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mance can be obtained with greater amounts of prestressed reinforcement, this restriction is needed to allow the use of the same response modification and deflection amplification factors as those specified in model codes for special moment frames without prestressed reinforcement. Prestressed special moment frames will generally contain continuous prestressed reinforcement that is anchored with adequate cover at or beyond the exterior face of each beam-column connection located at the ends of the moment frame.

Fatigue testing for 50 cycles of loading between 40 and 80% of the specified tensile strength of the prestressed reinforcement has been a long-standing industry practice (ACI PRC-423.3; ACI SPEC-423.7). The 80% limit was increased to 85% to correspond to the 1% limit on the strain in prestressed reinforcement. Testing over this range of stress is intended to conservatively simulate the effect of a severe earthquake. Additional details on testing procedures are provided in ACI SPEC-423.7.

18.6.4 *Transverse reinforcement*

R18.6.4 *Transverse reinforcement*

Transverse reinforcement is required primarily to confine the concrete and provide lateral support for the reinforcing bars in regions where yielding is expected. Examples of transverse reinforcement suitable for beams are shown in Fig. R18.6.4.

In earlier Code editions, the upper limit on hoop spacing was the least of $d/4$, eight longitudinal bar diameters, 24 tie bar diameters, and 12 in. The upper limits were changed in the 2011 edition because of concerns about adequacy of longitudinal bar buckling restraint and confinement in large beams.

In the case of members with varying strength along the span or members for which the permanent load represents a large proportion of the total design load, concentrations of inelastic rotation may occur within the span. If such a condition is anticipated, transverse reinforcement is also required in regions where yielding is expected. Because spalling of the concrete shell might occur, especially at and near regions of flexural yielding, all web reinforcement is required to be provided in the form of closed hoops.

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18.6.4.1 Hoops or closed stirrups in accordance with 18.6.4.3 shall be provided in the following regions of a beam:

(a) Over a length equal to twice the beam depth measured from the face of the supporting column toward midspan, at both ends of the beam

(b) Over lengths equal to twice the beam depth on both sides of a section where flexural yielding is likely to occur as a result of lateral displacements beyond the elastic range of behavior.

18.6.4.2 In regions of the beam defined in 18.6.4.1, primary longitudinal reinforcing bars closest to the tension and compression faces shall have lateral support in accor-

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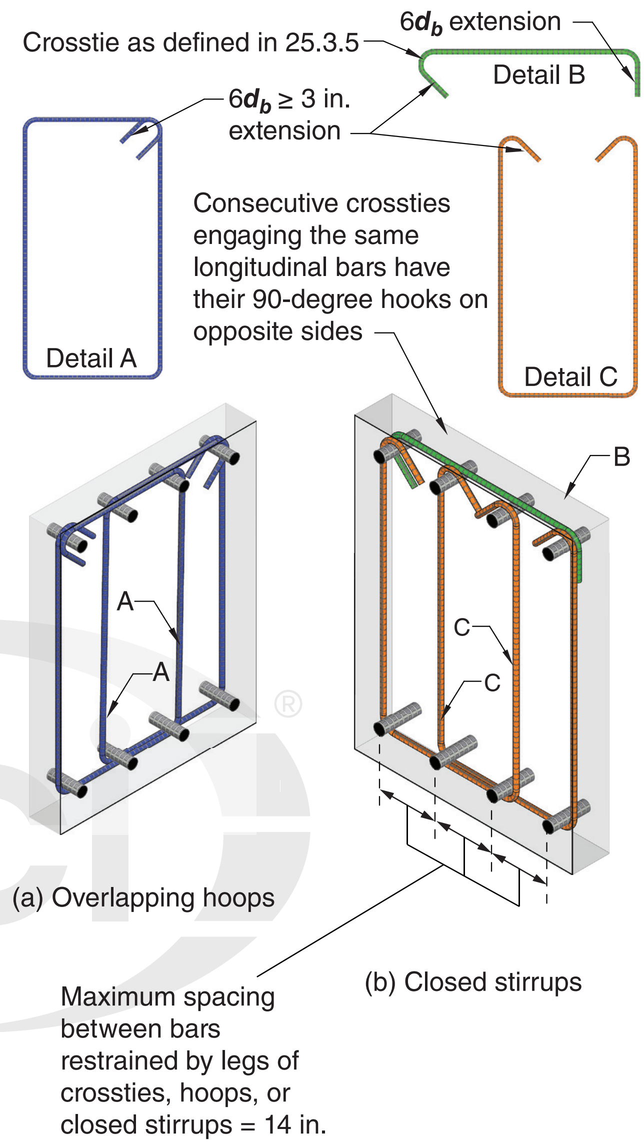

Fig. R18.6.4—Examples of beam transverse reinforcement and illustration of limit on maximum horizontal spacing of supported longitudinal bars.

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dance with 25.7.2.3 and 25.7.2.4. The transverse spacing of supported flexural reinforcing bars shall not exceed 14 in. Skin reinforcement required by 9.7.2.3 need not be laterally supported.

18.6.4.3 Closed stirrups in beams shall be permitted to be made up of one or more U-stirrups having seismic hooks at both ends, closed by a crosstie. Consecutive crossties engaging the same longitudinal bar shall have their 90-degree hooks at opposite sides of the flexural member. If the longitudinal reinforcing bars secured by the crossties are confined by a slab on only one side of the beam, the 90-degree hooks of the crossties shall be placed on that side.

18.6.4.4 The first hoop or closed stirrup shall be located not more than 2 in. from the face of a supporting column. Spacing of the hoops or closed stirrups shall not exceed the least of (a) through (d):

(a) $d/4$

(b) 6 in.

(c) For Grade 60, $6d_b$ of the smallest primary flexural reinforcing bar excluding longitudinal skin reinforcement required by 9.7.2.3

(d) For Grade 80, $5d_b$ of the smallest primary flexural reinforcing bar excluding longitudinal skin reinforcement required by 9.7.2.3

18.6.4.5 Where hoops are not required, stirrups with seismic hooks at both ends shall be spaced at a distance not more than $d/2$ throughout the length of the beam.

18.6.4.6 In beams having factored axial compressive force exceeding $A_g f_c'/10$, hoops satisfying 18.7.5.2 through 18.7.5.4 shall be provided along lengths given in 18.6.4.1. Along the remaining length, hoops satisfying 18.7.5.2 shall have spacing s not exceeding the least of 6 in., $6d_b$ of the smallest Grade 60 enclosed longitudinal beam bar, and $5d_b$ of the smallest Grade 80 enclosed longitudinal beam bar. Where concrete cover over transverse reinforcement exceeds 4 in., additional transverse reinforcement having cover not exceeding 4 in. and spacing not exceeding 12 in. shall be provided.

18.6.5 *Shear strength*

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R18.6.5 *Shear strength*

Unless a beam possesses a moment strength that is on the order of 3 or 4 times the design moment, it should be assumed that it will yield in flexure in the event of a major earthquake. The design shear force should be selected so as to be a good approximation of the maximum shear that may develop in a member. Therefore, required shear strength for frame members is related to flexural strengths of the designed member rather than to factored shear forces indicated by lateral load analysis. The conditions described by 18.6.5.1 are illustrated in Fig. R18.6.5. The figure also shows that vertical earthquake effects are to be included, as is typi-

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cally required by the general building code. For example, ASCE/SEI 7 requires vertical earthquake effects, $0.2S_{DS}$, to be included.

Because the actual yield strength of the longitudinal reinforcement may exceed the specified yield strength and because strain hardening of the reinforcement is likely to take place at a joint subjected to large rotations, required shear strengths are determined using a stress of at least $1.25f_y$ in the longitudinal reinforcement.

Experimental studies (Popov et al. 1972) of reinforced concrete members subjected to cyclic loading have demonstrated that more shear reinforcement is required to ensure a flexural failure if the member is subjected to alternating nonlinear displacements than if the member is loaded in only one direction: the necessary increase of shear reinforcement being higher in the case of no axial load. This observation is reflected in the Code (refer to 18.6.5.2) by eliminating the term representing the contribution of concrete to shear strength. The added conservatism on shear is deemed necessary in locations where potential flexural hinging may occur. However, this stratagem, chosen for its relative simplicity, should not be interpreted to mean that no concrete is required to resist shear. On the contrary, it may be argued that the concrete core resists all the shear with the shear (transverse) reinforcement confining and strengthening the concrete. The confined concrete core plays an important role in the behavior of the beam and should not be reduced to a minimum just because the design expression does not explicitly recognize it.

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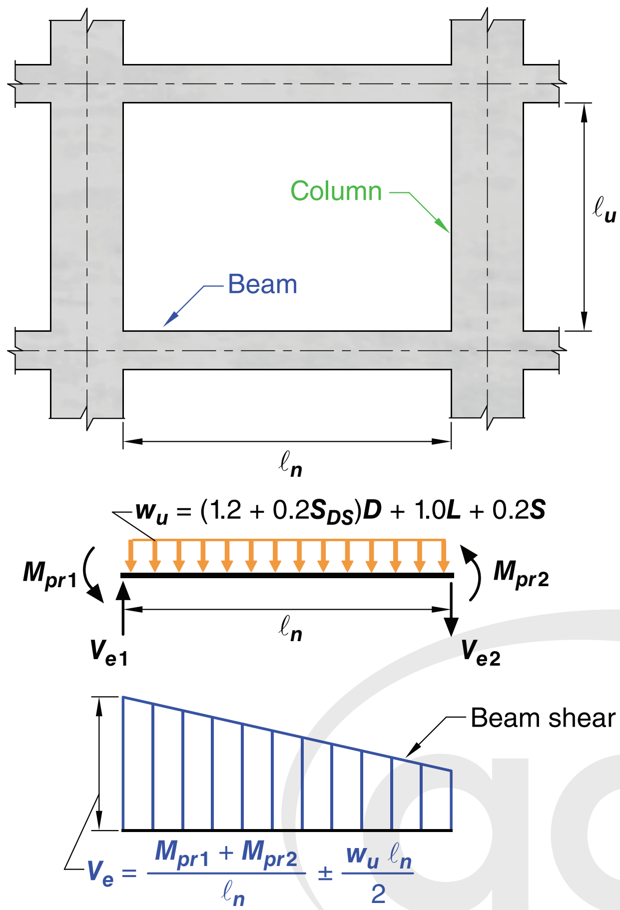

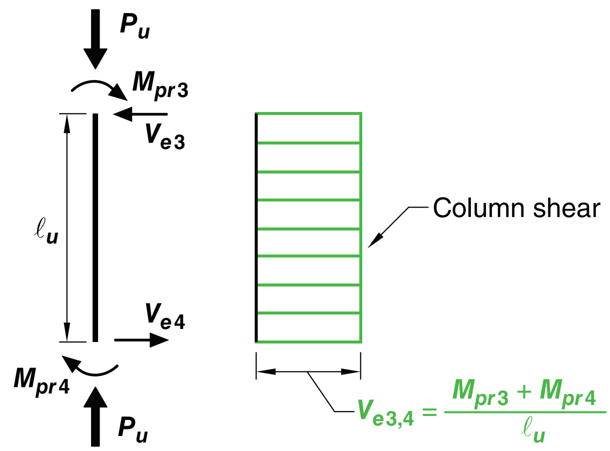

Fig. R18.6.5—Design shears for beams and columns.

Notes on Fig. R18.6.5:

1. Direction of shear force V_e depends on relative magnitudes of gravity loads and shear generated by end moments.
2. End moments M_{pr} based on steel tensile stress of $1.25f_y$, where f_y is specified yield strength. (Both end moments should be considered in both directions, clockwise and counter-clockwise).
3. End moment M_{pr} for columns need not be greater than moments generated by the M_{pr} of the beams framing into the beam-column joints. V_e should not be less than that required by analysis of the structure.

18.6.5.1 *Design forces*

The design shear force V_e shall be calculated from consideration of the forces on the portion of the beam between faces of the joints. It shall be assumed that moments of opposite sign corresponding to probable flexural strength, M_{pr}, act at the joint faces and that the beam is loaded with the factored gravity and vertical earthquake loads along its span.

18.6.5.2 *Transverse reinforcement*

Transverse reinforcement over the lengths identified in 18.6.4.1 shall be designed to resist shear assuming $V_c = 0$ when both (a) and (b) occur:

(a) The earthquake-induced shear force calculated in accordance with 18.6.5.1 represents at least one-half of the maximum required shear strength within those lengths.

(b) The factored axial compressive force P_u including earthquake effects is less than $A_g f_c'/20$.

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18.7—Columns of special moment frames

18.7.1 *Scope*

18.7.1.1 This section shall apply to columns of special moment frames that form part of the seismic-force-resisting system and are proportioned primarily to resist flexure, shear, and axial forces.

18.7.2 *Dimensional limits*

18.7.2.1 Columns shall satisfy (a) and (b):

(a) The shortest cross-sectional dimension, measured on a straight line passing through the geometric centroid, shall be at least 12 in.

(b) The ratio of the shortest cross-sectional dimension to the perpendicular dimension shall be at least 0.4.

18.7.3 *Minimum flexural strength of columns*

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R18.7—Columns of special moment frames

R18.7.1 *Scope*

This section applies to columns of special moment frames regardless of the magnitude of axial force. Before 2014, the Code permitted columns with low levels of axial stress to be detailed as beams.

R18.7.2 *Dimensional limits*

The geometric constraints in this provision follow from previous practice (Seismology Committee of SEAOC [1996]).

R18.7.3 *Minimum flexural strength of columns*

The intent of 18.7.3.2 is to reduce the likelihood of yielding in columns that are considered as part of the seismic-force-resisting system. If columns are not stronger than beams framing into a joint, there is increased likelihood of inelastic action. In the worst case of weak columns, flexural yielding can occur at both ends of all columns in a given story, resulting in a column failure mechanism that can lead to collapse. Connections with discontinuous columns above the connection, such as roof-level connections, are exempted if the column axial load is low, because special moment frame columns with low axial stress are inherently ductile and column yielding at such levels is unlikely to create a column failure mechanism that can lead to collapse.

In 18.7.3.2, the nominal strengths of the beams and columns are calculated at the joint faces, and those strengths are compared directly using Eq. (18.7.3.2). The 1995 and earlier Codes required design strengths to be compared at the center of the joint, which typically produced similar results but with added calculation effort.

In determining the nominal moment strength of a beam section in negative bending (top in tension), longitudinal reinforcement contained within an effective flange width of a top slab that acts monolithically with the beam increases the beam strength. French and Moehle (1991), on beam-column subassemblies under lateral loading, indicates that using the effective flange widths defined in 6.3.2 gives reasonable estimates of beam negative moment strengths of interior connections at story displacements approaching 2 percent of

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story height. This effective width is conservative where the slab terminates in a weak spandrel.

If 18.7.3.2 cannot be satisfied at a joint, 18.7.3.3 requires that any positive contribution of the column or columns involved to the lateral strength and stiffness of the structure is to be ignored. Negative contributions of the column or columns should not be ignored. For example, ignoring the stiffness of the columns ought not to be used as a justification for reducing the design base shear. If inclusion of those columns in the analytical model of the building results in an increase in torsional effects, the increase should be considered as required by the general building code. Furthermore, the column must be provided with transverse reinforcement to increase its resistance to shear and axial forces.

18.7.3.1 Columns shall satisfy 18.7.3.2 or 18.7.3.3, except at connections where the column is discontinuous above the connection and the column factored axial compressive force P_u under load combinations including earthquake effect, E, are less than $A_g f_c'/10$.

18.7.3.2 The flexural strengths of the columns shall satisfy

$$\sum M_{nc} \geq (6/5)\sum M_{nb} \qquad (18.7.3.2)$$

where

$\sum M_{nc}$ is sum of nominal flexural strengths of columns framing into the joint, evaluated at the faces of the joint. Column flexural strength shall be calculated for the factored axial force, consistent with the direction of the lateral forces considered, resulting in the lowest flexural strength.

$\sum M_{nb}$ is sum of nominal flexural strengths of the beams framing into the joint, evaluated at the faces of the joint. In T-beam construction, where the slab is in tension under moments at the face of the joint, slab reinforcement within an effective slab width defined in accordance with 6.3.2 shall be assumed to contribute to M_{nb} if the slab reinforcement is developed at the critical section for flexure.

Flexural strengths shall be summed such that the column moments oppose the beam moments. Equation (18.7.3.2) shall be satisfied for beam moments acting in both directions in the vertical plane of the frame considered.

18.7.3.3 If 18.7.3.2 is not satisfied at a joint, the lateral strength and stiffness of the columns framing into that joint shall be ignored when calculating strength and stiffness of the structure. These columns shall conform to 18.14.

18.7.4 *Longitudinal reinforcement*

R18.7.4 *Longitudinal reinforcement*

The lower limit of the area of longitudinal reinforcement is to control time-dependent deformations and to have the yield moment exceed the cracking moment. The upper limit of the area reflects concern for reinforcement congestion, load transfer from floor elements to column (especially in low-rise construction) and the development of high shear stresses.

Spalling of the shell concrete, which is likely to occur near the ends of the column in frames of typical configuration, makes lap splices in these locations vulnerable. If lap splices are to be used at all, they should be located near the midheight where stress reversal is likely to be limited to a smaller stress range than at locations near the joints. Transverse reinforcement is required along the lap-splice length because of the uncertainty in moment distributions along the height and the need for confinement of lap splices subjected to stress reversals (Sivakumar et al. 1983).

18.7.4.1 Area of longitudinal reinforcement, A_{st}, shall be at least $0.01A_g$ and shall not exceed $0.06A_g$.

18.7.4.2 In columns with circular hoops, there shall be at least six longitudinal bars.

18.7.4.3 Over column clear height, either (a) or (b) shall be satisfied:

(a) Longitudinal reinforcement shall be selected such that $1.25\ell_d \leq \ell_u/2$.

(b) Transverse reinforcement shall be selected such that $K_{tr} \geq 1.2d_b$.

R18.7.4.3 Bond splitting failure along longitudinal bars within the clear column height may occur under earthquake demands (Ichinose 1995; Sokoli and Ghannoum 2016).

Splitting can be controlled by restricting longitudinal bar size, increasing the amount of transverse reinforcement, or increasing concrete strength, all of which reduce the development length of longitudinal bars (ℓ_d) over column clear height (ℓ_u).

18.7.4.4 Mechanical splices shall conform to 18.2.7 and welded splices shall conform to 18.2.8. Lap splices shall be permitted only within the center half of the member length, shall be designed as tension lap splices, and shall be enclosed within transverse reinforcement in accordance with 18.7.5.2 and 18.7.5.3.

18.7.5 *Transverse reinforcement*

R18.7.5 *Transverse reinforcement*

This section is concerned with confining the concrete and providing lateral support to the longitudinal reinforcement.

18.7.5.1 Transverse reinforcement required in 18.7.5.2 through 18.7.5.4 shall be provided over a length ℓ_o from each joint face and on both sides of any section where flexural yielding is likely to occur as a result of lateral displacements beyond the elastic range of behavior. Length ℓ_o shall be at least the greatest of (a) through (c):

(a) The depth of the column at the joint face or at the section where flexural yielding is likely to occur

(b) One-sixth of the clear span of the column

(c) 18 in.

R18.7.5.1 This section stipulates a minimum length over which to provide closely-spaced transverse reinforcement at the column ends, where flexural yielding normally occurs. Research results indicate that the length should be increased by 50% or more in locations, such as the base of a building, where axial loads and flexural demands may be especially high (Watson et al. 1994)

18.7.5.2 Transverse reinforcement shall be in accordance with (a) through (f):

R18.7.5.2 Sections 18.7.5.2 and 18.7.5.3 provide requirements for configuration of transverse reinforcement for columns and joints of special moment frames. Figure R18.7.5.2 shows an example of transverse reinforcement

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(a) Transverse reinforcement shall comprise either single or overlapping spirals, circular hoops, or single or overlapping rectilinear hoops with or without crossties.

(b) Bends of rectilinear hoops and crossties shall engage peripheral longitudinal reinforcing bars.

(c) Crossties of the same or smaller bar size as the hoops shall be permitted, subject to the limitation of 25.7.2.2. Consecutive crossties shall be alternated end for end along the longitudinal reinforcement and around the perimeter of the cross section.

(d) Where rectilinear hoops or crossties are used, they shall provide lateral support to longitudinal reinforcement in accordance with 25.7.2.2 and 25.7.2.3.

(e) Reinforcement shall be arranged such that the spacing h_x of longitudinal bars laterally supported by the corner of a crosstie or hoop leg shall not exceed 14 in. around the perimeter of the column.

(f) Where $P_u > 0.3A_gf_c'$ or $f_c' > 10{,}000$ psi in columns with rectilinear hoops, every longitudinal bar or bundle of bars around the perimeter of the column core shall have lateral support provided by the corner of a hoop or by a seismic hook, and the value of h_x shall not exceed 8 in. P_u shall be the largest value in compression consistent with factored load combinations including E.

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provided by one hoop and three crossties. Crossties with a 90-degree hook are not as effective as either crossties with 135-degree hooks or hoops in providing confinement. For lower values of P_u/A_gf_c' and lower concrete compressive strengths, crossties with 90-degree hooks are adequate if the ends are alternated along the length and around the perimeter of the column. For higher values of P_u/A_gf_c', for which compression-controlled behavior is expected, and for higher compressive strengths, for which behavior tends to be more brittle, the improved confinement provided by having corners of hoops or seismic hooks supporting all longitudinal bars is important to achieving intended performance. Where these conditions apply, crossties with seismic hooks at both ends are required. The 8 in. limit on h_x is also intended to improve performance under these critical conditions. For bundled bars, bends or hooks of hoops and crossties need to enclose the bundle, and longer extensions on hooks should be considered. Column axial load P_u should reflect factored compressive demands from both earthquake and gravity loads.

In past editions of the Code, the requirements for transverse reinforcement in columns, walls, beam-column joints, and diagonally reinforced coupling beams referred to the same equations. In the 2014 edition of the Code, the equations and detailing requirements differ among the member types based on consideration of their loadings, deformations, and performance requirements. Additionally, h_x previously referred to the distance between legs of hoops or crossties. In the 2014 edition of the Code, h_x refers to the distance between longitudinal bars supported by those hoops or crossties.

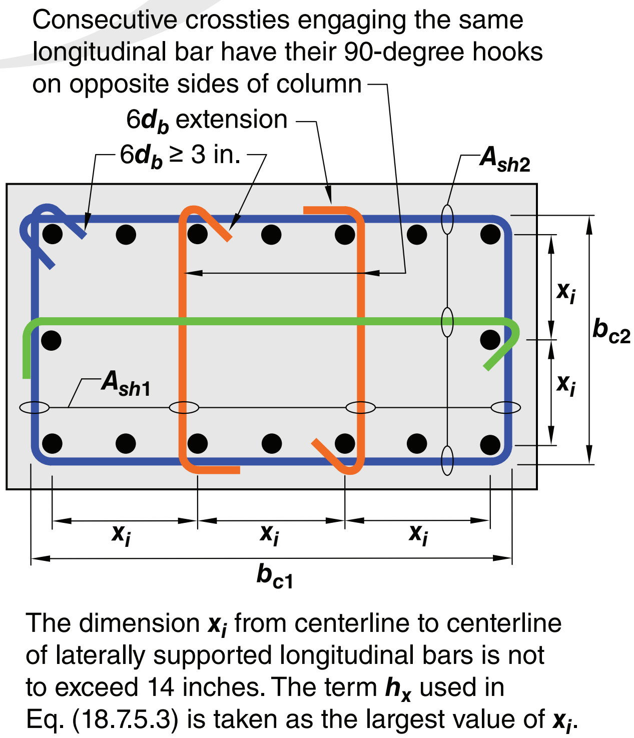

Fig. R18.7.5.2—Example of transverse reinforcement in columns.

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18.7.5.3 Spacing of transverse reinforcement shall not exceed the least of (a) through (d):

(a) One-fourth of the minimum column dimension

(b) For Grade 60, $6d_b$ of the smallest longitudinal bar

(c) For Grade 80, $5d_b$ of the smallest longitudinal bar

(d) s_o, as calculated by:

$$s_o = 4 + \left(\frac{14 - h_x}{3}\right) \quad (18.7.5.3)$$

The value of s_o from Eq. (18.7.5.3) shall not exceed 6 in. and need not be taken less than 4 in.

18.7.5.4 Amount of transverse reinforcement shall be in accordance with Table 18.7.5.4.

The concrete strength factor k_f and confinement effectiveness factor k_n are calculated according to Eq. (18.7.5.4a) and (18.7.5.4b).

$$\text{(a) } k_f = \frac{f_c'}{25{,}000} + 0.6 \geq 1.0 \quad (18.7.5.4a)$$

$$\text{(b) } k_n = \frac{n_l}{n_l - 2} \quad (18.7.5.4b)$$

where n_l is the number of longitudinal bars or bar bundles around the perimeter of a column core with rectilinear hoops that are laterally supported by the corner of hoops or by seismic hooks.

Table 18.7.5.4—Transverse reinforcement for columns of special moment frames

Transverse reinforcement	Conditions	Applicable expressions	
A_{sh}/sb_c for rectilinear hoop	$P_u \leq 0.3A_gf_c'$ and $f_c' \leq 10{,}000$ psi	Greater of (a) and (b)	$0.3\left(\frac{A_g}{A_{ch}} - 1\right)\frac{f_c'}{f_{yt}}$ (a)
			$0.09\frac{f_c'}{f_{yt}}$ (b)
	$P_u > 0.3A_gf_c'$ or $f_c' > 10{,}000$ psi	Greatest of (a), (b), and (c)	$0.2k_fk_n\frac{P_u}{f_{yt}A_{ch}}$ (c)
ρ_s for spiral or circular hoop	$P_u \leq 0.3A_gf_c'$ and $f_c' \leq 10{,}000$ psi	Greater of (d) and (e)	$0.45\left(\frac{A_g}{A_{ch}} - 1\right)\frac{f_c'}{f_{yt}}$ (d)
			$0.12\frac{f_c'}{f_{yt}}$ (e)
	$P_u > 0.3A_gf_c'$ or $f_c' > 10{,}000$ psi	Greatest of (d), (e), and (f)	$0.35k_f\frac{P_u}{f_{yt}A_{ch}}$ (f)

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R18.7.5.3 The requirement that spacing not exceed one-fourth of the minimum member dimension or 6 in. is for concrete confinement. If the maximum spacing of crossties or legs of overlapping hoops within the section is less than 14 in., then the 4 in. limit can be increased as permitted by Eq. (18.7.5.3). The spacing limit as a function of the longitudinal bar diameter is intended to provide adequate longitudinal bar restraint to control buckling after spalling.

R18.7.5.4 The effect of helical (spiral) reinforcement and adequately configured rectilinear hoop reinforcement on deformation capacity of columns is well established (Sakai and Sheikh 1989). Expressions (a), (b), (d), and (e) in Table 18.7.5.4 have historically been used in ACI 318 to calculate the required confinement reinforcement to ensure that spalling of shell concrete does not result in a loss of column axial load strength. Expressions (c) and (f) were developed from a review of column test data (Elwood et al. 2009) and are intended to result in columns capable of sustaining a drift ratio of 0.03 with limited strength degradation. Expressions (c) and (f) are triggered for axial load greater than $0.3A_gf_c'$, which corresponds approximately to the onset of compression-controlled behavior for symmetrically reinforced columns. The k_n term (Paultre and Légeron 2008) decreases the required confinement for columns with closely spaced, laterally supported longitudinal reinforcement because such columns are more effectively confined than columns with more widely spaced longitudinal reinforcement. The k_f term increases the required confinement for columns with $f_c' > 10{,}000$ psi because such columns can experience brittle failure if not well confined. Concrete strengths greater than 15,000 psi should be used with caution given the limited test data for such columns. The concrete strength used to determine the confinement reinforcement is required to be the same as that specified in the construction documents.

Expressions (a), (b), and (c) in Table 18.7.5.4 are to be satisfied in both cross-sectional directions of the rectangular core. For each direction, b_c is the core dimension perpendicular to the tie legs that constitute A_{sh}, as shown in Fig. R18.7.5.2.

Research results indicate that high strength reinforcement can be used effectively as confinement reinforcement. Section 20.2.2.4 permits a value of f_{yt} as high as 100,000 psi to be used in Table 18.7.5.4.

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18.7.5.5 Beyond the length ℓ_o given in 18.7.5.1, the column shall contain spiral reinforcement satisfying 25.7.3 or hoop and crosstie reinforcement satisfying 25.7.2 and 25.7.4 with spacing s not exceeding the least of 6 in., $6d_b$ of the smallest Grade 60 longitudinal column bar, and $5d_b$ of the smallest Grade 80 longitudinal column bar, unless a greater amount of transverse reinforcement is required by 18.7.4.4 or 18.7.6.

18.7.5.6 Columns supporting reactions from discontinued stiff members, such as walls, shall satisfy (a) and (b):

(a) Transverse reinforcement required by 18.7.5.2 through 18.7.5.4 shall be provided over the full height at all levels beneath the discontinuity if the factored axial compressive force in these columns, related to earthquake effect, exceeds $A_g f_c'/10$. Where design forces have been magnified to account for the overstrength of the vertical elements of the seismic-force-resisting system, the limit of $A_g f_c'/10$ shall be increased to $A_g f_c'/4$.

(b) Transverse reinforcement shall extend into the discontinued member at least ℓ_d of the largest longitudinal column bar, where ℓ_d is in accordance with 18.8.5. Where the lower end of the column terminates on a wall, the required transverse reinforcement shall extend into the wall at least ℓ_d of the largest longitudinal column bar at the point of termination. Where the column terminates on a footing or mat, the required transverse reinforcement shall extend at least 12 in. into the footing or mat.

18.7.5.7 If the concrete cover outside the confining transverse reinforcement required by 18.7.5.1, 18.7.5.5, and 18.7.5.6 exceeds 4 in., additional transverse reinforcement having cover not exceeding 4 in. and spacing not exceeding 12 in. shall be provided.

18.7.6 *Shear strength*
18.7.6.1 *Design forces*

18.7.6.1.1 The design shear force V_e shall be calculated from considering the maximum forces that can be generated at the faces of the joints at each end of the column. These joint forces shall be calculated using the maximum probable flexural strengths, M_{pr}, at each end of the column associated with the range of factored axial forces, P_u, acting on the column. The column shears need not exceed those calculated from joint strengths based on M_{pr} of the beams framing into the joint. In no case shall V_e be less than the factored shear calculated by analysis of the structure.

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R18.7.5.5 This provision is intended to provide reasonable protection to the midheight of columns outside the length ℓ_o. Observations after earthquakes have shown significant damage to columns in this region, and the minimum hoops or spirals required should provide more uniform strength of the column along its length.

R18.7.5.6 Columns supporting discontinued stiff members, such as walls or trusses, may develop considerable inelastic response. Therefore, it is required that these columns have the specified reinforcement throughout their length. This covers all columns beneath the level at which the stiff member has been discontinued, unless the factored forces corresponding to earthquake effect are low. Refer to R18.12.7.6 for discussion of the overstrength factor Ω_o.

R18.7.5.7 The unreinforced shell may spall as the column deforms to resist earthquake effects. Separation of portions of the shell from the core caused by local spalling creates a falling hazard. The additional reinforcement is required to reduce the risk of portions of the shell falling away from the column.

R18.7.6 *Shear strength*
R18.7.6.1 *Design forces*

R18.7.6.1.1 The procedures of 18.6.5.1 also apply to columns. Above the ground floor, the moment at a joint may be limited by the flexural strength of the beams framing into the joint. Where beams frame into opposite sides of a joint, the combined strength is the sum of the negative moment strength of the beam on one side of the joint and the positive moment strength of the beam on the other side of the joint. Moment strengths are to be determined using a strength reduction factor of 1.0 and reinforcement with an effective yield stress equal to at least $1.25f_y$. Distribution of the combined moment strength of the beams to the columns above and below the joint should be based on analysis.

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18.7.6.2 *Transverse reinforcement*

18.7.6.2.1 Transverse reinforcement over the lengths ℓ_o, given in 18.7.5.1, shall be designed to resist shear assuming $V_c = 0$ when both (a) and (b) occur:

(a) The earthquake-induced shear force, calculated in accordance with 18.7.6.1, is at least one-half of the maximum required shear strength within ℓ_o.

(b) The factored axial compressive force P_u including earthquake effects is less than $A_g f_c'/20$.

18.8—Joints of special moment frames

18.8.1 *Scope*

18.8.1.1 This section shall apply to beam-column joints of special moment frames forming part of the seismic-force-resisting system.

18.8.2 *General*

18.8.2.1 Forces in longitudinal beam reinforcement at the joint face shall be calculated assuming that the stress in the flexural tensile reinforcement is $1.25f_y$.

18.8.2.2 Longitudinal reinforcement terminated in a joint shall extend to the far face of the joint core and shall be developed in tension in accordance with 18.8.5.

18.8.2.3 Where longitudinal beam reinforcement extends through a beam-column joint, the depth h of the joint parallel to the beam longitudinal reinforcement shall be at least the greatest of (a) through (c):

(a) $(20/\lambda)d_b$ of the largest Grade 60 longitudinal bar, where $\lambda = 0.75$ for lightweight concrete and 1.0 for all other cases

(b) $26d_b$ of the largest Grade 80 longitudinal bar

(c) $h/2$ of any beam framing into the joint and generating joint shear as part of the seismic-force-resisting system in the direction under consideration

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R18.8—Joints of special moment frames

R18.8.2 *General*

Development of inelastic rotations at the faces of joints of reinforced concrete frames is associated with strains in the flexural reinforcement well in excess of the yield strain. Consequently, joint shear force generated by the flexural reinforcement is calculated for a stress of $1.2f_y$ in the reinforcement (refer to 18.8.2.1). A detailed explanation of the reasons for the possible development of stresses in excess of the yield strength in beam tensile reinforcement is provided in ACI PRC-352.

R18.8.2.2 The design provisions for hooked bars in special moment frames are based mainly on research and experience for joints with standard 90-degree hooks. Therefore, standard 90-degree hooks generally are preferred to standard 180-degree hooks unless unusual considerations dictate use of 180-degree hooks. Prior to the 2025 edition of the Code, it was required to check compression development length of longitudinal reinforcement. Assessment of experimental data indicates this check is unnecessary to achieve satisfactory joint behavior (Uzumeri and Seckin 1974; Kang et al. 2009).

R18.8.2.3 Depth h of the joint is defined in Fig. R15.5.2.2. The column dimension parallel to the beam reinforcement in joints with circular columns may be taken as that of a square section of equivalent area. Research (Meinheit and Jirsa 1977; Briss et al. 1978; Ehsani 1982; Durrani and Wight 1982; Leon 1989; Aoyama 2001; Lin et al. 2000) has shown that straight longitudinal beam bars may slip within the beam-column joint during a series of large moment reversals. The bond stresses on these straight bars may be very large. To reduce slip substantially during the formation of

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adjacent beam hinging, it would be necessary to have a ratio of column dimension to bar diameter of approximately 32 for Grade 60 bars, which would result in very large joints. Tests demonstrate adequate behavior if the ratio of joint depth to maximum beam longitudinal bar diameter for Grade 60 reinforcement is at least 20 for normalweight concrete and 26 for lightweight concrete. A joint depth of $26d_b$ for Grade 80 reinforcement is intended to achieve similar performance to that of a joint depth of $20d_b$ for Grade 60 reinforcement and normalweight concrete. The limits on joint depth provide reasonable control on the amount of slip of the beam bars in a beam-column joint, considering the number of anticipated inelastic excursions of the building frame during a major earthquake. A thorough treatment of this topic is given in Zhu and Jirsa (1983).

Requirement (c) on joint aspect ratio applies only to beams that are designated as part of the seismic-force-resisting system. Joints having depth less than half the beam depth require a steep diagonal compression strut across the joint, which may be less effective in resisting joint shear. Tests to demonstrate performance of such joints have not been reported in the literature.

18.8.2.3.1 Concrete used in joints with Grade 80 longitudinal reinforcement shall be normalweight concrete.

R18.8.2.3.1 Test data justifying the combination of lightweight concrete and Grade 80 longitudinal reinforcement in joints are not available.

18.8.3 *Transverse reinforcement*

R18.8.3 *Transverse reinforcement*

The Code requires transverse reinforcement in a joint regardless of the magnitude of the calculated shear force.

18.8.3.1 Joint transverse reinforcement shall satisfy 18.7.5.2, 18.7.5.3, 18.7.5.4, and 18.7.5.7, except as permitted in 18.8.3.2.

18.8.3.2 Where beams frame into all four sides of the joint and where each beam width is at least three-fourths the column width, the amount of reinforcement required by 18.7.5.4 shall be permitted to be reduced by one-half, and the spacing required by 18.7.5.3 shall be permitted to be increased to 6 in. within the overall depth h of the shallowest framing beam.

R18.8.3.2 The amount of confining reinforcement may be reduced and the spacing may be increased if beams of adequate dimensions frame into all four sides of the joint.

18.8.3.3 Longitudinal beam reinforcement outside the column core shall be confined by transverse reinforcement passing through the column that satisfies spacing requirements of 18.6.4.4, and requirements of 18.6.4.2, and 18.6.4.3, if such confinement is not provided by a beam framing into the joint.

R18.8.3.3 The required transverse reinforcement, or transverse beam if present, is intended to confine the beam longitudinal reinforcement and improve force transfer to the beam-column joint.

An example of transverse reinforcement through the column provided to confine the beam reinforcement passing outside the column core is shown in Fig. R18.6.2. Additional detailing guidance and design recommendations for both interior and exterior wide-beam connections with beam reinforcement passing outside the column core may be found in ACI PRC-352.

18.8.4 *Shear strength*

R18.8.4 *Shear strength*

The shear strength values given in 18.8.4.3 are based on the recommendation in ACI PRC-352 for joints with members that are expected to undergo reversals of deformation into the inelastic range, although the ACI PRC-352 definition of effective cross-sectional joint area is sometimes different. The given nominal joint shear strengths do not explicitly consider transverse reinforcement in the joint because tests of joints (Meinheit and Jirsa 1977) and deep beams (Hirosawa 1977) have indicated that joint shear strength is not sensitive to transverse reinforcement if at least the required minimum amount is provided in the joint.

Cyclic loading tests of joints with extensions of beams with lengths at least equal to their depths have indicated similar joint shear strengths to those of joints with continuous beams. These findings suggest that extensions of beams and columns, when properly dimensioned and reinforced with longitudinal and transverse bars, provide effective confinement to the joint faces, thus delaying joint strength deterioration at large deformations (Meinheit and Jirsa 1981).

18.8.4.1 Joint shear force V_u shall be calculated on a plane at mid-height of the joint from calculated forces at the joint faces using tensile and compressive beam forces determined in accordance with 18.8.2.1 and column shear consistent with beam probable flexural strengths M_{pr}.

18.8.4.2 ϕ shall be in accordance with 21.2.4.4.

18.8.4.3 V_n of the joint shall be in accordance with Table 18.8.4.3.

Table 18.8.4.3—Nominal joint shear strength V_n

Column	Beam in direction of V_u	Confinement by transverse beams according to 15.5.2.5	V_n, lb[1]
Continuous or meets 15.5.2.3	Continuous or meets 15.5.2.4	Confined	$20\lambda\sqrt{f_c'}A_j$
		Not confined	$15\lambda\sqrt{f_c'}A_j$
	Other	Confined	$15\lambda\sqrt{f_c'}A_j$
		Not confined	$12\lambda\sqrt{f_c'}A_j$
Other	Continuous or meets 15.5.2.4	Confined	$15\lambda\sqrt{f_c'}A_j$
		Not confined	$12\lambda\sqrt{f_c'}A_j$
	Other	Confined	$12\lambda\sqrt{f_c'}A_j$
		Not confined	$8\lambda\sqrt{f_c'}A_j$

[1] λ shall be 0.75 for lightweight concrete and 1.0 for normalweight concrete. A_j shall be calculated in accordance with 15.5.2.2 .

18.8.5 *Development length of bars in tension*

18.8.5.1 For bar sizes No. 3 through No. 11 terminating in a standard hook, ℓ_{dh} shall be calculated by Eq. (18.8.5.1), but ℓ_{dh} shall be at least the greater of $8d_b$ and 6 in. for normal-

R18.8.5 *Development length of bars in tension*

R18.8.5.1 Minimum embedment length in tension for deformed bars with standard hooks is determined using Eq. (18.8.5.1), which is based on the requirements of 25.4.3 of ACI 318-14. The embedment length of a bar with a stan-

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weight concrete and at least the greater of $10d_b$ and 7-1/2 in. for lightweight concrete.

$$\ell_{dh} = f_y d_b/(65\lambda\sqrt{f_c'}) \quad (18.8.5.1)$$

The value of λ shall be 0.75 for concrete containing lightweight aggregate and 1.0 otherwise.

The hook shall be located within the confined core of a column or of a boundary element, with the hook bent into the joint.

18.8.5.2 Headed deformed bars satisfying 20.2.1.6 shall develop $1.25f_y$ in tension in accordance with 25.4.4 by substituting a bar stress of $1.25f_y$ for f_y.

18.8.5.3 For bar sizes No. 3 through No. 11, ℓ_d, the development length in tension for a straight bar, shall be at least the greater of (a) and (b):

(a) 2.5 times the length in accordance with 18.8.5.1 if the depth of the concrete cast in one lift beneath the bar does not exceed 12 in.

(b) 3.25 times the length in accordance with 18.8.5.1 if the depth of the concrete cast in one lift beneath the bar exceeds 12 in.

18.8.5.4 Straight bars terminated at a joint shall pass through the confined core of a column or a boundary element. Any portion of ℓ_d not within the confined core shall be increased by a factor of 1.6.

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dard hook is the distance, parallel to the bar, from the critical section (where the bar is to be developed) to a tangent drawn to the outside edge of the hook. The tangent is to be drawn perpendicular to the axis of the bar (refer to Table 25.3.1).

Equation (18.8.5.1) was derived from the equation for development length ℓ_{dh} in 25.4.3 of ACI 318-14 using coefficients of 1.0 (no epoxy coating), 0.7 (cover) and 0.8 (confinement reinforcement) because Chapter 18 stipulates that the hook is to be embedded in confined concrete. The development length that would be derived directly from 25.4.3 in ACI 318-14 was increased to reflect the effect of load reversals. Factors such as the actual stress in the reinforcement being more than the yield strength and the effective development length not necessarily starting at the face of the joint were implicitly considered in the formulation of the expression for basic development length that has been used as the basis for Eq. (18.8.5.1).

The requirement for the hook to project into the joint is to improve development of a diagonal compression strut across the joint. The requirement applies to beam and column bars terminated at a joint with a standard hook, preferably a standard 90-degree hook.

R18.8.5.2 The factor 1.25 is intended to represent the potential increase in stresses due to inelastic response, including strain hardening that may occur in beams of special moment frames.

R18.8.5.3 Minimum development length in tension for straight bars is a multiple of the length indicated by 18.8.5.1. Section 18.8.5.3(b) refers to top bars. Lack of reference to No. 14 and No. 18 bars in 18.8.5 is due to the paucity of information on anchorage of such bars subjected to load reversals simulating earthquake effects.

R18.8.5.4 If the required straight embedment length of a reinforcing bar extends beyond the confined volume of concrete (as defined in 18.6.4, 18.7.5, or 18.8.3), the required development length is increased on the premise that the limiting bond stress outside the confined region is less than that inside.

$$\ell = 1.6(\ell_d - \ell_{dc}) + \ell_{dc}$$

or

$$\ell_{dm} = 1.6\ell_d - 0.6\ell_{dc}$$

where ℓ_{dm} is the required development length if bar is not entirely embedded in confined concrete; ℓ_d is the required development length in tension for straight bar as defined in 18.8.5.3; and ℓ_{dc} is the length of bar embedded in confined concrete.

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18.8.5.5 If epoxy-coated reinforcement is used, the development lengths in 18.8.5.1, 18.8.5.3, and 18.8.5.4 shall be multiplied by applicable factors in 25.4.2.5 or 25.4.3.2.

18.9—Special moment frames constructed using precast concrete

18.9.1 *Scope*

18.9.1.1 This section shall apply to special moment frames constructed using precast concrete forming part of the seismic-force-resisting system.

18.9.2 *General*

18.9.2.1 Special moment frames with ductile connections constructed using precast concrete shall satisfy (a) through (c):

(a) Requirements of 18.6 through 18.8 for special moment frames constructed with cast-in-place concrete

(b) V_n for connections calculated according to 22.9 shall be at least $2V_e$, where V_e is in accordance with 18.6.5.1 or 18.7.6.1

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R18.9—Special moment frames constructed using precast concrete

The detailing provisions in 18.9.2.1 and 18.9.2.2 are intended to produce frames that respond to design displacements essentially like monolithic special moment frames.

Precast frame systems composed of concrete elements with ductile connections are expected to experience flexural yielding in connection regions (Yoshioka and Sekine 1991; Kurose et al. 1991; Restrepo et al. 1995a,b). The restriction on location of mechanical splices is intended to avoid strain concentrations over a short length of reinforcement adjacent to a splice device. Additional requirements for shear strength are provided in 18.9.2.1 to prevent sliding on connection faces. Precast frames composed of elements with ductile connections may be designed to promote yielding at locations not adjacent to the joints. Therefore, design shear V_e, as calculated according to 18.6.5.1 or 18.7.6.1, may not be conservative.

Precast concrete frame systems composed of elements joined using strong connections are intended to experience flexural yielding outside the connections. Strong connections include the length of the mechanical splice hardware as shown in Fig. R18.9.2.2. Capacity-design techniques are used in 18.9.2.2(c) to ensure the strong connection remains elastic following formation of plastic hinges. Additional column requirements are provided to avoid hinging and strength deterioration of column-to-column connections.

Strain concentrations have been observed to cause brittle fracture of reinforcing bars at the face of mechanical splices in laboratory tests of precast beam-column connections (Palmieri et al. 1996). Locations of strong connections should be selected carefully or other measures should be taken, such as debonding of reinforcing bars in highly stressed regions, to avoid strain concentrations that can result in premature fracture of reinforcement.

R18.9.2 *General*

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(c) Mechanical splices of beam reinforcement shall be located not closer than $h/2$ from the joint face and shall be Class S.

18.9.2.2 Special moment frames with strong connections constructed using precast concrete shall satisfy (a) through (e):

(a) Requirements of 18.6 through 18.8 for special moment frames constructed with cast-in-place concrete

(b) Provision 18.6.2.1(a) shall apply to segments between locations where flexural yielding is intended to occur due to design displacements

(c) Design strength of the strong connection, ϕS_n, shall be at least S_e

(d) Primary longitudinal reinforcement shall be made continuous across connections and shall be developed outside both the strong connection and the plastic hinge region

(e) For column-to-column connections, ϕS_n shall be at least $1.4S_e$, ϕM_n shall be at least $0.4M_{pr}$ for the column within the story height, and ϕV_n shall be at least V_e in accordance with 18.7.6.1

18.9.2.3 Special moment frames constructed using precast concrete and not satisfying 18.9.2.1 or 18.9.2.2 shall satisfy (a) through (c):

(a) ACI CODE-374.1

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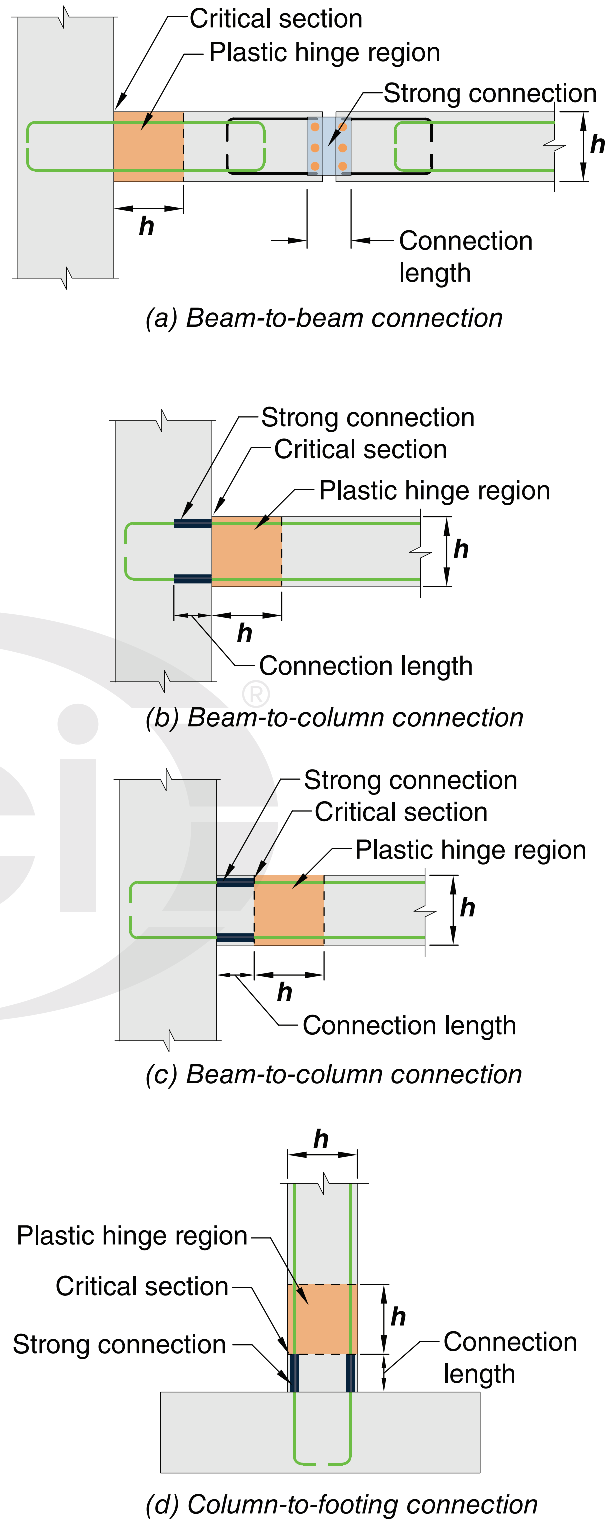

Fig. R18.9.2.2—Strong connection examples.

R18.9.2.3 Precast frame systems not satisfying the prescriptive requirements of Chapter 18 have been demonstrated in experimental studies to provide satisfactory seismic performance characteristics (Stone et al. 1995; Nakaki et al. 1999). ACI CODE-374.1 defines a protocol for establishing

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(b) Details and materials used in the test specimens shall be representative of those used in the structure

(c) The design procedure used to proportion the test specimens shall define the mechanism by which the frame resists gravity and earthquake effects, and shall establish acceptance values for sustaining that mechanism. Portions of the mechanism that deviate from Code requirements shall be contained in the test specimens and shall be tested to determine upper bounds for acceptance values.

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a design procedure, validated by analysis and laboratory tests, for such frames. The design procedure should identify the load path or mechanism by which the frame resists gravity and earthquake effects. The tests should be configured to investigate critical behaviors, and the measured quantities should establish upper-bound acceptance values for components of the load path, which may be in terms of limiting stresses, forces, strains, or other quantities. The design procedure used for the structure should not deviate from that used to design the test specimens, and acceptance values should not exceed values that were demonstrated by the tests to be acceptable. Materials and components used in the structure should be similar to those used in the tests. Deviations may be acceptable if the licensed design professional can demonstrate that those deviations do not adversely affect the behavior of the framing system.

ACI CODE-550.3 defines design requirements for one type of special precast concrete moment frame for use in accordance with 18.9.2.3.

18.10—Special structural walls

18.10.1 *Scope*

R18.10—Special structural walls

R18.10.1 *Scope*

This section contains requirements for the dimensions and details of special structural walls and all components including coupling beams and wall piers. Wall piers are defined in Chapter 2. Design provisions for vertical wall segments depend on the aspect ratio of the wall segment in the plane of the wall (h_w/ℓ_w), and the aspect ratio of the horizontal cross section (ℓ_w/b_w), and generally follow the descriptions in Table R18.10.1. The limiting aspect ratios for wall piers are based on engineering judgment. It is intended that flexural yielding of the vertical reinforcement in the pier should limit shear demand on the pier.

Bearing wall systems utilizing special structural walls with $h_{wcs}/\ell_w \geq 2.0$ that are designed and detailed according to these provisions are expected to meet the seismic performance objectives of Building Frame Systems: Special reinforced concrete shear walls as defined by ASCE/SEI 7.

Table R18.10.1—Governing design provisions for vertical wall segments[1]

Clear height of vertical wall segment/length of vertical wall segment (h_w/ℓ_w)	Length of vertical wall segment/wall thickness (ℓ_w/b_w)		
	$(\ell_w/b_w) \leq 2.5$	$2.5 < (\ell_w/b_w) \leq 6.0$	$(\ell_w/b_w) > 6.0$
$h_w/\ell_w < 2.0$	Wall	Wall	Wall
$h_w/\ell_w \geq 2.0$	Wall pier required to satisfy specified column design requirements; refer to 18.10.8.1	Wall pier required to satisfy specified column design requirements or alternative requirements; refer to 18.10.8.1	Wall

[1] h_w is the clear height, ℓ_w is the horizontal length, and b_w is the width of the web of the wall segment.

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18.10.1.1 This section shall apply to special structural walls, including ductile coupled walls, and all components of special structural walls including coupling beams and wall piers forming part of the seismic-force-resisting system.

18.10.1.2 Special structural walls constructed using precast concrete shall be in accordance with 18.11 in addition to 18.10.

18.10.2 *Reinforcement*

18.10.2.1 The distributed web reinforcement ratios, ρ_ℓ and ρ_t, for structural walls shall be at least 0.0025, except that if V_u does not exceed $\lambda\sqrt{f_c'}A_{cv}$, ρ_t shall be permitted to be reduced to the values in 11.6. Reinforcement spacing each way in structural walls shall not exceed 18 in. Reinforcement contributing to V_n shall be continuous and shall be distributed across the shear plane.

18.10.2.2 At least two curtains of reinforcement shall be used in a wall if $V_u > 2\lambda\sqrt{f_c'}A_{cv}$ or $h_w/\ell_w \geq 2.0$, in which h_w and ℓ_w refer to height and length of entire wall, respectively.

18.10.2.3 Reinforcement in structural walls shall be developed or spliced for f_y in tension in accordance with 25.4, 25.5, and (a) through (d):

(a) Except at the top of a wall, longitudinal reinforcement shall extend at least 12 ft above the point at which it is no longer required to resist flexure but need not extend more than ℓ_d above the next floor level.

(b) At locations where yielding of longitudinal reinforcement is likely to occur as a result of lateral displacements, longitudinal reinforcement shall develop 1.25 f_y in tension in accordance with 25.4 by substituting a bar stress of $1.25f_y$ for f_y.

(c) Lap splices of longitudinal reinforcement within boundary regions shall not be permitted over a height equal to h_{sx} above, and ℓ_d below, critical sections where yielding of longitudinal reinforcement is likely to occur

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R18.10.2 *Reinforcement*

Minimum reinforcement requirements in 18.10.2.1 follow from preceding Codes. The requirement for distributed shear reinforcement is related to the intent to control the width of inclined cracks. The requirement for two layers of reinforcement in walls resisting substantial design shears in 18.10.2.2 is based on the observation that, under ordinary construction conditions, the probability of maintaining a single layer of reinforcement near the middle of the wall section is quite low. Furthermore, presence of reinforcement close to the surface tends to inhibit fragmentation of the concrete in the event of severe cracking during an earthquake. The requirement for two layers of vertical reinforcement in more slender walls is to improve lateral stability of the compression zone under cyclic loads following yielding of vertical reinforcement in tension.

R18.10.2.3 Requirements are based on provisions in Chapter 25, with modifications to address issues specific to structural walls, as well as to the use of high-strength reinforcement. Because actual forces in longitudinal reinforcement of structural walls may exceed calculated forces, reinforcement should be developed or spliced to reach the yield strength of the bar in tension. Termination of longitudinal (vertical) reinforcement in structural walls should be specified so that bars extend above elevations where they are no longer required to resist design flexure and axial force; extending bars ℓ_d above the next floor level is a practical approach to achieving this requirement. A limit of 12 ft is included for cases with large story heights. Bar terminations should be accomplished gradually over a wall height and should not be located close to critical sections where yielding of longitudinal reinforcement is expected,

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as a result of lateral displacements. The value of h_{sx} need not exceed 20 ft. Boundary regions include those within lengths specified in 18.10.6.4(a) and within a length equal to the wall thickness measured beyond the intersecting region(s) of connected walls.

(d) Mechanical splices of reinforcement shall conform to 18.2.7 and welded splices of reinforcement shall conform to 18.2.8.

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which typically occurs at the base of a wall with a uniform, or nearly uniform, cross section over the building height. Strain hardening of reinforcement results in spread of plasticity away from critical sections as lateral deformations increase. Research (Aaleti et al. 2013; Hardisty et al. 2015) shows that lap splices should be avoided in walls where flexural yielding is anticipated, for example at the base of walls, because they may lead to large localized strains and bar fractures. Figure R18.10.2.3 illustrates boundary regions where lap splices are not permitted.

At locations where yielding of longitudinal reinforcement is expected, the reinforcement is developed for $1.25f_y$ to account for the likelihood that the actual yield strength exceeds the specified yield strength of the bar, as well as the influence of strain hardening and cyclic load reversals. Where transverse reinforcement is used, development lengths for straight and hooked bars may be reduced as permitted in 25.4.2 and 25.4.3, respectively, because closely spaced transverse reinforcement improves the performance of splices and hooks subjected to repeated inelastic demands (ACI PRC-408.2).

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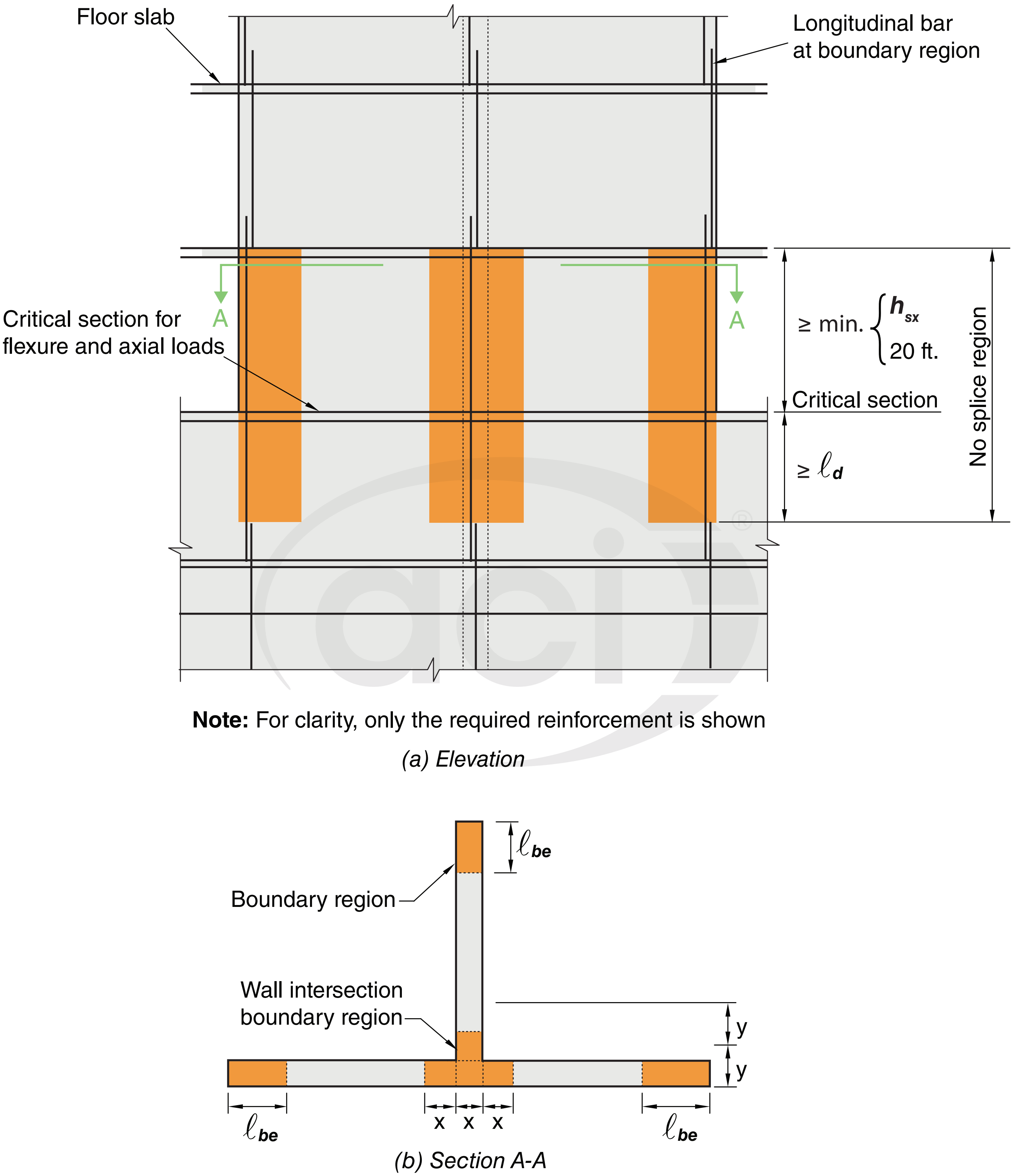

Fig. R18.10.2.3—Wall boundary regions within heights where lap splices are not permitted.

18.10.2.4 Walls or wall piers with $h_w/\ell_w \geq 2.0$ that are effectively continuous from the base of structure to top of wall and are designed to have a single critical section for

R18.10.2.4 This provision is based on the assumption that inelastic response of the wall is dominated by flexural action at a critical, yielding section. The wall should be propor-