CHAPTER 20—STEEL REINFORCEMENT PROPERTIES, DURABILITY, AND EMBEDMENTS

CODE

20.1—Scope

20.1.1 This chapter shall apply to steel reinforcement and shall govern for (a) through (c):

(a) Material properties
(b) Properties to be used for design
(c) Durability requirements, including minimum specified cover requirements

20.1.2 Provisions of 20.6 shall apply to embedments.

20.2—Nonprestressed bars and wires

20.2.1 *Material properties*

20.2.1.1 Nonprestressed bars and wires shall be deformed, except plain bars or wires are permitted for use in spirals.

20.2.1.2 Yield strength of nonprestressed bars and wires shall be determined by either (a) or (b):

(a) The offset method, using an offset of 0.2% in accordance with ASTM A370
(b) The yield point by the halt-of-force method, provided the nonprestressed bar or wire has a sharp-kneed or well-defined yield point

20.2.1.3 Deformed bars shall conform to (a), (b), (c), (d), or (e), except bar sizes larger than No. 18 shall not be permitted:

(a) ASTM A615 – carbon steel
(b) ASTM A706 including Supplementary Requirements S1 – low-alloy steel
(c) ASTM A996 – axle steel and rail steel; bars from rail steel shall be Type R
(d) ASTM A955 – stainless steel
(e) ASTM A1035 – low-carbon chromium steel

COMMENTARY

R20.1—Scope

R20.1.1 Materials permitted for use as reinforcement are specified. Other metal elements, such as inserts, anchor bolts, or plain bars for dowels at isolation or contraction joints, are not normally considered reinforcement under the provisions of this Code. Fiber-reinforced polymer (FRP) reinforcement is not addressed in the Code. ACI Committee 440 has developed guidelines for the use of FRP reinforcement (ACI PRC-440.1 and ACI PRC-440.2) and a code for design of members reinforced with glass fiber-reinforced polymer (GFRP) bars (ACI CODE-440.11).

R20.2—Nonprestressed bars and wires

R20.2.1 *Material properties*

R20.2.1.2 The majority of nonprestressed steel bar reinforcement exhibits actual stress-strain behavior that is sharply yielding or sharp-kneed (elasto-plastic stress-strain behavior). However, bars of higher strength grade, steel wire, coiled steel bar, and stainless steel bars and wire generally do not exhibit sharply-yielding stress-strain behavior, but instead are gradually-yielding. The method used to measure yield strength of reinforcement needs to provide for both types of reinforcement stress-strain relationships.

Paulson et al. (2013) considered reinforcement manufactured during 2008 through 2012, and found that the offset method (0.2% offset), provides for a reasonable estimate of the strength of reinforced concrete structures.

The yield strength is determined by the manufacturer during tensile tests performed at the mill on samples of reinforcement. Test methods for determining yield strength of steel, including the offset method and yield point by halt-of-force method, are referenced either in the ASTM standards for nonprestressed bars and wire or in ASTM A370 Test Methods and Definitions.

R20.2.1.3 ASTM A615-24, Table 2 includes the minimum ratio of actual tensile strength to actual yield strength.

ASTM A706, Supplementary Requirements S1 are necessary to be specified in the project specifications and general notes. ASTM requires the bar purchaser to specify the Supplementary Requirements S1. Refer to R26.6.1.1.

Low-alloy steel deformed bars conforming to ASTM A706 are intended for applications where controlled tensile properties are required. ASTM A706 also includes restrictions on chemical composition to enhance weldability for Grades

CODE

COMMENTARY

60, 80 and 100 . Use of ASTM A706 reinforcement requires specifying the Supplementary Requirements S1 of this standard, "Additional Requirements for Bars Used in Earthquake Resistant Structures." This supplement includes the deformation radius requirements, and uniform elongation requirements in Table S1.1 of the supplement.

Rail-steel deformed bars used with the Code are required to conform to ASTM A996, including the provisions for Type R bars. Type R bars are required to meet more restrictive provisions for bend tests than other types of rail steel.

Stainless steel deformed bars are used in applications where high corrosion resistance or controlled magnetic permeability are required.

Low-carbon chromium steel is a high-strength material that is permitted for use as transverse reinforcement for confinement in special earthquake-resistant structural systems and spirals in columns. Refer to Tables 20.2.2.4(a) and (b). ASTM A1035 provides requirements for bars of two minimum yield strength levels—100,000 psi and 120,000 psi—designated as Grade 100 and Grade 120, respectively, but the maximum f_{yt} permitted for design calculations in the Code is limited in accordance with 20.2.2.3.

In 2015, ASTM A615 included bar sizes larger than No. 18, and in 2016, ASTM A1035 also included bar sizes larger than No. 18. Bar sizes larger than No. 18 are not permitted by the Code due to the lack of information on their performance including bar bends and development lengths.

20.2.1.4 Plain bars for spiral reinforcement shall conform to ASTM A615, A706, A955, or A1035.

R20.2.1.4 Plain bars are permitted only for spiral reinforcement used as transverse reinforcement for columns, transverse reinforcement for shear and torsion, or confining reinforcement for splices.

20.2.1.5 Welded deformed bar mats shall conform to ASTM A184. Deformed bars used in welded deformed bar mats shall conform to ASTM A615 or A706.

20.2.1.6 Headed deformed bars shall conform to ASTM A970, including Annex A1 requirements for Class HA head dimensions.

R20.2.1.6 The limitation to Class HA head dimensions from Annex A1 of ASTM A970 is due to a lack of test data for headed deformed bars that do not meet Class HA dimensional requirements. Heads not conforming to Class HA limits on bar deformation obstructions and bearing face features have been shown to provide lower anchorage strength than the heads used in the tests that serve as the basis for 25.4.4 (Shao et al. 2016).

20.2.1.7 Deformed wire, plain wire, welded deformed wire reinforcement, and welded plain wire reinforcement shall conform to (a) or (b), except that yield strength shall be determined in accordance with 20.2.1.2:

(a) ASTM A1064 – carbon steel
(b) ASTM A1022 – stainless steel

R20.2.1.7 Plain wire is permitted only for spiral reinforcement and in welded plain wire reinforcement, the latter of which is considered deformed. Stainless steel wire and stainless steel welded wire reinforcement are used in applications where high corrosion resistance or controlled magnetic permeability is required. The physical and mechanical property requirements for deformed stainless steel wire and deformed and plain welded wire reinforcement under

CODE

20.2.1.7.1 Deformed wire sizes D4 through D31 shall be permitted.

20.2.1.7.2 Deformed wire sizes larger than D31 shall be permitted in welded wire reinforcement if treated as plain wire for calculation of development and splice lengths in accordance with 25.4.7 and 25.5.4, respectively.

20.2.1.7.3 Except as permitted for welded wire reinforcement used as stirrups in accordance with 25.7.1, spacing of welded intersections in welded wire reinforcement in the direction of calculated stress shall not exceed (a) or (b):

(a) 16 in. for welded deformed wire reinforcement

(b) 12 in. for welded plain wire reinforcement

20.2.2 *Design properties*

20.2.2.1 For nonprestressed bars and wires, the stress below f_y shall be E_s times steel strain. For strains greater than that corresponding to f_y, stress shall be considered independent of strain and equal to f_y.

20.2.2.2 Modulus of elasticity, E_s, for nonprestressed bars and wires shall be permitted to be taken as 29,000,000 psi.

20.2.2.3 Yield strength for nonprestressed bars and wires shall be based on the specified grade of reinforcement and shall not exceed the values given in 20.2.2.4 for the associated applications.

20.2.2.4 Types of nonprestressed bars and wires to be specified for particular structural applications shall be in accordance with Table 20.2.2.4(a) for deformed reinforcement and Table 20.2.2.4(b) for plain reinforcement.

COMMENTARY

ASTM A1022 are the same as those for deformed wire, deformed welded wire reinforcement, and plain welded wire reinforcement under ASTM A1064.

R20.2.1.7.1 An upper limit is placed on the size of deformed wire because test results Rutledge and Devries (2002) have shown that D45 wire will achieve only approximately 60% of the bond strength in tension given by Eq. (25.4.2.4a).

R20.2.2 *Design properties*

R20.2.2.1 For deformed reinforcement, it is reasonably accurate to assume that the stress in reinforcement is proportional to strain below the specified yield strength f_y. The increase in strength due to strain hardening of the reinforcement is neglected for nominal strength calculations. In nominal strength calculations, the force developed in tension or compression reinforcement is calculated as:

if $\varepsilon_s < \varepsilon_y$ (yield strain)

$$A_s f_s = A_s E_s \varepsilon_s$$

if $\varepsilon_s \geq \varepsilon_y$

$$A_s f_s = A_s f_y$$

where ε_s is the value from the strain diagram at the location of the reinforcement.

R20.2.2.4 Tables 20.2.2.4(a) and 20.2.2.4(b) limit the maximum values of yield strength to be used in design calculations for nonprestressed deformed reinforcement and nonprestressed plain spiral reinforcement, respectively.

CODE

COMMENTARY

Grade 100 reinforcement is now permitted to resist tension and compression in some applications. For reinforcement resisting compression, strain compatibility calculations indicate that stresses are not likely to exceed 80,000 psi before strain in unconfined concrete reaches the strain limit of 0.003 unless special confinement reinforcement is provided to increase the limiting concrete compressive strain. For beams, the deflection provisions of 24.2 and the limitations on distribution of flexural reinforcement of 24.3 become increasingly critical as f_y increases.

In Table 20.2.2.4(a), for deformed reinforcement in special moment frames and special structural walls, the use of longitudinal reinforcement with strength substantially higher than that assumed in design will lead to higher shear and bond stresses at the time of development of yield moments. These conditions may lead to brittle failures in shear or bond and should be avoided even if such failures may occur at higher loads than those anticipated in design. Therefore, ASTM A706 specifies both a lower and an upper limit on the actual yield strength of the steel and requires a minimum tensile-to-yield strength ratio. ASTM A615 reinforcement is not permitted as longitudinal reinforcement in special seismic systems (refer to R20.2.2.5). For reinforcement resisting compression, strain compatibility calculations indicate that stresses are not likely to exceed 80,000 psi before strain in unconfined concrete reaches the strain limit of 0.003 unless special confinement reinforcement is provided to increase the limiting concrete compressive strain.

The maximum value of yield strength for calculation purposes is limited to 100,000 psi for both nonprestressed deformed reinforcement and plain spiral reinforcement in Tables 20.2.2.4(a) and (b), respectively, when used for lateral support of longitudinal bars or for concrete confinement. The research that supports this limit for confinement is given in Saatcioglu and Razvi (2002), Pessiki et al. (2001), and Richart et al. (1929). For reinforcement in special moment frames and special structural walls, the research that indicated that higher yield strengths can be used effectively for confinement reinforcement is given in Budek et al. (2002), Muguruma and Watanabe (1990), and Sugano et al. (1990).

The limit of 60,000 psi on the values of f_y and f_{yt} used in design for most shear and torsional reinforcement is intended to control the width of inclined cracks under service-level gravity loads. The higher yield strength of 80,000 psi permitted in shear design for welded deformed wire reinforcement is also intended to control width of inclined cracks and is based on Guimaraes et al. (1992), Griezic et al. (1994), and Furlong et al. (1991). In particular, full-scale beam tests described in Griezic et al. (1994) indicated that the widths of inclined shear cracks at service load levels were less for beams reinforced with smaller diameter welded deformed wire reinforcement cages designed on the basis of a yield strength of 75,000 psi than beams reinforced with deformed Grade 60 stirrups.

CODE

COMMENTARY

For strength-level earthquake load effects, tests of members using higher strength reinforcement have shown acceptable behavior (Wallace 1998; Aoyama 2001; Budek et al. 2002; Sokoli and Ghannoum 2016; Cheng et al. 2016; Huq et al. 2018; Weber-Kamin et al. 2020), leading to the allowance of ASTM A706 Grade 80 reinforcement for special seismic systems and ASTM A706 Grade 100 for special structural walls in the 2019 Code, as indicated in Table 20.2.2.4(a).

Footnote [6] of Table 20.2.2.4(a) is provided because ASTM A1064 and A1022 only require the welds to develop 35,000 psi in the interconnected wires. Hoops, stirrups, and other elements used in special seismic systems should have anchorages that are capable of developing $1.25f_y$ or $1.25f_{yt}$, as applicable, or tensile strength of the bar or wire, whichever is less, so that moderate ductility capacity can be achieved. A welded product that is capable of developing these stress limits could be approved for use through Code Section 1.10.

Footnote [3] of Table 20.2.2.4(a) limiting slab and beam bars passing through or extending from special structural walls to reinforcement meeting 20.2.2.5 provides for greater ductility of these members that are not designated as part of the seismic-force-resisting system but are likely to undergo large nonlinear rotational demands.

The 80,000 psi limit on f_y for ties of members or regions of members designed using the strut-and-tie method is imposed because of scarcity of test data justifying a higher limit. The yield strength f_y of "other" ties is limited to 60,000 psi for consistency with the usage "shear."

CODE

COMMENTARY

Table 20.2.2.4(a)—Nonprestressed deformed reinforcement

Usage	Application		Maximum value of f_y or f_{yt} permitted for design calculations, psi	Applicable ASTM specification			
				Deformed bars	Deformed wires	Welded wire reinforcement	Welded deformed bar mats
Flexure; axial force; and shrinkage and temperature	Special seismic systems	Special moment frames	80,000	A706[2]	Not permitted	Not permitted	Not permitted
		Special structural walls[1]	100,000				
	Other		100,000[3] [4]	A615, A706, A955, A996, A1035	A1064, A1022	A1064, A1022	A184[5]
Lateral support of longitudinal bars; or concrete confinement	Special seismic systems		100,000	A615, A706, A955, A996, A1035	A1064, A1022	A1064[6], A1022[6]	Not permitted
	Spirals		100,000	A615, A706, A955, A996, A1035	A1064, A1022	Not permitted	Not permitted
	Other		80,000	A615, A706, A955, A996	A1064, A1022	A1064, A1022	Not permitted
Shear [7]	Special seismic systems[8]	Special moment frames[9]	80,000	A615, A706, A955, A996	A1064, A1022	A1064[6], A1022[6]	Not permitted
		Special structural walls[10]	100,000				
	Spirals		60,000	A615, A706, A955, A996	A1064, A1022	Not permitted	Not permitted
	Shear friction		60,000	A615, A706, A955, A996	A1064, A1022	A1064, A1022	Not permitted
	Stirrups, ties, hoops		60,000	A615, A706, A955, A996, A1035	A1064, A1022	A1064 and A1022 welded plain wire	Not permitted
			80,000	Not permitted	Not permitted	A1064 and A1022 welded deformed wire	Not permitted
Torsion	Longitudinal and transverse		60,000	A615, A706, A955, A996	A1064, A1022	A1064, A1022	Not permitted
Anchor reinforcement	Seismic Design Category (SDC) C, D, E, or F		80,000	A706[11]	Not permitted	Not permitted	Not permitted
	Other		80,000	A615, A706, A955, A996	A1064, A1022	A1064, A1022	A184[5]
Regions designed using strut-and-tie method	Longitudinal ties		80,000	A615, A706, A955, A996	A1064, A1022	A1064, A1022	Not permitted
	Other		60,000				

[1]All components of special structural walls, including coupling beams and wall piers.
[2] Reinforcement shall comply with 20.2.2.5.
[3]In slabs and beams not part of a special seismic system, bars that pass through or extend from special structural walls shall comply with 20.2.2.5.
[4]Longitudinal reinforcement with f_y > 80,000 psi is not permitted for intermediate moment frames and ordinary moment frames resisting earthquake demands E.
[5]Welded deformed bar mats shall be permitted to be assembled using only ASTM A615 or A706 deformed bars of Grade 60 or Grade 80.
[6]ASTM A1064 and A1022 are not permitted in special seismic systems if the weld is required to resist stresses in response to confinement, lateral support of longitudinal bars, shear, or other actions.
[7]Steel fiber reinforcement for shear shall conform to ASTM A820 in accordance with 26.4.1.6.1.
[8]This application also includes shear reinforcement with a maximum value of 80,000 psi f_y or f_{yt} permitted for design calculations for diaphragms and foundations for load combinations including earthquake forces if part of a building with a special seismic system.
[9]Shear reinforcement in this application includes stirrups, ties, hoops, and spirals in special moment frames.
[10]Shear reinforcement in this application includes all transverse reinforcement in special structural walls, coupling beams, and wall piers. Diagonal bars in coupling beams shall comply with 20.2.2.5.
[11]Anchor reinforcement shall comply with 20.2.2.6.

CODE

COMMENTARY

Table 20.2.2.4(b)—Nonprestressed plain spiral reinforcement

Usage	Application	Maximum value of f_y or f_{yt} permitted for design calculations, psi	Applicable ASTM specification	
			Plain bars	Plain wires
Lateral support of longitudinal bars; or concrete confinement	Spirals in special seismic systems	100,000	A615, A706, A955, A1035	A1064, A1022
	Spirals	100,000	A615, A706, A955, A1035	A1064, A1022
Shear	Spirals	60,000	A615, A706, A955, A1035	A1064, A1022
Torsion in nonprestressed beams	Spirals	60,000	A615, A706, A955, A1035	A1064, A1022

20.2.2.5 Deformed nonprestressed longitudinal reinforcement resisting earthquake-induced moment, axial force, or both, in special seismic systems shall comply with ASTM A706, Grade 60, 80, or 100 for special structural walls and ASTM A706 Grade 60 or 80 for special moment frames.

R20.2.2.5 Additional requirements for ASTM A706 reinforcement are provided in 20.2.1.3(b). Refer to R18.2.6 for commentary regarding the requirements in 20.2.1.3(b) for a tensile strength greater than the yield strength of the reinforcement.

ASTM A706 reinforcement is required because of its inelastic fatigue performance and its controlled mechanical properties and chemical composition. ASTM A615 reinforcement is not permitted as longitudinal reinforcement to resist moments and axial forces in special seismic systems because of concern associated with low-cycle fatigue behavior (Slavin and Ghannoum 2015) and because the mechanical properties and chemical composition of ASTM A615 reinforcement are less restricted.

20.2.2.6 Anchor reinforcement in Seismic Design Category (SDC) C, D, E, or F shall comply with ASTM A706 Grade 60 or 80.

20.3—Prestressing strands, wires, and bars

20.3.1 *Material properties*

20.3.1.1 Except as required in 20.3.1.3 for special moment frames and special structural walls, prestressing reinforcement shall conform to (a), (b), (c), or (d):

(a) ASTM A416 – strand

(b) ASTM A421 – wire

(c) ASTM A421 – low-relaxation wire including Supplementary Requirement S1, “Low-Relaxation Wire and Relaxation Testing”

(d) ASTM A722 – high-strength bar

20.3.1.2 Prestressing strands, wires, and bars not listed in ASTM A416, A421, or A722 are permitted provided they conform to minimum requirements of these specifications and are shown by test or analysis not to impair the performance of the member.

20.3.1.3 Prestressing reinforcement resisting earthquake-induced moment, axial force, or both, in special moment frames, special structural walls, and all components of special structural walls including coupling beams and wall piers, cast using precast concrete shall comply with ASTM A416 or ASTM A722.

R20.3—Prestressing strands, wires, and bars

R20.3.1 *Material properties*

R20.3.1.1 Because low-relaxation prestressing reinforcement is addressed in a supplementary requirement to ASTM A421, which applies only if low-relaxation material is specified, the appropriate ASTM reference is listed as a separate entity.

CODE

20.3.2 *Design properties*

20.3.2.1 Modulus of elasticity, E_p, for prestressing reinforcement shall be determined from tests or as reported by the manufacturer.

20.3.2.2 Tensile strength, f_{pu}, shall be based on the specified grade or type of prestressing reinforcement and shall not exceed the values given in Table 20.3.2.2.

Table 20.3.2.2—Prestressing strands, wires, and bars

Type	Maximum value of f_{pu} permitted for design calculations, psi	Applicable ASTM Specification
Strand (stress-relieved and low-relaxation)	270,000	A416
Wire (stress-relieved and low-relaxation)	250,000	A421
		A421, including Supplementary Requirement S1 “Low-Relaxation Wire and Relaxation Testing”
High-strength bar	150,000	A722

20.3.2.3 *Stress in bonded prestressed reinforcement at nominal flexural strength*, f_{ps}

20.3.2.3.1 As an alternative to a more accurate calculation of f_{ps} based on strain compatibility, values of f_{ps} calculated in accordance with Eq. (20.3.2.3.1) shall be permitted for members with bonded prestressed reinforcement if all prestressed reinforcement is in the tension zone and $f_{se} \geq 0.5f_{pu}$.

$$f_{ps} = f_{pu}\left\{1 - \frac{\gamma_p}{\beta_1}\left[\rho_p\frac{f_{pu}}{f_c'} + \frac{d}{d_p}\frac{f_y}{f_c'}(\rho - \rho')\right]\right\} \quad (20.3.2.3.1)$$

where γ_p is in accordance with Table 20.3.2.3.1.

If compression reinforcement is considered for the calculation of f_{ps} by Eq. (20.3.2.3.1), (a) and (b) shall be satisfied.

(a) If d' exceeds $0.15d_p$, the compression reinforcement shall be neglected in Eq. (20.3.2.3.1).

COMMENTARY

R20.3.2 *Design properties*

R20.3.2.1 Default values of E_p between 28,500,000 and 29,000,000 psi are commonly used for design purposes. More accurate values based on tests or the manufacturer’s reports may be needed for elongation checks during stressing.

R20.3.2.2 ASTM A416 specifies two grades of strand tensile strength: 250,000 and 270,000 psi.

ASTM A421 specifies tensile strengths of 235,000, 240,000, and 250,000 psi, depending on the diameter and type of wire. For the most common diameter, 0.25 in., ASTM A421 specifies a tensile strength of 240,000 psi.

R20.3.2.3 *Stress in bonded prestressed reinforcement at nominal flexural strength*, f_{ps}

R20.3.2.3.1 Use of Eq. (20.3.2.3.1) may underestimate the strength of beams with high percentages of reinforcement and, for more accurate evaluations of their strength, the strain compatibility and equilibrium method should be used. If part of the prestressed reinforcement is in the compression zone, a strain compatibility and equilibrium method should be used.

The γ_p term in Eq. (20.3.2.3.1) and Table 20.3.2.3.1 reflects the influence of different types of prestressing reinforcement on the value of f_{ps}. Table R20.3.2.3.1 shows prestressing reinforcement type and the associated ratio f_{py}/f_{pu}.

Table R20.3.2.3.1—Ratio of f_{py}/f_{pu} associated with reinforcement type

Prestressing reinforcement type		f_{py}/f_{pu}
High-strength prestressing bars	ASTM A722 Type I (Plain)	≥0.85
	ASTM A722 Type II (Deformed)	≥0.80
Stress-relieved strand and wire	ASTM A416 ASTM A421	≥0.85
Low-relaxation strand and wire	ASTM A416 ASTM A421	≥0.90

CODE

(b) If compression reinforcement is included in Eq. (20.3.2.3.1), the term

$$\left[\rho_p \frac{f_{pu}}{f_c'} + \frac{d}{d_p}\frac{f_y}{f_c'}(\rho - \rho')\right]$$

shall not be taken less than 0.17.

Table 20.3.2.3.1—Values of γ_p for use in Eq. (20.3.2.3.1)

f_{py}/f_{pu}	γ_p
≥0.80	0.55
≥0.85	0.40
≥0.90	0.28

20.3.2.3.2 For pretensioned strands, the strand design stress at sections of members located within ℓ_d from the free end of strand shall not exceed that calculated in accordance with 25.4.8.3.

20.3.2.4 *Stress in unbonded prestressed reinforcement at nominal flexural strength*, f_{ps}

20.3.2.4.1 As an alternative to a more accurate calculation of f_{ps}, values of f_{ps} calculated in accordance with Table 20.3.2.4.1 shall be permitted for members prestressed with unbonded tendons if $f_{se} \geq 0.5f_{pu}$.

Table 20.3.2.4.1—Approximate values of f_{ps} at nominal flexural strength for unbonded tendons

ℓ_n/h	f_{ps}	
≤35	The least of:	$f_{se} + 10{,}000 + f_c'/(100\rho_p)$
		$f_{se} + 60{,}000$
		f_{py}
>35	The least of:	$f_{se} + 10{,}000 + f_c'/(300\rho_p)$
		$f_{se} + 30{,}000$
		f_{py}

20.3.2.5 *Permissible tensile stresses in prestressed reinforcement*

20.3.2.5.1 The tensile stress in prestressed reinforcement shall not exceed the limits in Table 20.3.2.5.1.

COMMENTARY

R20.3.2.3.1(a) If d' is large, the strain in compression reinforcement can be considerably less than its yield strain. In such a case, the compression reinforcement does not influence f_{ps} as favorably as implied by Eq. (20.3.2.3.1). For this reason, if d' exceeds $0.15d_p$, Eq. (20.3.2.3.1) is applicable only if the compression reinforcement is neglected.

R20.3.2.3.1(b) The ρ' term in Eq. (20.3.2.3.1) reflects the increased value of f_{ps} obtained when compression reinforcement is provided in a beam with a large reinforcement index. If the term $[\rho_p(f_{pu}/f_c') + (d/d_p)(f_y/f_c')(\rho - \rho')]$ is small, the neutral axis depth is small, the compressive reinforcement does not develop its yield strength, and Eq. (20.3.2.3.1) becomes unconservative. For this reason, the term $[\rho_p(f_{pu}/f_c') + (d/d_p)(f_y/f_c')(\rho - \rho')]$ may not be taken less than 0.17 if compression reinforcement is taken into account when calculating f_{ps}. The compression reinforcement may be conservatively neglected when using Eq. (20.3.2.3.1) by taking ρ' as zero, in which case the term $[\rho_p(f_{pu}/f_c') + (d/d_p)(f_y/f_c')(\rho)]$ may be less than 0.17 and an acceptable value of f_{ps} is obtained.

R20.3.2.4 *Stress in unbonded prestressed reinforcement at nominal flexural strength*, f_{ps}

R20.3.2.4.1 The term $[f_{se} + 10{,}000 + f_c'/(300\rho_p)]$ reflects results of tests on members with unbonded tendons and span-to-depth ratios greater than 35 (one-way slabs, flat plates, and flat slabs) (Mojtahedi and Gamble 1978). These tests also indicate that the term $[f_{se} + 10{,}000 + f_c'/(100\rho_p)]$, formerly used for all span-depth ratios, overestimates the amount of stress increase in such members. Although these same tests indicate that the moment strength of those shallow members designed using $[f_{se} + 10{,}000 + f_c'/(100\rho_p)]$ meets the factored load strength requirements, this reflects the effect of the Code requirements for minimum bonded reinforcement as well as the limitation on concrete tensile stress that often control the amount of prestressing force provided.

R20.3.2.5 *Permissible tensile stresses in prestressed reinforcement*

R20.3.2.5.1 Because of the high yield strength of low-relaxation strand and wire meeting the requirements of ASTM A416 and ASTM A421 including Supplementary Requirement S1 "Low-Relaxation Wire and Relaxation Testing," it is appropriate to specify permissible stresses

CODE

Table 20.3.2.5.1—Maximum permissible tensile stresses in prestressed reinforcement

Stage	Location	Maximum tensile stress	
During stressing	At jacking end	Least of:	$0.94f_{py}$
			$0.80f_{pu}$
			Maximum jacking force recommended by the supplier of anchorage device
Immediately prior to force transfer	At jacking end of pretensioned strands	$0.75f_{pu}$	
Immediately after force transfer	At post-tensioning anchorage devices and couplers	$0.70f_{pu}$	

20.3.2.6 *Prestress losses*

20.3.2.6.1 Prestress losses shall be considered in the calculation of the effective tensile stress in the prestressed reinforcement, f_{se}, and shall include (a) through (f):

(a) Prestressed reinforcement seating at transfer
(b) Elastic shortening of concrete
(c) Creep of concrete
(d) Shrinkage of concrete
(e) Relaxation of prestressed reinforcement
(f) Friction loss due to intended or unintended curvature in post-tensioning tendons

20.3.2.6.2 Calculated friction loss in post-tensioning tendons shall be based on experimentally determined wobble and curvature friction coefficients.

20.3.2.6.3 Where loss of prestress in a member is anticipated due to connection of the member to adjoining construction, such loss of prestress shall be included in design calculations.

COMMENTARY

in terms of specified minimum ASTM yield strength along with the specified minimum ASTM tensile strength. Because of the higher allowable initial prestressed reinforcement stresses permitted since the 1983 Code, final stresses can be greater. For structures subject to corrosive conditions or repeated loadings, consideration should be given to limiting the final stress.

The margin between the maximum stress during stressing and the maximum stress immediately prior to force transfer for pretensioned strands allows the manufacturer to stress the strands to compensate for prestress losses accrued between stressing and force transfer.

R20.3.2.6 *Prestress losses*

R20.3.2.6.1 ACI PRC-423.10 provides a comprehensive treatment of the estimation of prestress losses.

Actual losses, greater or smaller than the calculated values, have little effect on the design strength of the member, but affect service load behavior (deflections, camber, cracking load) and connections. At service loads, overestimation of prestress losses can be almost as detrimental as underestimation because the former can result in excessive camber and horizontal movement.

R20.3.2.6.2 Estimation of friction losses in post-tensioned tendons is addressed in the *Post-Tensioning Manual* (TAB.1). Values of the wobble and curvature friction coefficients to be used for the particular types of prestressing reinforcement and particular types of ducts should be obtained from the manufacturers of the tendons. An unrealistically low estimate of the friction loss can lead to improper camber, or potential deflection, of the member and inadequate prestress. Overestimation of the friction may result in extra prestressing force. This could lead to excessive camber and excessive shortening of a member. If the friction factors are determined to be less than those assumed in the design, the tendon stressing should be adjusted to provide only that prestressing force in the critical portions of the structure required by the design.

When safety or serviceability of the structure may be involved, the acceptable range of prestressing reinforcement jacking forces or other limiting requirements should either be given or approved by the licensed design professional in conformance with the permissible stresses of 20.3.2.5 and 24.5.

CODE

20.4—Headed shear stud reinforcement

20.4.1 Headed shear stud reinforcement and stud assemblies shall conform to ASTM A1044.

COMMENTARY

R20.4—Headed shear stud reinforcement

R20.4.1 The configuration of the studs for headed shear stud reinforcement differs from the configuration of the headed-type shear studs prescribed in Section 7 of AWS D1.1 (2015) and referenced for use in Chapter 17 of this Code (Fig. R20.4.1). Ratios of the head to shank cross-sectional areas of the AWS D1.1 studs range from approximately 2.5 to 4. In contrast, ASTM A1044 requires the area of the head of headed shear stud reinforcement to be at least 10 times the area of the shank. Thus, the AWS D1.1 headed studs are not suitable for use as headed shear stud reinforcement. The base rail, where provided, anchors one end of the studs; ASTM A1044 specifies material width and thickness of the base rail that are sufficient to provide the required anchorage without yielding for stud shank diameters of 0.375, 0.500, 0.625, and 0.750 in. In ASTM A1044, the minimum specified yield strength of headed shear studs is 51,000 psi.

Headed shear studs also differ from headed deformed bars, which are required to conform to 20.2.1.6 and may be used as an alternative to hooks for anchoring transverse reinforcement as permitted in 25.7.1.8.

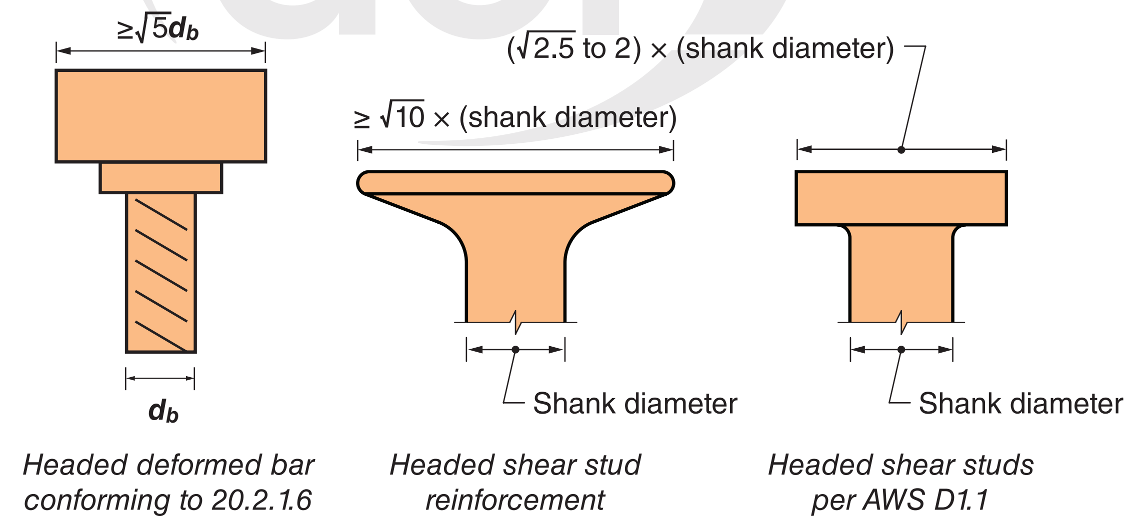


Fig. R20.4.1—Example stud head configurations .

20.5—Provisions for durability of steel reinforcement

20.5.1 *Specified concrete cover*

R20.5—Provisions for durability of steel reinforcement

R20.5.1 *Specified concrete cover*

This section addresses concrete cover over reinforcement and does not include requirements for concrete cover over embedments such as pipes, conduits, and fittings, which are addressed in 20.6.5.

CODE

20.5.1.1 Unless the general building code requires a greater concrete cover for fire protection, the minimum specified concrete cover shall be in accordance with 20.5.1.2 through 20.5.1.4.

COMMENTARY

R20.5.1.1 Concrete cover as protection of reinforcement from weather and other effects is measured from the concrete surface to the outermost surface of the reinforcement to which the cover requirement applies. Where concrete cover is prescribed for a class of structural members, it is measured to the outer edge of stirrups, ties, or spirals if transverse reinforcement encloses main bars; to the outermost layer of bars if more than one layer is used without stirrups or ties; to the metal end fitting or duct of post-tensioning tendons; or to the outermost part of the head on headed bars.

The condition "exposed to weather or in contact with ground" refers to direct exposure to moisture changes and not just to temperature changes. The term "exposed to weather" also includes exposure to moisture and airborne chlorides as described in R19.3.1. Slab soffits are not usually considered directly exposed unless subject to road spray from deicing chemicals or airborne chlorides, or alternate wetting and drying, (including that due to condensation conditions or direct leakage from exposed top surface, run off, or similar effects), or both.

Alternative methods of protecting the reinforcement from weather may be provided if they are equivalent to the additional concrete cover required by the Code. When approved by the building official under the provisions of 1.10, reinforcement with alternative protection from weather may not have concrete cover less than the cover required for reinforcement not exposed to weather.

Development length provisions given in Chapter 25 are a function of cover over the reinforcement. To meet requirements for development length, it may be necessary to use cover greater than the minimums specified in 20.5.1.

20.5.1.2 It shall be permitted to consider concrete floor finishes as part of required cover for nonstructural purposes.

R20.5.1.2 Concrete floor finishes may be considered for nonstructural purposes such as cover for reinforcement and fire protection. Provisions should be made, however, to ensure that the concrete finish will not spall off, thus resulting in decreased cover. Furthermore, considerations for development of reinforcement require minimum monolithic concrete cover in accordance with 20.5.1.3.

20.5.1.3 *Specified concrete cover requirements*

R20.5.1.3 *Specified concrete cover requirements*

20.5.1.3.1 Nonprestressed cast-in-place concrete members shall have specified concrete cover for reinforcement at least that given in Table 20.5.1.3.1.

CODE

Table 20.5.1.3.1—Specified concrete cover for cast-in-place nonprestressed concrete members

Concrete exposure	Member	Reinforcement	Specified cover, in.
Cast against and permanently incontact with ground	All	All	3
Exposed to weather or in contact with ground	All	No. 6 through No. 18 bars	2
		No. 5 bar, W31 or D31 wire, and smaller	1-1/2
Not exposed to weather or in contact with ground	Slabs, joists, and walls	No. 14 and No. 18 bars	1-1/2
		No. 11 bar and smaller	3/4
	Beams, columns, pedestals, and tension ties	Primary reinforcement, stirrups, ties, spirals, and hoops	1-1/2

20.5.1.3.2 Cast-in-place prestressed concrete members shall have specified concrete cover for reinforcement, ducts, and end fittings at least that given in Table 20.5.1.3.2.

Table 20.5.1.3.2—Specified concrete cover for cast-in-place prestressed concrete members

Concrete exposure	Member	Reinforcement	Specified cover, in.
Cast against and permanently in contact with ground	All	All	3
Exposed to weather or in contact with ground	Slabs, joists, and walls	All	1
	All other	All	1-1/2
Not exposed to weather or in contact with ground	Slabs, joists, and walls	All	3/4
	Beams, columns, and tension ties	Primary reinforcement	1-1/2
		Stirrups, ties, spirals, and hoops	1

20.5.1.3.3 Precast nonprestressed or prestressed concrete members manufactured under plant conditions shall have specified concrete cover for reinforcement, ducts, and end fittings at least that given in Table 20.5.1.3.3.

COMMENTARY

R20.5.1.3.3 The lesser cover thicknesses for precast construction reflect the greater control for proportioning, placing, and curing inherent in precasting. Manufactured under plant conditions does not imply that precast members should be manufactured in a plant. Structural elements precast at the job site will also qualify under this section if the control of form dimensions, placing of reinforcement, quality control of concrete, and curing procedures are equal to that normally expected in a plant.

Concrete cover to pretensioned strand as described in this section is intended to provide minimum protection from weather and other effects. Such cover may not be sufficient to transfer or develop the stress in the strand, and it may be necessary to increase the cover accordingly.

CODE

Table 20.5.1.3.3—Specified concrete cover for precast-nonprestressed or prestressed concrete members manufactured under plant conditions

Concrete exposure	Member	Reinforcement	Specified cover, in.
Exposed to weather or in contact with ground	Walls	No. 14 and No. 18 bars; tendons larger than 1-1/2 in. diameter	1-1/2
		No. 11 bars and smaller; W31 and D31 wire and smaller; tendons and strands 1-1/2 in. diameter and smaller	3/4
	All other	No. 14 and No. 18 bars; tendons larger than 1-1/2 in. diameter	2
		No. 6 through No. 11 bars; tendons and strands larger than 5/8 in. diameter through 1-1/2 in. diameter	1-1/2
		No. 5 bar, W31 or D31 wire, and smaller; tendons and strands 5/8 in. diameter and smaller	1-1/4
Not exposed to weather or in contact with ground	Slabs, joists, and walls	No. 14 and No. 18 bars; tendons larger than 1-1/2 in. diameter	1-1/4
		Tendons and strands 1-1/2 in. diameter and smaller	3/4
		No. 11 bar, W31 or D31 wire, and smaller	5/8
	Beams, columns, pedestals, and tension ties	Primary reinforcement	Greater of d_b and 5/8 and need not exceed 1-1/2
		Stirrups, ties, spirals, and hoops	3/8

20.5.1.3.4 Deep foundation members shall have specified concrete cover for reinforcement at least that given in Table 20.5.1.3.4.

COMMENTARY

CODE

Table 20.5.1.3.4—Specified concrete cover for deep foundation members

Concrete exposure	Deep foundation member type	Reinforcement	Specified cover, in.
Cast against and permanently in contact with ground, not enclosed by steel pipe, tube permanent casing, or stable rock socket	Cast-in-place	All	3
Enclosed by steel pipe, tube, permanent casing, or stable rock socket	Cast-in-place	All	1-1/2
Permanently in contact with ground	Precast-nonprestressed	All	1-1/2
	Precast-prestressed		
Exposed to seawater	Precast-nonprestressed	All	2-1/2
	Precast-prestressed	All	2

20.5.1.3.5 For bundled bars, specified concrete cover shall be at least the smaller of (a) and (b):

(a) The equivalent diameter of the bundle

(b) 2 in.

and for concrete cast against and permanently in contact with ground, the specified cover shall be at least 3 in.

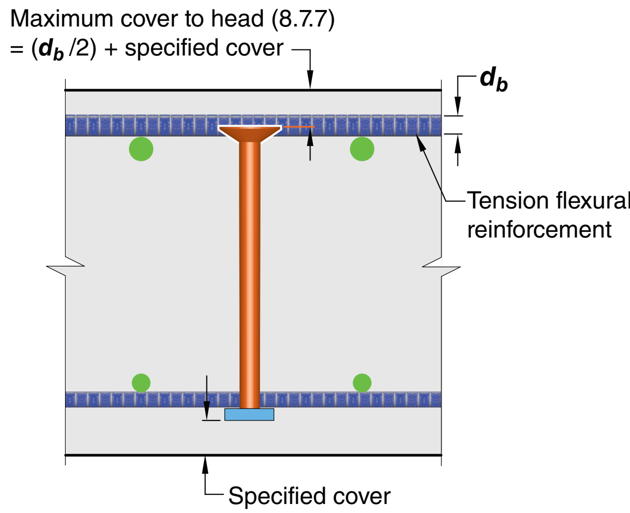
20.5.1.3.6 For headed shear stud reinforcement, specified concrete cover for the heads and base rails shall be at least that required for the reinforcement in the member.

COMMENTARY

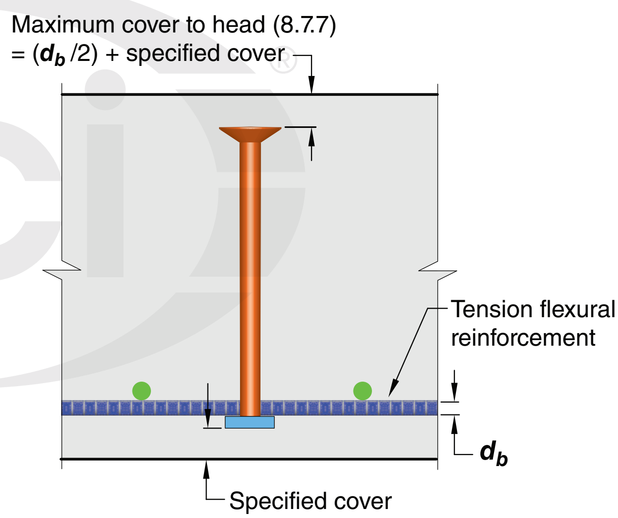
R20.5.1.3.6 Concrete cover requirements for headed shear stud reinforcement are illustrated in Fig. R20.5.1.3.6.

CODE

COMMENTARY



(a) Slab with top and bottom bars



(b) Footing with only bottom bars

Fig. R20.5.1.3.6—Concrete cover requirements for headed shear stud reinforcement.

20.5.1.4 *Specified concrete cover requirements for corrosive environments*

R20.5.1.4 *Specified concrete cover requirements for corrosive environments*

Corrosive environments are defined in 19.3.1, R19.3.1, and R19.3.2. Additional information on corrosion in parking structures is given in ACI PRC-362.1.

20.5.1.4.1 In corrosive environments or other severe exposure conditions, the specified concrete cover shall be increased as deemed necessary. The applicable requirements for concrete based on exposure categories in 19.3 shall be satisfied, or other protection shall be provided.

R20.5.1.4.1 Where concrete will be exposed to external sources of chlorides in service, such as deicing chemicals, brackish water, seawater, spray from these sources, and airborne chlorides as described in R19.3.1, concrete should be proportioned to satisfy the requirements for the applicable exposure class in Chapter 19. These include maximum *w/cm*, minimum strength for normalweight and lightweight

CODE | COMMENTARY

concrete, and maximum chloride ion in the concrete. Additionally, for corrosion protection, a specified concrete cover for reinforcement not less than 2 in. for walls and slabs and not less than 2-1/2 in. for other members is recommended. For precast concrete members manufactured under plant control conditions, a specified concrete cover not less than 1-1/2 in. for walls and slabs and not less than 2 in. for other members is recommended.

20.5.1.4.2 For prestressed concrete members classified as Class T or C in 24.5.2 and exposed to corrosive environments or other severe exposure categories such as those given in 19.3, the specified concrete cover for prestressed reinforcement shall be at least one and one-half times the cover in 20.5.1.3.2 for cast-in-place members and in 20.5.1.3.3 for precast members.

20.5.1.4.3 If the precompressed tension zone is not in tension under sustained loads, 20.5.1.4.2 need not be satisfied.

20.5.2 *Nonprestressed coated reinforcement*

20.5.2.1 Nonprestressed coated reinforcement shall conform to Table 20.5.2.1.

Table 20.5.2.1—Nonprestressed coated reinforcement

Type of coating	Applicable ASTM specifications		
	Bar	Wire	Welded wire
Zinc-coated	A767	Not permitted	A1060
Epoxy-coated	A775 or A934	A884	A884
Zinc and epoxy dual-coated	A1055	Not permitted	Not permitted

20.5.2.2 Deformed bars to be zinc-coated, epoxy-coated, or zinc and epoxy dual-coated shall conform to 20.2.1.3(a), (b), or (c).

20.5.2.3 Wire and welded wire reinforcement to be epoxy-coated shall conform to 20.2.1.7(a).

R20.5.2 *Nonprestressed coated reinforcement*

R20.5.2.1 Zinc-coated (hot-dipped galvanized) bars (ASTM A767), epoxy-coated bars (ASTM A775 and A934), and zinc and epoxy dual-coated bars (ASTM A1055) are used in applications where corrosion resistance of reinforcement is of particular concern such as in parking structures, bridge structures, and other highly corrosive environments.

20.5.3 *Corrosion protection for unbonded prestressing reinforcement*

20.5.3.1 Unbonded prestressing reinforcement shall be encased in sheathing, and the space between the prestressing reinforcement and the sheathing shall be completely filled with a material formulated to inhibit corrosion. Sheathing shall be watertight and continuous over the unbonded length.

R20.5.3 *Corrosion protection for unbonded prestressing reinforcement*

R20.5.3.1 Material for corrosion protection of unbonded prestressing reinforcement should have the properties identified in 19.1 of Breen et al. (1994).

Typically, sheathing is a continuous, seamless, high-density polyethylene material that is extruded directly onto the coated prestressing reinforcement.

20.5.3.2 The sheathing shall be connected to all stressing, intermediate, and fixed anchorages in a watertight fashion.

20.5.3.3 Unbonded single-strand tendons shall be protected to provide resistance to corrosion in accordance with ACI SPEC-423.7.

20.5.4 *Corrosion protection for grouted tendons*

R20.5.4 *Corrosion protection for grouted tendons*

20.5.4.1 Ducts for grouted tendons shall be grout-tight and nonreactive with concrete, prestressing reinforcement, grout, and corrosion inhibitor admixtures.

20.5.4.2 Ducts shall be maintained free of water.

R20.5.4.2 Water in ducts may cause corrosion of the prestressing reinforcement, may lead to bleeding and segregation of grout, and may cause distress to the surrounding concrete if subjected to freezing conditions. A corrosion inhibitor should be used to provide temporary corrosion protection if prestressing reinforcement is exposed in the ducts for prolonged periods of time before grouting (ACI SPEC-423.7).

20.5.4.3 Ducts for grouted single-wire, single-strand, or single-bar tendons shall have an inside diameter at least 1/4 in. larger than the diameter of the prestressing reinforcement.

20.5.4.4 Ducts for grouted multiple wire, multiple strand, or multiple bar tendons shall have an inside cross-sectional area at least two times the cross-sectional area of the prestressing reinforcement.

20.5.5 *Corrosion protection for post-tensioning anchorages, couplers, and end fittings*

R20.5.5 *Corrosion protection for post-tensioning anchorages, couplers, and end fittings*

20.5.5.1 Anchorages, couplers, and end fittings shall be protected to provide long-term resistance to corrosion.

R20.5.5.1 For recommendations regarding protection, refer to ACI PRC-423.3 and ACI SPEC-423.7.

20.5.6 *Corrosion protection for external post-tensioning*

R20.5.6 *Corrosion protection for external post-tensioning*

20.5.6.1 External tendons and tendon anchorage regions shall be protected to provide resistance to corrosion.

R20.5.6.1 Corrosion protection can be achieved by a variety of methods. The corrosion protection provided should be suitable to the environment in which the tendons are located. Some conditions will require that the prestressing reinforcement be protected by concrete cover or by cement grout in polyethylene or metal tubing; other conditions will permit the protection provided by coatings such as paint or grease. Corrosion protection methods should meet the fire protection requirements of the general building code, unless the installation of external post-tensioning is to only improve serviceability.

CODE

20.6—Embedments

20.6.1 Embedments shall not significantly impair the strength of the structure and shall not reduce fire protection.

20.6.2 Embedment materials shall not be harmful to concrete or reinforcement.

20.6.3 Aluminum embedments shall be coated or covered to prevent aluminum-concrete reaction and electrically isolated to prevent electrolytic action between aluminum and steel or other embedded metals.

20.6.4 Reinforcement with an area at least 0.002 times the area of the concrete section shall be provided perpendicular to pipe embedments.

20.6.5 Specified concrete cover for pipe embedments with their fittings shall be at least 1-1/2 in. for concrete exposed to earth or weather, and at least 3/4 in. for concrete not exposed to weather, or not in contact with ground.

COMMENTARY

R20.6—Embedments

R20.6.1 The placement of nonstructural embedments such as conduit and piping in stress-critical regions and joints should be avoided. Where unavoidable, care should be taken to ensure that the embedments will not impair the strength or serviceability of the structure. The contractor should not be permitted to install conduits, pipes, ducts, or sleeves that are not shown in the construction documents or not approved by the licensed design professional.

R20.6.3 The Code prohibits the use of aluminum in structural concrete unless it is effectively protected. Coatings and coverings prevent aluminum reaction with concrete, which can cause expansion and cracking. Electrical isolation prevents electrolytic reactions with steel or other embedded metals, which can cause corrosion. The presence of chloride ions in the concrete increases the rate of reaction in both cases. Aluminum electrical conduits present a special problem because of likely contact with reinforcing steel and any stray electric current accelerates the adverse reaction. Provision prohibits calcium chloride or any admixture containing chloride, other than background amounts as an impurity in the admixture ingredients, from being used in concrete with aluminum embedments.

Notes