Changes in ACI 318 Code Provisions for Earthquake-Resistant Structures, Part 1

Changes in sections governing structural systems, mechanical splices, and the design of moment frames

by S.K. Ghosh and Andrew W. Taylor

"Building Code Requirements for Structural Concrete and Commentary (ACI 318-19)" maintains the format established in the previous edition.[1,2] However, Chapter 18—Earthquake-Resistant Structures, has substantive and consequential changes. Out of the 14 sections in Chapter 18, only 18.1—Scope, 18.5—Intermediate precast structural walls, and 18.9—Special moment frames constructed using precast concrete, remain unchanged. Section 18.11—Special structural walls constructed using precast concrete, was updated to include a single change prompted by a requirement added elsewhere in the chapter. However, Section 18.10—Special structural walls, underwent quite extensive changes.

Using the section numbers in the Code as headers, this and a second article will outline the significant changes in Chapter 18 relative to the previous edition of the Code. Underlined and stricken texts indicate additions and deletions, respectively. Where warranted, a brief explanation is provided, and the significance of a change is discussed. Readers are reminded that Code sections are identified by numerals separated by decimal points, and Commentary sections are identified by the letter R plus the corresponding Code section identifier.

This article, Part 1, covers changes in:

- 18.2—General;
- 18.3—Ordinary moment frames;
- 18.4—Intermediate moment frames;
- 18.6—Beams of special moment frames;
- 18.7—Columns of special moment frames; and
- 18.8—Joints of special moment frames.

Part 2 will cover changes in:

- 18.10—Special structural walls;
- 18.11—Special structural walls constructed using precast concrete;
- 18.12—Diaphragms and trusses;
- 18.13—Foundations; and
- 18.14—Members not designated as part of the seismic-force-resisting system.

18.2—General

18.2.1 *Structural systems*

18.2.1.4 Structures assigned to Seismic Design Category (SDC) C are now required to satisfy 18.13—Foundations, which now contains provisions for shallow as well as deep foundations supporting buildings assigned to SDC C.

R18.2 Table R18.2—Sections of Chapter 18 to be satisfied in typical applications, is updated.

18.2.6 *Reinforcement in special moment frames and special structural walls*

R18.2.6.1 Very important and extensive commentary is added to point out that reinforcing bars meeting ASTM A706 Grades 80 and 100 are permitted to resist bending moments, shear forces, and axial forces in special structural walls and wall components such as coupling beams and wall piers. ASTM A706 Grade 80 reinforcement is also permitted in special moment frames. However, Grade 100 bars are not allowed to be used in special moment frames because there is insufficient data to demonstrate satisfactory seismic performance.

18.2.7 *Mechanical splices in special moment frames and special structural walls*

18.2.7.2 This section is revised to require that mechanical splices be located outside of the regions of plastic hinges unless they are Type 2 mechanical splices of Grade 60 reinforcement. ACI 318-14 placed no restriction on the bar grade for Type 2 mechanical splices because 20.2.2.4

allowed only Grade 60 reinforcement in special seismic systems.

R18.2.7 This section has been revised to note that Type 1 mechanical splices of any grade of reinforcement and Type 2 mechanical splices of Grade 80 and Grade 100 reinforcement may not be capable of resisting the stress levels expected in regions of potential plastic hinging. The locations of these mechanical splices are therefore restricted. As in the previous edition, the restriction applies to all reinforcement resisting earthquake effects, including transverse reinforcement.

18.3—Ordinary moment frames

18.3.4 Beam-column joints of ordinary moment frames that are part of the seismic-force-resisting system of an SDC B building are now required to satisfy the requirements in Chapter 15—Beam-Column and Slab-Column Joints, with factored joint shear V_u calculated on a plane at midheight of the joint using tensile and compressive beam forces and column shear consistent with beam nominal moment strengths M_n (Fig. 1).

18.4—Intermediate moment frames

18.4.2 *Beams*

18.4.2.3 The text is slightly modified to agree with a change in Commentary Fig. R18.4.2, part of which is reproduced here as Fig. 2. The illustration shows that factored beam shear V_u is given by $V_u = (M_{nl} + M_{nr})/l_n + w_u l_n/2$, where $w_u = (1.2 + 0.2S_{DS})D + 1.0L + 0.2S$. Here, the dead load factor of 1.2 is increased by $0.2S_{DS}$ in recognition of vertical earthquake accelerations. This increase was missing in the corresponding ACI 318-14 Commentary figure.

18.4.3 *Columns*

18.4.3.3 Within the potential plastic hinge region at the end of an intermediate moment frame column, the required hoop spacing in ACI 318-14 was the smallest of $8d_b$ of the smallest longitudinal bar enclosed, $24d_b$ of the hoop bar, one-half of the smallest cross-sectional dimension of the column, and 12 in.

In ACI 318-19, the hoop spacing within this region is limited to one-half of the smallest cross-sectional dimension of the column and:

- The smaller of $8d_b$ of the smallest longitudinal bar enclosed and 8 in. for columns with Grade 60 longitudinal bars; or
- The smaller of $6d_b$ of the smallest longitudinal bar enclosed and 6 in. for columns with Grade 80 longitudinal bars.

18.4.4 *Joints*

Requirements for beam-column joints of intermediate moment frames are revised, and new requirements are added in 18.4.4.2 through 18.4.4.5. These joints are now required to satisfy all the following requirements:

15.3.1.2 Joint transverse reinforcement must consist of ties (25.7.2), spirals (25.7.3), or hoops (25.7.4).

15.3.1.3 At least two layers of horizontal transverse reinforcement must be provided within the depth of the shallowest beam framing into the joint.

18.4.4.2 If a beam framing into the joint and generating

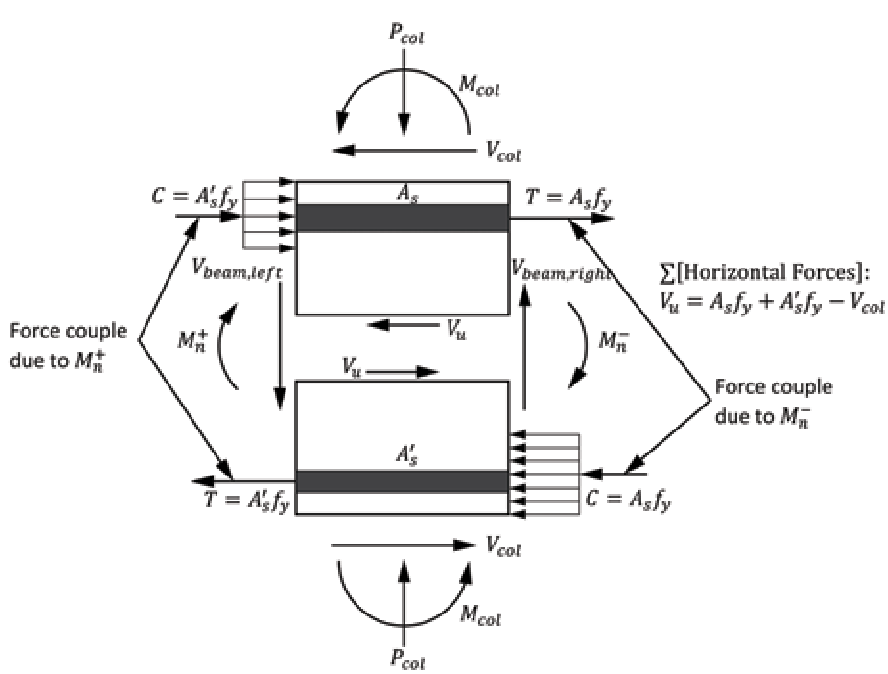


Fig. 1: Free body diagram for calculation of factored shear force V_u at midheight of a beam-column joint in ordinary and intermediate moment frames

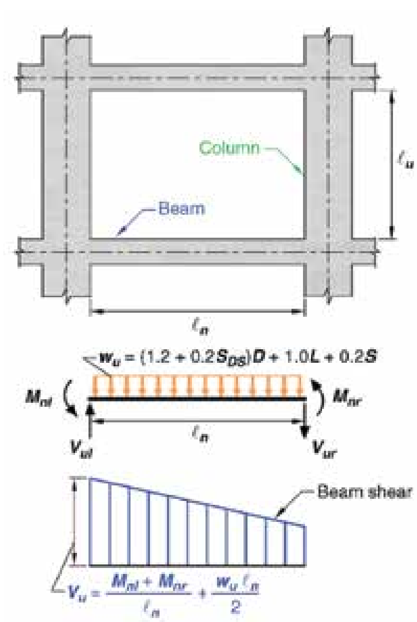


Fig. 2: Moment and shear diagrams for calculation of factored shear force on a beam in an intermediate moment frame (adapted from ACI 318-19 Fig. R18.4.2[1])

joint shear has depth h, exceeding twice the column depth, analysis and design of the joint is required to be based on the strut-and-tie method of Chapter 23.

18.4.4.3 Longitudinal deformed reinforcing bars terminated in a joint are required to extend to the far face of the joint core and to be developed in tension per 18.8.5 and in compression per 25.4.9.

18.4.4.4 Spacing of joint transverse reinforcement within the height of the deepest beam framing into the joint is required not to exceed the maximum hoop spacing within the region of potential plastic hinging at the end of an intermediate moment frame column (18.4.3.3).

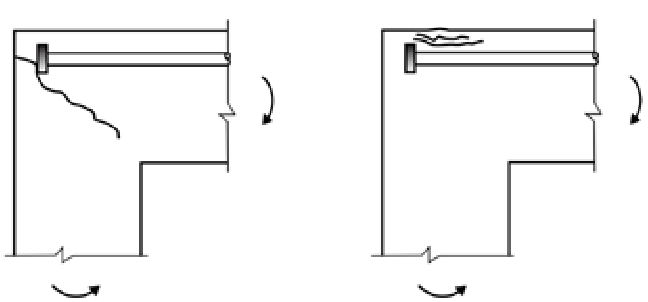
18.4.4.5 Knee joints with headed beam reinforcement require special consideration. Joint failure can occur by a diagonal crack that extends beyond the headed bars, or by top face blowout above the beam bars (Fig. 3). The column is required to extend above the joint to confine the top face of the joint. The extension must be by at least the depth of the joint (column dimension parallel to the beam reinforcement generating joint shear). As an alternative to extending the column above the joint, the beam reinforcement is required to be enclosed by additional vertical joint reinforcement providing equivalent confinement to the top face of the joint. Typically, this reinforcement consists of a series of U-shaped bars with the legs pointed downward, enclosing the top layer of flexural reinforcement.

18.4.4.6 Slab-column joints are now required to satisfy transverse reinforcement requirements of 15.3.2, so any column with one or more free edges must have at least one layer of joint transverse reinforcement between the top and bottom slab reinforcement.

18.4.4.7 Beam-column joints of intermediate moment frames must satisfy: $\phi V_n \geq V_u$ where $\phi = 0.75$ in accordance with 21.2.1; V_n is the nominal shear strength of the joint, as given in Table 18.8.4.3 (reproduced herein as Table 1); and V_u is the factored shear force at midheight of the joint, calculated as shown in Fig. 1.

18.4.5 *Two-way slabs without beams*

18.4.5.8 ACI 318-14 limited shear stress caused by factored gravity loads without moment transfer to $0.4\phi v_c$ at the critical sections for connections between columns and two-way slabs without beams. A higher limit of $0.5\phi v_c$ is now allowed for unbonded post-tensioned slab-column connections with effective prestress in each direction meeting the requirements of 8.6.2.1. Both stress limits are waived if the connection meets the requirements of 18.14.5.



(a) (b)

Fig. 3: Potential failure modes for a knee joint with headed top reinforcement: (a) diagonal cracking; and (b) top face blowout

18.6—Beams of special moment frames

18.6.3 *Longitudinal reinforcement*

18.6.3.1 The maximum reinforcement ratio of 0.025 for longitudinal reinforcement in special moment frame beams is now restricted to Grade 60 reinforcement. A maximum ratio of 0.020 is imposed on beams with Grade 80 reinforcement.

18.6.4 *Transverse reinforcement*

18.6.4.4 ACI 318-14 limited the spacing of hoops within the region of potential plastic hinging at the ends of special moment frame beams to the least of $d/4$; $6d_b$ of the smallest primary flexural reinforcing bars, excluding longitudinal skin reinforcement required by 9.7.2.3; and 6 in.

In ACI 318-19, the spacing of hoops within the region of potential plastic hinging at the ends of special moment frame beams is limited to the least of $d/4$, 6 in., and:

- $6d_b$ of the smallest primary flexural reinforcing bars for beams with Grade 60 flexural reinforcement; or
- $5d_b$ of the smallest primary flexural reinforcing bars for beams with Grade 80 flexural reinforcement.

Table 1:
Values for nominal joint shear strength V_n in ACI 318-19[1] (Table 18.8.4.3)

Column	Beam in direction of V_u	Confinement by transverse beams according to 15.2.8	V_n, lb*
Continuous or meets 15.2.6	Continuous or meets 15.2.7	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 15.2.7	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	$8\lambda\sqrt{f'_c}A_j$

*λ shall be 0.75 for lightweight concrete and 1.0 for normalweight concrete. A_j shall be calculated in accordance with 15.4.2.4.

As in ACI 318-14, d_b is the nominal diameter of the smallest primary flexural reinforcing bars, excluding longitudinal skin reinforcement.

18.6.4.7 As with 18.6.4.4, this section has been updated in ACI 318-19 to account for the addition of Grade 80 reinforcement. The section now limits hoop spacing s outside of the region defined in 18.6.4.1 to the least of 6 in. and:

- $6d_b$ of the smallest enclosed longitudinal beam bars for beams with Grade 60 flexural reinforcement; or
- $5d_b$ of the smallest enclosed longitudinal beam bars for beams with Grade 80 flexural reinforcement.

18.7—Columns of special moment frames

18.7.3 *Minimum flexural strength of columns*

18.7.3.1 Columns of special moment frames are required to satisfy the strong column–weak beam requirement of 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 $A_g f_c'/10$." The underlined exception is new in ACI 318-19. Added commentary in R18.7.3 explains that special moment frame columns that are discontinuous above the connection and have low axial stress are inherently ductile, so column yielding is unlikely to create a column failure mechanism that can lead to collapse.

18.7.4 *Longitudinal reinforcement*

18.7.4.3 This is a new section that effectively requires the longitudinal bars to have a development length of no more than 40% of the column clear height. R18.7.4.3 explains that splitting failure along longitudinal bars within the clear column height can be controlled by reducing the development length of longitudinal bars, and it lists some of the relevant factors. The commentary further emphasizes the benefit of satisfying the strong column–weak beam requirement.

18.7.5 *Transverse reinforcement*

18.7.5.3 ACI 318-14 limited the spacing of transverse reinforcement within the region of potential plastic hinging (18.7.5.1) at the ends of special moment frame columns to the least of: one-fourth of the minimum column dimension; $6d_b$ of the smallest longitudinal bar; and a value from 4 to 6 in., as calculated by Eq. (18.7.5.3). In ACI 318-19, the limit of $6d_b$ of the smallest longitudinal bars applies to columns with Grade 60 longitudinal reinforcement. A tighter limit of $5d_b$ of the smallest longitudinal bar applies to columns with Grade 80 longitudinal reinforcement.

18.7.5.5 This section has been revised as shown below. "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 ~~through~~ and 25.7.4 with spacing s not exceeding the ~~lesser~~ least of 6 in., $6d_b$ ~~six times the diameter~~ of the smallest Grade 60 longitudinal column bar, and $5d_b$ of the smallest Grade 80 longitudinal column bar, ~~and 6 in.,~~ unless a greater amount of transverse reinforcement is required by 18.7.4.~~3~~4 or 18.7.6."

18.8—Joints of special moment frames

18.8.2 *General*

18.8.2.3 This provision is directed at minimizing bond slip of longitudinal beam reinforcement extending through a cast-in-place beam-column joint. In both ACI 318-14 and ACI 318-19, this is achieved by defining the minimum depth h of the joint parallel to the beam longitudinal reinforcement extending through the joint. In ACI 318-14, h was defined in Fig. R18.8.4. In ACI 318-19, h is defined in Fig. R15.4.2 and is associated with an expanded 15.4.2 that defines the shear strength of beam-column joints: In ACI 318-19, h is at least the greatest of:

(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; and

(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.

Item (a) effectively replicates the requirements in 18.8.2.3 in ACI 318-14. Item (b) is new. Item (c) defines joint depth h in terms of beam depth h. It effectively replicates the requirements in 18.8.2.4 in ACI 318-14, which has been deleted in ACI 318-19.

18.8.2.3.1 This is a new provision, and it requires that joints with Grade 80 longitudinal reinforcement comprise normalweight concrete. The commentary notes that there is insufficient data regarding Grade 80 bars in joints comprising lightweight concrete.

18.8.3 *Transverse reinforcement*

The first three provisions in this section remain unchanged from ACI 318-14. However, 18.8.3.4, which would have been the counterpart of 18.4.4.5 in ACI 318-19, has been deleted because the same requirements are stated in 25.4.4.6.

18.8.4 *Shear strength*

This section is similar to 18.4.4.7, in that it governs the evaluation of joint shear strength per $V_u \leq \phi V_n$. However, the parameters are unique to special moment frames. In ACI 318-19, 18.8.4.1, 18.8.4.2, and 18.8.4.3 define factored shear strength V_u, strength reduction factor ϕ, and nominal shear strength V_n, respectively. V_u is calculated using the forces shown in Fig. 4; $\phi = 0.85$ in accordance with 21.2.4.4, and V_n is defined in Table 18.8.4.3 (reproduced herein as Table 1). In ACI 318-14, these sections define V_n per Table 18.8.4.1 (reproduced herein as Table 2 to highlight the changes), factors that create a confined face of a transverse moment frame joint, and the

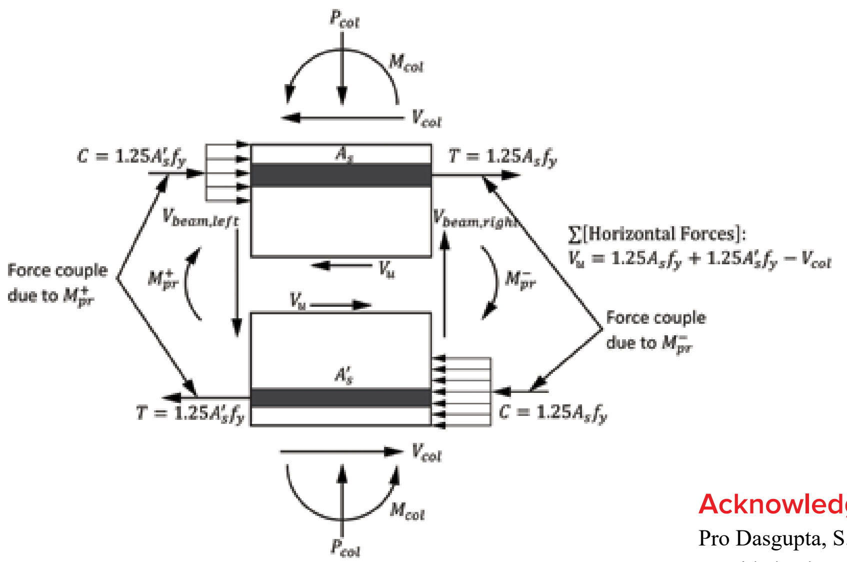


Fig. 4: Free body diagram for calculation of V_u at midheight of a beam-column joint in a special moment frame

Table 2:

Values for nominal joint shear strength V_n in ACI 318-14[2] (Table 18.8.4.1)

Joint configuration	V_n
For joints confined by beams on all four faces[*]	$20\lambda\sqrt{f'_c}A_j$[†]
For joints confined by beams on three faces or on two opposite faces[*]	$15\lambda\sqrt{f'_c}A_j$[†]
For other cases	$12\lambda\sqrt{f'_c}A_j$[†]

[*]Refer to 18.8.4.2.

[†]λ shall be 0.75 for lightweight concrete and 1.0 for normalweight concrete. A_j is given in 18.8.4.3.

effective cross-sectional area in a joint, respectively. The latter two items are now addressed in 15.2.8 and 15.4.2.4, respectively.

18.8.5 *Development length of bars in tension*

18.8.5.2 This section deals with the development in tension of headed bars terminating in exterior joints of special moment frames; it has been modified as shown below:

"For headed deformed bars satisfying 20.2.1.6, development in tension shall be in accordance with 25.4.4, by substituting a bar stress of $1.25f_y$ for f_y ~~except clear spacing between bars shall be permitted to be at least $3d_b$ or greater~~."

R18.8.5.2 explains that the 1.25 factor 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. As given in 25.4.4.1(f), the minimum center-to-center bar spacing is $3d_b$ (rather than the minimum clear spacing of $3d_b$ required in ACI 318-14).

Concluding Remarks

ACI 318-19 Chapter 18—Earthquake-Resistant Structures, includes many substantive changes. This article summarizes the changes in Sections 18.2—General, plus changes in Sections 18.3 through 18.8, which govern the design of ordinary and intermediate moment frames as well as the design of beams, columns, and joints of special moment frames. Many of the modifications were made to account for ASTM A706 Grade 80 bars, which are now permitted as flexural reinforcement in special moment frames.

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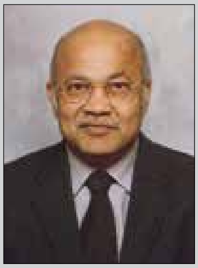

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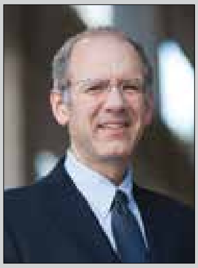

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