.9.

9.7.4.3.2 Post-tensioning anchorages and couplers shall be designed and detailed in accordance with 25.8.

9.7.4.4 *Termination of deformed reinforcement in beams with unbonded tendons*

9.7.4.4.1 Length of deformed reinforcement required by 9.6.2.3 shall be in accordance with (a) and (b):

(a) At least $\ell_n/3$ in positive moment areas and be centered in those areas
(b) At least $\ell_n/6$ on each side of the face of support in negative moment areas

9.7.5 *Longitudinal torsional reinforcement*

9.7.5.1 If torsional reinforcement is required, longitudinal torsional reinforcement shall be distributed around the perimeter of closed stirrups that satisfy 25.7.1.6 or hoops with a spacing not greater than 12 in. The longitudinal reinforcement shall be inside the stirrup or hoop, and at least one longitudinal bar or tendon shall be placed in each corner.

9.7.5.2 Longitudinal torsional reinforcement shall have a diameter at least 0.042 times the transverse reinforcement spacing, but not less than 3/8 in.

9.7.5.3 Longitudinal torsional reinforcement shall extend for a distance of at least (b_t + d) beyond the point required by analysis.

COMMENTARY

R9.7.4 *Flexural reinforcement in prestressed beams*

R9.7.4.1 External tendons are often attached to the concrete beam at various locations between anchorages, such as midspan, quarter points, or third points, for desired load balancing effects, for tendon alignment, or to address tendon vibration concerns. Consideration should be given to effects caused by the tendon profile shifting in relationship to the concrete centroid as the member deforms under effects of post-tensioning and applied load.

R9.7.4.2 The requirements of 9.7.3 provide that bonded reinforcement required for flexural strength under factored loads is developed to achieve tensile or compressive forces.

R9.7.4.4 *Termination of deformed reinforcement in beams with unbonded tendons*

R9.7.4.4.1 Research (Odello and Mehta 1967) on continuous spans shows that minimum lengths required by 9.6.2.3 provide satisfactory behavior under service load and factored load conditions.

R9.7.5 *Longitudinal torsional reinforcement*

R9.7.5.1 Longitudinal reinforcement is needed to resist the sum of the longitudinal tensile forces due to torsion. The centroid of the additional longitudinal reinforcement for torsion should approximately coincide with the centroid of the section. The Code accomplishes this by requiring the longitudinal torsional reinforcement be distributed around the perimeter of the closed stirrups. Longitudinal bars or tendons are required in each corner of the stirrups to provide anchorage for the stirrup legs. Corner bars have also been found to be effective in developing torsional strength and controlling cracks.

R9.7.5.3 The distance (b_t + d) beyond the point at which longitudinal torsional reinforcement is no longer required is greater than that used for shear and flexural reinforce-

CODE

9.7.5.4 Longitudinal torsional reinforcement shall be developed at the face of the support at both ends of the beam.

9.7.6 *Transverse reinforcement*

9.7.6.1 *General*

9.7.6.1.1 Transverse reinforcement shall be in accordance with this section. The most restrictive requirements shall apply.

9.7.6.1.2 Details of transverse reinforcement shall be in accordance with 25.7.

9.7.6.2 *Shear*

9.7.6.2.1 If required, shear reinforcement shall be provided using stirrups, hoops, or longitudinal bent bars.

COMMENTARY

ment because torsional diagonal tension cracks develop in a helical form. The same distance is required by 9.7.6.3.2 for transverse torsional reinforcement.

R9.7.5.4 Development length should be provided beyond the interior face of the support. For bars, this may require hooks or heads.Alternatively, horizontal U-shaped bars may be lapspliced with the longitudinal torsional reinforcement.

R9.7.6 *Transverse reinforcement*

R9.7.6.2 *Shear*

R9.7.6.2.1 If a reinforced concrete beam is cast monolithically with a supporting beam and intersects one or both side faces of a supporting beam, the soffit of the supporting beam may be subject to premature failure unless additional transverse reinforcement, commonly referred to as hanger reinforcement, is provided (Mattock and Shen 1992). The hanger reinforcement (Fig. R9.7.6.2.1), placed in addition to other transverse reinforcement, is provided to transfer shear from the end of the supported beam. Research indicates that if the bottom of the supported beam is at or above middepth of the supporting beam or if the factored shear transferred from the supported beam is less than $3\sqrt{f_c'}b_wd$, hanger reinforcement is not required.

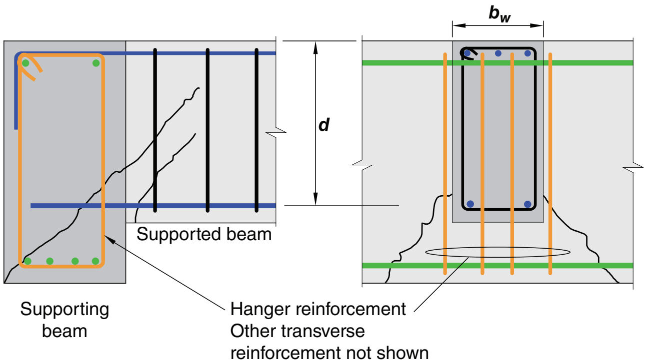

Fig. R9.7.6.2.1—Hanger reinforcement for shear transfer.

9 Beams

CODE

9.7.6.2.2 Maximum spacing of legs of shear reinforcement along the length of the member and across the width of the member shall be in accordance with Table 9.7.6.2.2.

Table 9.7.6.2.2—Maximum spacing of legs of shear reinforcement

Required V_s		Maximum s, in.			
		Nonprestressed beam		Prestressed beam	
		Along length	Across width	Along length	Across width
$\leq 4\sqrt{f_c'}b_w d$	Lesser of:	$d/2$	d	$3h/4$	$3h/2$
		24 in.			
$> 4\sqrt{f_c'}b_w d$	Lesser of:	$d/4$	$d/2$	$3h/8$	$3h/4$
		12 in.			

9.7.6.2.3 Inclined stirrups and longitudinal bars bent to act as shear reinforcement shall be spaced so that every 45-degree line, extending $d/2$ toward the reaction from mid-depth of member to longitudinal tension reinforcement, shall be crossed by at least one line of shear reinforcement.

9.7.6.2.4 Longitudinal bars bent to act as shear reinforcement, if extended into a region of tension, shall be continuous with longitudinal reinforcement and, if extended into a region of compression, shall be anchored $d/2$ beyond mid-depth of member.

9.7.6.3 *Torsion*

9.7.6.3.1 If required, transverse torsional reinforcement shall be closed stirrups satisfying 25.7.1.6 or hoops.

9.7.6.3.2 Transverse torsional reinforcement shall extend a distance of at least $(b_t + d)$ beyond the point required by analysis.

9.7.6.3.3 Spacing of transverse torsional reinforcement shall not exceed the lesser of $p_h/8$ and 12 in.

9.7.6.3.4 For hollow sections, the distance from the centerline of the transverse torsional reinforcement to the inside face of the wall of the hollow section shall be at least $0.5A_{oh}/p_h$.

COMMENTARY

R9.7.6.2.2 Reduced stirrup spacing across the beam width provides a more uniform transfer of diagonal compression across the beam web, enhancing shear capacity. Laboratory tests (Leonhardt and Walther 1964; Anderson and Ramirez 1989; Lubell et al. 2009) of wide members with large spacing of legs of shear reinforcement across the member width indicate that the nominal shear capacity is not always achieved. The intent of this provision is to provide multiple stirrup legs across wide beams and one-way slabs that require stirrups.

R9.7.6.3 *Torsion*

R9.7.6.3.1 Stirrups are required to be closed because inclined cracking due to torsion may occur on all faces of a member, and because the concrete cover spalls off at high torsional moments. Guidance on designing stirrups for torsion is provided in R25.7.1.6.

R9.7.6.3.2 The distance $(b_t + d)$ beyond the point at which transverse torsional reinforcement is no longer required is greater than that used for shear and flexural reinforcement because torsional diagonal tension cracks develop in a helical form. The same distance is required by 9.7.5.3 for longitudinal torsional reinforcement.

R9.7.6.3.3 Spacing of transverse torsional reinforcement is limited to ensure development of torsional strength of the beam, prevent excessive loss of torsional stiffness after cracking, and control crack widths. For a square cross section, the $p_h/8$ limitation requires stirrups at approximately $d/2$, which corresponds to 9.7.6.2.

R9.7.6.3.4 Transverse torsional reinforcement in a hollow section should be located in the outer half of the wall thickness effective for torsion where the wall thickness can be taken as A_{oh}/p_h.

CODE

9.7.6.4 *Lateral support of compression reinforcement*

9.7.6.4.1 Transverse reinforcement shall be provided throughout the distance where longitudinal compression reinforcement is required. Lateral support of longitudinal compression reinforcement shall be provided by closed stirrups or hoops in accordance with 9.7.6.4.2 through 9.7.6.4.4.

9.7.6.4.2 Size of transverse reinforcement shall be at least (a) or (b). Deformed wire or welded wire reinforcement of equivalent area shall be permitted.

(a) No. 3 for longitudinal bars No. 10 and smaller
(b) No. 4 for longitudinal bars No. 11 and larger and for longitudinal bundled bars

9.7.6.4.3 Spacing of transverse reinforcement shall not exceed the least of (a) through (c):

(a) $16d_b$ of longitudinal reinforcement
(b) $48d_b$ of transverse reinforcement
(c) Least dimension of beam

9.7.6.4.4 Longitudinal compression reinforcement shall be arranged such that every corner and alternate compression bar shall be enclosed by the corner of the transverse reinforcement with an included angle of not more than 135 degrees, and no bar shall be farther than 6 in. clear on each side along the transverse reinforcement from such an enclosed bar.

9.7.7 *Structural integrity reinforcement in cast-in-place beams*

COMMENTARY

R9.7.6.4 *Lateral support of compression reinforcement*

R9.7.6.4.1 Compression reinforcement in beams should be enclosed by transverse reinforcement to prevent buckling.

R9.7.7 *Structural integrity reinforcement in cast-in-place beams*

Experience has shown that overall integrity of a structure can be substantially enhanced by minor changes in detailing of reinforcement and connections. It is the intent of this section of the Code to improve redundancy and ductility in structures so that in the event of damage to a major supporting element or an abnormal loading event, resulting damage may be localized and the structure will have a higher probability of maintaining overall stability.

With damage to a support, top reinforcement that is continuous over the support, but not confined by stirrups, will tend to tear out of the concrete and will not provide the catenary action required to bridge the damaged support. By making a portion of the bottom reinforcement continuous, catenary action can be provided.

If the depth of a continuous beam changes at a support, bottom reinforcement in the deeper member should be terminated into the support with a standard hook or headed bar to develop in tension in accordance with 25.4 by substituting a bar stress of $1.25f_y$ for f_y and the bottom reinforcement in the shallower member should also extend into the joint and be similarly developed.

CODE

9.7.7.1 For beams along the perimeter of the structure, structural integrity reinforcement shall be in accordance with (a) through (c):

(a) At least one-fourth of the maximum positive moment reinforcement, but not less than two bars or strands, shall be continuous

(b) At least one-sixth of the negative moment reinforcement at the support, but not less than two bars or strands, shall be continuous

(c) Longitudinal structural integrity reinforcement shall be enclosed by closed stirrups in accordance with 25.7.1.6 or hoops along the clear span of the beam with a spacing not greater than $d/2$ for nonprestressed beams or $3h/4$ for prestressed beams. At each supported end of the beam, the closed stirrup or hoop spacing shall not exceed the least of (i) through (iv) over a length of at least $2h$ from the face of the support.

(i) $d/4$ for nonprestressed beams or $3h/8$ for prestressed beams

(ii) $8d_b$ of the smallest longitudinal bar enclosed

(iii) $24d_b$ of the closed stirrup or hoop

(iv) 12 in.

9.7.7.2 For other than perimeter beams, structural integrity reinforcement shall be in accordance with (a) or (b):

(a) At least one-quarter of the maximum positive moment reinforcement, but not less than two bars or strands, shall be continuous.

(b) Longitudinal reinforcement shall be enclosed by closed stirrups in accordance with 25.7.1.6 or hoops along the clear span of the beam.

9.7.7.3 Longitudinal structural integrity reinforcement shall pass through the region bounded by the longitudinal reinforcement of the column.

9.7.7.4 Longitudinal structural integrity reinforcement at noncontinuous supports shall be developed in tension in accordance with 25.4 by substituting a bar stress of $1.25f_y$ for f_y at the face of the support.

9.7.7.5 If splices are necessary in continuous structural integrity reinforcement, the reinforcement shall be spliced in accordance with (a) and (b):

COMMENTARY

Development of bottom bars for structural integrity is clarified in the 2025 Code to develop $1.25f_y$, recognizing that standard development is intended to develop the specified f_y.

R9.7.7.1 Requiring continuous top and bottom reinforcement in perimeter or spandrel beams provides a continuous tie around the structure. One-half of the top flexural reinforcement is required to extend past the point of inflection by 9.7.3.8.4 and be further extended and spliced at or near midspan as required by 9.7.7.5. Similarly, the bottom reinforcement required to extend into the support in 9.7.3.8.2 should be made continuous or spliced with bottom reinforcement from the adjacent span. At noncontinuous supports, longitudinal reinforcement is anchored as required by 9.7.7.4.

The spacing limits of transverse reinforcement enclosing integrity reinforcement are intended to allow beams to accommodate the rotational demands associated with large vertical displacements that occur after the unintended loss of a vertical-load-carrying member. Tests by Rivera-Cruz et al. (2021) demonstrated that beams with spacing of transverse reinforcement spacing in compliance with SDC A or B may form wide diagonal cracks in the hinge region that limit the rotational capacity of beams experiencing large vertical displacements. Beams with spacing of transverse reinforcement in compliance with the requirements for SDC C through F were observed to develop end rotations associated with large vertical displacements, allowing the development of alternate load paths after loss of a vertical load carrying member (Lew et al. 2014).

R9.7.7.2 At noncontinuous supports, longitudinal reinforcement is anchored as required by 9.7.7.4.

R9.7.7.3 In the case of walls providing vertical support, longitudinal reinforcement should pass through or be anchored in the wall.

CODE

(a) Positive moment reinforcement shall be spliced at or near the support

(b) Negative moment reinforcement shall be spliced at or near midspan

9.7.7.6 Splices shall be mechanical or welded in accordance with 25.5.7 or Class B tension lap splices in accordance with 25.5.2.

9.8—Nonprestressed one-way joist systems

9.8.1 *General*

9.8.1.1 Nonprestressed one-way joist construction consists of a monolithic combination of regularly spaced ribs and a top slab designed to span in one direction.

9.8.1.2 Width of ribs shall be at least 4 in. at any location along the depth.

9.8.1.3 Overall depth of ribs, excluding slab thickness, shall not exceed 3.5 times the minimum width.

9.8.1.4 Clear spacing between ribs shall not exceed 30 in.

9.8.1.5 V_c shall be permitted to be taken as 1.1 times the value calculated in 22.5.

9.8.1.6 For structural integrity, at least one bottom bar in each joist shall be continuous and shall be developed in tension in accordance with 25.4 by substituting a bar stress of $1.25f_y$ for f_y at the face of supports.

9.8.1.7 Reinforcement perpendicular to the ribs shall be provided in the slab as required for flexure, considering load concentrations, and shall be at least that required for shrinkage and temperature in accordance with 24.4.

9.8.1.8 One-way joist construction not satisfying the limitations of 9.8.1.1 through 9.8.1.4 shall be designed as slabs and beams.

COMMENTARY

R9.8—Nonprestressed one-way joist systems

R9.8.1 *General*

Empirical limits established for nonprestressed reinforced concrete joist floors are based on successful past performance of joist construction using common joist forming systems. For prestressed joist construction, this section may be used as a guide.

R9.8.1.4 A limit on maximum spacing of ribs is required because of provisions permitting higher shear strengths and less concrete cover for the reinforcement for these relatively small, repetitive members.

R9.8.1.5 This increase in shear strength is justified on the basis of: 1) satisfactory performance of joist construction designed with higher calculated shear strengths specified in previous Codes which allowed comparable shear stresses; and 2) potential for redistribution of local overloads to adjacent joists.

Beams

9

CODE

9.8.2 *Joist systems with structural fillers*

9.8.2.1 If permanent burned clay or concrete tile fillers of material having a unit compressive strength at least equal to f_c' in the joists are used, 9.8.2.1.1 and 9.8.2.1.2 shall apply.

9.8.2.1.1 Slab thickness over fillers shall be at least the greater of one-twelfth the clear distance between ribs and 1.5 in.

9.8.2.1.2 For calculation of shear and negative moment strength, it shall be permitted to include the vertical shells of fillers in contact with the ribs. Other portions of fillers shall not be included in strength calculations.

9.8.3 *Joist systems with other fillers*

9.8.3.1 If fillers not complying with 9.8.2.1 or removable forms are used, slab thickness shall be at least the greater of one-twelfth the clear distance between ribs and 2 in.

9.9—Deep beams

9.9.1 *General*

9.9.1.1 Deep beams are members that are loaded on one face and supported on the opposite face such that strut-like compression elements can develop between the loads and supports and that satisfy (a) or (b):

(a) Clear span does not exceed four times the overall member depth h

(b) Concentrated loads exist within a distance $2h$ from the face of the support

9.9.1.2 Deep beams shall be designed taking into account nonlinear distribution of longitudinal strain over the depth of the beam.

9.9.1.3 The strut-and-tie method in accordance with Chapter 23 is deemed to satisfy 9.9.1.2.

9.9.2 *Dimensional limits*

9.9.2.1 Except as permitted by 23.4.4, deep beam dimensions shall be selected such that:

$$V_u \leq \phi 10\sqrt{f_c'}\, b_w d \qquad (9.9.2.1)$$

COMMENTARY

R9.9—Deep beams

R9.9.1 *General*

R9.9.1.1 Behavior of deep beams is discussed in Schlaich et al. (1987), Rogowsky and MacGregor (1986), Marti (1985), and Crist (1966). This provision applies if loads are applied on the top of the beam and the beam is supported on its bottom face. If loads are applied through the sides or bottom of such a member, the strut-and-tie method, as defined in Chapter 23, should be used to design reinforcement to internally transfer the loads to the top of the beam and distribute them to adjacent supports.

R9.9.1.2 The Code does not contain detailed requirements for designing deep beams for moment, except that a nonlinear strain distribution should be considered. Guidance for design of deep beams for flexure is given in Chow et al. (1953), Portland Cement Association (1946), and Park and Paulay (1975).

R9.9.2 *Dimensional limits*

R9.9.2.1 This limit imposes a dimensional restriction to control cracking under service loads and to guard against diagonal compression failures in deep beams.

CODE

9.9.3 *Reinforcement limits*

9.9.3.1 Distributed reinforcement in deep beams shall be at least that required in (a) and (b):

(a) The area of transverse distributed reinforcement over the longitudinal distance s_{td} shall be $A_{td} \geq 0.0025 b_w s_{td}$

(b) The area of longitudinal distributed reinforcement in each layer spaced over the vertical distance $s_{\ell d}$ shall be $A_{\ell d} \geq 0.0025 b_w s_{\ell d}$

9.9.3.2 The minimum area of flexural tension reinforcement, $A_{s,min}$, shall be determined in accordance with 9.6.1.

9.9.4 *Reinforcement detailing*

9.9.4.1 Concrete cover shall be in accordance with 20.5.1.

9.9.4.2 Minimum spacing for longitudinal reinforcement shall be in accordance with 25.2.

9.9.4.3 Spacing of distributed reinforcement required in 9.9.3.1 shall not exceed the lesser of d/5 and 12 in.

COMMENTARY

R9.9.3 *Reinforcement limits*

R9.9.3.1 The minimum reinforcement requirements of this section are intended to control the width and propagation of inclined cracks. Tests (Rogowsky and MacGregor 1986; Marti 1985; Crist 1966) have shown that in a deep beam, reinforcement perpendicular to the longitudinal axis of the member is more effective for member shear strength than shear reinforcement parallel to the longitudinal axis of the member; however, the specified minimum reinforcement is the same in both directions to control the growth and width of diagonal cracks.

R9.9.4 *Reinforcement detailing*

R9.9.4.3 Figure R9.9.4.3 illustrates the spacing requirements for the distributed reinforcement defined in 9.9.3.1. Spacing determined by the requirements of 9.9.4.3 and 9.9.4.4 is dependent on the cross-sectional dimensions and can be more stringent than the requirements in 23.5.

CODE

COMMENTARY

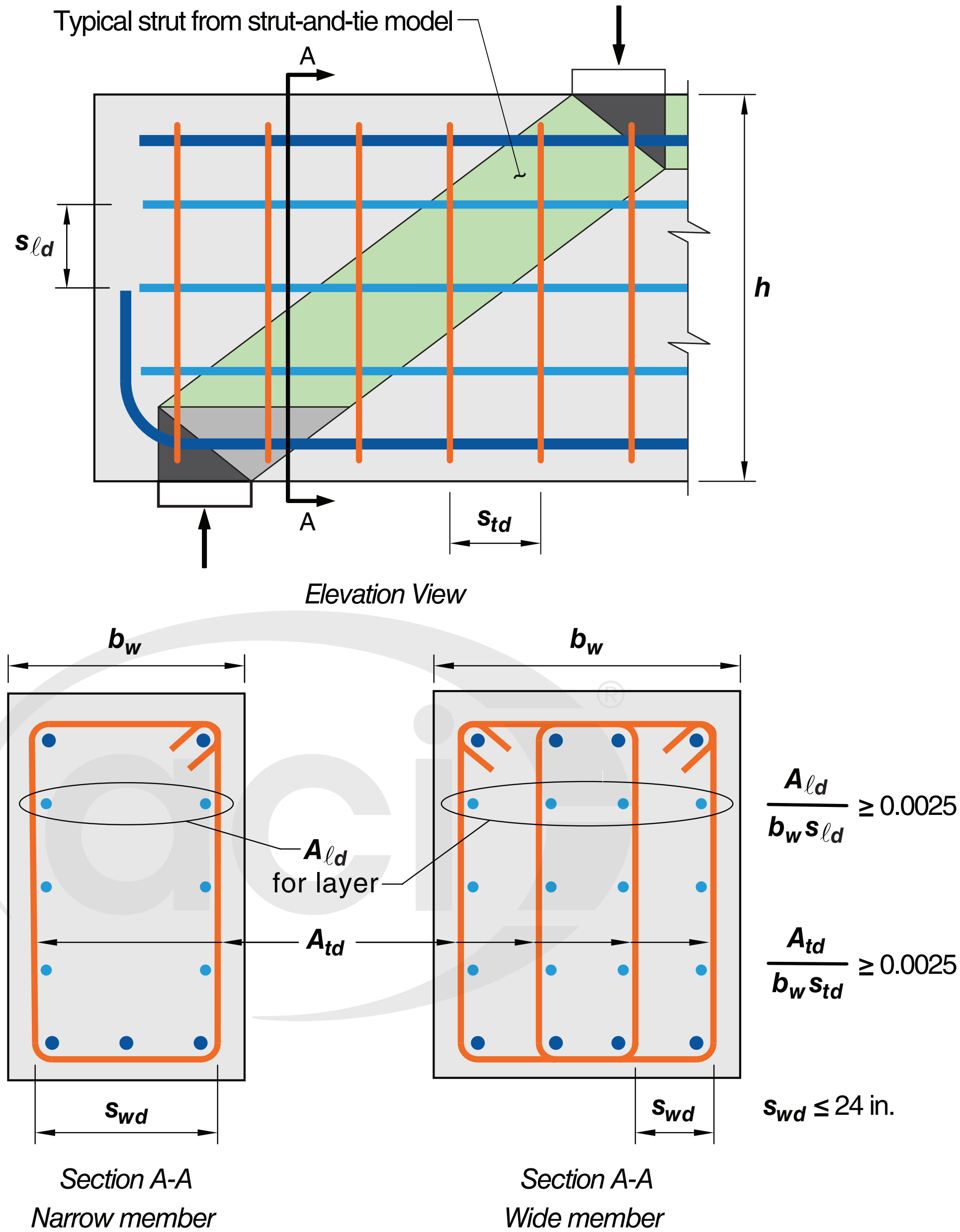

Fig. R9.9.4.3—Distributed reinforcement in deep beams

9.9.4.4 For deep beams having a width > 8 in., distributed reinforcement required by 9.9.3.1 shall be placed in accordance with (a) and (b):

(a) At least two curtains of reinforcement shall be provided with one near each side face.

(b) Spacing s_{wd} between any adjacent curtains shall not exceed 24 in.

R9.9.4.4 To the extent practicable, multiple curtains of reinforcement, whether parallel with the beam depth or width, should be placed symmetrically with respect to the center planes of the beam. The spacing limit of 24 in. is consistent with the maximum spacing of shear reinforcement legs in 9.7.6.2.2.

9.9.4.5 Development of tension reinforcement shall account for distribution of stress in reinforcement that is not directly proportional to the bending moment.

R9.9.4.5 In deep beams, stress in longitudinal reinforcement is more uniform along the length than that of a beam that is not deep. High reinforcement stresses normally limited to the center region of a beam can extend to the supports in deep beams. Thus, ends of longitudinal reinforcement in

CODE

9.9.4.6 At simple supports, positive moment tension reinforcement shall develop f_y in tension at the face of the support. If a deep beam is designed using Chapter 23, the positive moment tension reinforcement shall be anchored in accordance with 23.8.4 and 23.8.5.

9.9.4.7 At interior supports, (a) and (b) shall be satisfied:

(a) Negative moment tension reinforcement shall be continuous with that of the adjacent spans.
(b) Positive moment tension reinforcement shall be continuous or spliced with that of the adjacent spans.

COMMENTARY

deep beams may require positive anchorage in the form of standard hooks, bar heads, or other mechanical anchorage at supports.

R9.9.4.6 Use of the strut-and-tie method for design of deep beams illustrates that tensile forces in the bottom tie reinforcement need to be anchored at the face of the support. From this consideration, tie reinforcement should be continuous or developed at the face of the support (Rogowsky and MacGregor 1986).

Notes