

ACI 423.3R-17

Recommendations for Concrete Members Prestressed with Single- Strand Unbonded Tendons

Reported by Joint ACI-ASCE Committee 423



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Recommendations for Concrete Members Prestressed with Single-Strand Unbonded Tendons

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

Recommendations for Concrete Members Prestressed with Single-Strand Unbonded Tendons

Reported by Joint ACI-ASCE Committee 423

Carin L. Roberts-Wollmann, Chair

Amy M. Reineke Trygestad, Secretary

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Rashid Ahmed*
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Brandon Ross
Bruce W. Russell
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Miroslav Vejvoda
Jeffrey S. Volz
H. Carl Walker
Zuming Xia
Paul Zia

Consulting Members

Kenneth B. Bondy*
Robert N. Bruce Jr.
Ned H. Burns

Chunsheng “Steve” Cai
Steven R. Close
Henry J. Cronin Jr.

Ward N. Marianos Jr.
Hani Melhem
Antoine E. Naaman

Thomas E. Nehil
Andrea J. Schokker

*Subcommittee members involved in updating this report.

This report provides information for the design of flexural concrete members in buildings post-tensioned with single-strand unbonded tendons. The report is intended to complement the commentary in ACI 318 and to provide suggestions for revisions and additions to ACI 318. Consideration is given to design for gravity and lateral loads, determination of fire endurance, design for seismic forces, and design for catastrophic loadings. Recommendations concerning details and properties of tendons, protection against corrosion, and construction procedures are presented.

Keywords: concrete slabs; cracking; fire resistance; joints; punching shear; unbonded post-tensioning.

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CHAPTER 1—INTRODUCTION**1.1—General**

Since the publication of previous ACI 423.3R reports, many of their recommendations have been incorporated into ACI 318. All references to ACI 318 refer to ACI 318-14 unless specifically noted. The recommendations in this report have been prepared to provide a comprehensive guide for design, materials, and construction for concrete members prestressed with single-strand unbonded tendons. Suggested revisions and additions to ACI 318 are also included in this report. Mandatory language used in this report reflects requirements in ACI 318.

1.2—Objective

This report presents recommendations for design, materials, and construction for concrete structures prestressed with unbonded tendons that are commensurate with the strength, serviceability, and safety requirements of ACI 318. Practitioners should use their judgment when applying the recommendations of this report. This report is not intended for reference in a specification or a code.

1.3—Scope

Recommendations pertinent to design with single-strand unbonded tendons considered in this report include the design of slabs, beams, and continuous members; details and properties of tendons and anchors; and protection from corrosion during construction and throughout the life of the structure.

The recommendations in this report are not intended for unbonded construction stages of elements using bonded tendons; for multistrand unbonded tendons used as external tendons; for members subject to direct tension, such as tiebacks, cable stays, arch ties, or circumferential tendons for containment structures; or for ground-supported post-tensioned slabs for light residential construction.

CHAPTER 2—NOTATION AND DEFINITIONS**2.1—Notation**

A_b = net bearing plate area, in.² (mm²)
 A_b' = maximum area of the portion of the concrete anchorage surface that is geometrically similar to and concentric with the area of the anchorage, in.² (mm²)
 A_c' = cross-sectional area of the slab, perpendicular to the slab edge, between the center of the exterior span and the slab edge, in.² (mm²)
 A_{cf} = larger of gross cross-sectional areas of the slab-beam strips of the two orthogonal equivalent frames intersecting at the column, in.² (mm²)
 A_{ps} = area of prestressed longitudinal tension reinforcement, in.² (mm²)
 $A_{s,min}$ = minimum bonded reinforcement in negative moment areas of two-way systems
 b = width of compression face of member, in. (mm)
 b_f = total flange width
 b_n = effective overhang flange width for normal forces, in. (mm)
 b_o = perimeter of critical section for two-way shear in slabs, in. (mm)
 b_w = effective flange width for normal forces at post-tension anchor, in. (mm)
 d_p = distance from extreme compression fiber to centroid of prestressing reinforcement, in. (mm)
 E_s = modulus of elasticity of prestressing reinforcement, psi (MPa)
 f_{ci}' = strength of concrete at time of initial prestress, psi (MPa)
 f_{cp} = permissible concrete compressive stress, psi (MPa)
 f_{pc} = compressive stress in concrete, after allowance for all prestress losses, at centroid of cross section resisting externally applied loads or at junction of web and flange where the centroid lies within the flange, psi (MPa); in a composite member, f_{pc} is the resultant compressive stress at centroid of composite section, or at junction of web and flange where the centroid lies within the flange, due to both prestress and moments resisted by precast member acting alone, psi (MPa)

f_{ps}	= stress in prestressing reinforcement at nominal flexural strength, psi (MPa)
f_{ps0}	= stress in post-tensioned tendons at nominal strength at high temperatures, psi (MPa)
f_{pu}	= specified tensile strength of prestressing reinforcement, psi (MPa)
f_{pu0}	= tensile strength of tendons at high temperatures, psi (MPa)
f_{se}	= effective stress in prestressing reinforcement, after allowance for all prestress losses, psi (MPa)
f_y	= specified yield stress of reinforcement, psi (MPa)
h	= slab thickness, in. (mm)
L	= span length of beam or one-way slab; clear projection of cantilever, in. (mm)
ℓ	= length of tendon, in. (mm)
M	= total applied static moment (unfactored), lb-in. (kN-m)
M_{tq}^+	= retained midspan moment, lb-in. (kN-m)
M_{t10}^-	= retained negative moment capacity at Column 1, lb-in. (N-m)
M_{t20}^-	= retained negative moment capacity at Column 2, lb-in. (N-m)
N_c	= resultant tensile force acting on the portion of the concrete cross section that is subjected to tensile stresses due to the combined effects of service loads and effective prestress, lb (N)
P	= average force in the prestressing reinforcement, lb (N)
V_p	= vertical component of effective prestress forces crossing the critical section
v_c	= stress corresponding to nominal two-way shear strength provided by concrete, psi (MPa)
v_{cw}	= nominal shear stress provided by concrete where diagonal cracking results from high principal tensile stress in web, lb (N)
w	= uniformly distributed load, plf (kN/m)
α_s	= constant used to calculate V_c in slabs, lb (MPa)
Δ_ℓ	= tendon elongation, in. (mm)
ϕ	= strength reduction factor
λ	= modification factor to reflect the reduced mechanical properties of lightweight concrete
ρ_p	= ratio of A_{ps} to bd_p

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <https://www.concrete.org/store/productdetail.aspx?ItemID=CT16>. Definitions provided herein complement that source.

encapsulated tendon—a tendon that is completely enclosed in a watertight covering from end to end, including anchorages, sheathing, post-tensioning coating, sleeves, and an encapsulation cap over the strand tail at each end.

post-tensioning coating—material between prestressing reinforcement and sheathing used to protect against corrosion and reduce friction.

prestressing reinforcement—strand, wire, or bar tensioned to impart forces to the concrete.

sheathing—material encasing prestressing reinforcement to prevent bonding of the prestressing reinforcement with the surrounding concrete, to provide corrosion protection, and to contain the corrosion-inhibiting coating.

CHAPTER 3—MEMBER DESIGN

3.1—General

The design provisions of ACI 318 apply to the contents of this chapter, but some recommendations are offered that complement those of ACI 318. Significant changes were made in [ACI 318-02](#), [ACI 318-08](#), [ACI 318-11](#), and [ACI 318-14](#) that impact the design of prestressed concrete members and unify the design approach for prestressed and nonprestressed members. ACI 318 limits for flexural reinforcement and moment redistribution are specified in terms of the net tensile strain in the extreme tension reinforcement ϵ_r . Prestressed members are grouped into three design categories: uncracked (U), transition (T), and cracked (C). Each category is defined according to the maximum calculated flexural tensile stress under service load conditions. For C members, there is no upper limit on calculated flexural tensile stresses under service loads, and any combination of stressed and unstressed reinforcement is permitted. Serviceability requirements related to C and T members are given in ACI 318.

3.2—One-way systems

One-way slabs are addressed in ACI 318-14 Chapter 7. The chapter organization provides design limits, required strength, required design strength, reinforcement limits, and reinforcing detailing.

3.2.1 Minimum bonded reinforcement—The minimum bonded reinforcement required in ACI 318-14, 7.6.2, is considered adequate to limit crack widths due to dead load and live load by providing adequate crack distribution ([Burns et al. 1978](#); [Yamazaki et al. 1969](#); [Burns and Pierce 1967](#)). This amount of reinforcement also provides an independent load-carrying system in the event of a catastrophic failure of the tendons or abnormal loading in one span of a continuous one-way post-tensioned element with unbonded tendons. For this reason, ACI 318-14, 7.7.4.2, requires that bonded reinforcement used as part of the design moment strength be detailed in accordance with the provisions of ACI 318-14, 7.7.3. Such bonded reinforcement provides an independent load path in one-way systems.

All prestressed concrete slabs (Classes U, T, and C) in ACI 318-11 were exempt from the reinforcement spacing limits in ACI 318-11, 7.6.5 (deformed flexural reinforcement spacing to be less than $3h$ and 18 in. [610 mm]). However, this requirement was changed in 7.7.2 of ACI 318-14 for Class C prestressed concrete slabs to make it similar to nonprestressed. Based on field experience with the performance of Class U and Class T unbonded post-tensioned slabs, the maximum spacing of the deformed reinforcement should be limited to six times the slab thickness or 36 in. (910 mm), whichever is less. Extension of this requirement to

reinforcement that is not part of the moment strength are given in [ACI 318-14](#), 7.7.4.4.

In one-way slabs, the use of service load design tensile stresses in the range of $9\sqrt{f'_c}$ to $12\sqrt{f'_c}$ psi ($0.75\sqrt{f'_c}$ to $1.0\sqrt{f'_c}$ MPa) usually results in bonded reinforcement strength requirements reasonably similar to those required by ACI 318-14, 7.6.2.3. Tests of slabs with this level of design tensile stress in conjunction with the bonded reinforcement requirements of ACI 318-14, 7.6.2.3, indicate that such slabs have performed satisfactorily ([Burns et al. 1978](#)). Prestressed concrete members categorized as Class C in ACI 318 have no upper limit on flexural tensile stresses, and the use of any combination of prestressed and nonprestressed reinforcement is permitted. The use of lower design tensile stresses, however, is preferable from the durability standpoint for applications in aggressive environments, such as parking structure decks in severe climates ([Walker 1980](#)).

One-way post-tensioned beams and slabs with unbonded tendons are waived from the $1.2M_{cr}$ requirement of ACI 318-14, 7.6.2.1, because the undesirable behavior due to sudden transfer of tensile force from concrete to prestressing reinforcement at first cracking in lightly reinforced sections does not occur in members with unbonded tendons.

3.2.2 Tendon spacing—The minimum bonded reinforcement requirements for one-way slabs under ACI 318-14, 7.6.2.3, typically result in the use of No. 4 (No. 13) bars at 21 in. (500 mm) centers for both positive and negative moments for a 4-1/2 in. (115 mm) thick slab. For an 8 in. (200 mm) thick one-way slab, No. 4 (No. 13) bars are required at approximately 12 in. (300 mm) centers; larger bars can be used at somewhat wider spacing. In consideration of this amount and spacing of bonded reinforcement, a maximum tendon spacing of eight times the slab thickness but not more than 5 ft (1.5 m) is recommended for one-way slabs with normal live loads and uniformly distributed loads (refer also to 3.3.5). Tendon spacing may need to be adjusted for slabs with concentrated loads, based on the size, configuration, and magnitude of the load concentration. ACI 318 contains no requirement for maximum tendon spacing or minimum axial compressive stress in one-way prestressed slabs. It is common practice to use an average minimum effective axial precompression stress of 125 psi (0.86 MPa) at every cross section tributary to the tendon, which can be further reduced to 100 psi (0.69 MPa) for short spans with little or no tension stresses.

In certain cases, such as external tendon retrofits, tendon spacing greater than eight times the slab thickness or 5 ft (1.5 m) may be applicable. In such cases, these limits may be exceeded, provided it can be shown by analysis that the slab system can adequately carry the design loads.

3.2.3 Minimum shear reinforcement—A minimum amount of shear reinforcement is necessary in all post-tensioned joists to provide a means of supporting the tendon design profile in the beam cross section. Where tendons are not adequately supported by stirrups, local deviations of the tendons from the assumed smooth parabolic curvature can result during placement of the concrete. When such tendons are stressed, the deviations from the intended curvature tend

to straighten out, and this process can impose large tensile stresses in webs of post-tensioned beams or joists. Severe cracking has been observed in several instances where no stirrups were provided. Unintended curvature of the tendons can be avoided by securely tying tendons to stirrups that are rigidly held in place by other elements of the reinforcing cage.

3.2.4 Prestressed shrinkage and temperature reinforcement—ACI 318-14, 24.4.4, is the result of an extensive revision in [ACI 318-11](#). The gross concrete area is now defined as the total beam web area, including the slab thickness and the area of the slab tributary to the beam. Beam tendons may be included in providing the required 100 psi (0.7 MPa) minimum average compression stress on this gross concrete area. The spacing of shrinkage and temperature tendons should not exceed 6 ft (1.8 m), measured between adjacent tendons, between faces of beams, or between walls and the closest tendon. When tendon spacing exceeds 4.5 ft (1.4 m), nonprestressed reinforcement, parallel to the tendons, is added at the slab edge in accordance with ACI 318-14, 7.7.6. At least one tendon is required in the slab between the faces of adjacent beams or walls.

Tendons used for shrinkage and temperature reinforcement should be positioned parallel to the beams and vertically as close as practicable to the center of the slab. Where shrinkage and temperature tendons support or conflict with the principal slab tendons, variation from the slab centroid is permissible, but the resultant eccentricity of the total shrinkage and temperature tendons within the slab should not extend outside the kern limits of the slab cross section. Figure 3.2.4 illustrates details for the use of unbonded tendons as shrinkage and temperature reinforcement in one-way beam and slab construction.

3.2.5 Structural integrity—ACI 318 contains no specific recommendations for structural integrity of one-way prestressed slabs with unbonded tendons.

3.3—Two-way systems

Two-way slabs are addressed in ACI 318-14 Chapter 8. The chapter organization provides design limits, design strength, required resistance, reinforcement limits, and reinforcing detailing.

3.3.1 Analysis—Slab systems prestressed in more than one direction for flexure should be analyzed in accordance with the provisions of equivalent frame or by more precise methods, including finite element techniques or classical elastic theory. The equivalent frame method of analysis has been shown by tests of large structural models to satisfactorily predict factored moments and shears in prestressed slab systems ([Post-Tensioning Institute 1977](#); [Burns and Hemakom 1977](#); [Scordelis et al. 1959](#); [Cleland et al. 1979](#)). The referenced research also shows that the yield-line theory accurately predicts the flexural strength of two-way post-tensioned slabs. Analysis using prismatic sections or other approximations of stiffness, which differ substantially from the equivalent frame method, may provide erroneous and unsafe results. Moment redistribution for post-tensioned slabs is covered in ACI 318-14, 6.6.3. [ACI 318-14](#), 8.11.6.5.

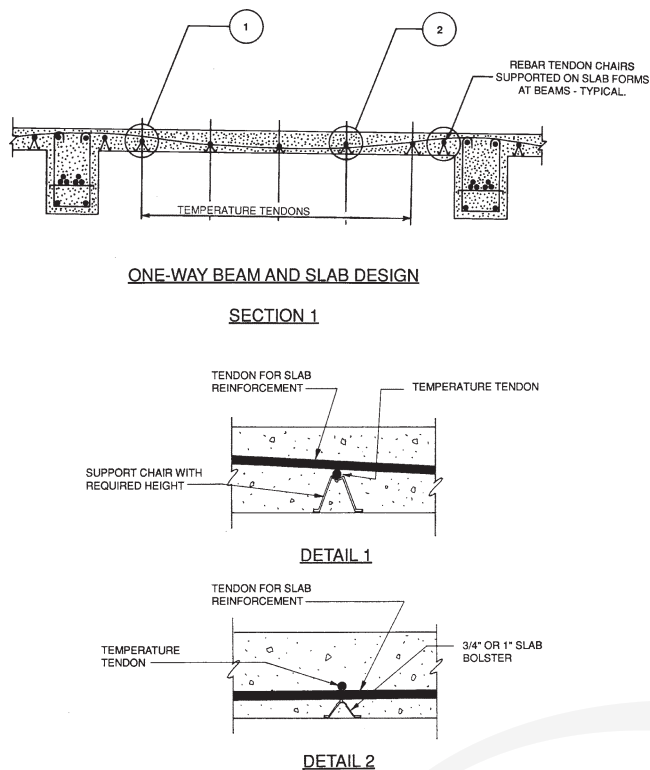


Fig. 3.2.4—Details for use of unbonded tendons as shrinkage and temperature reinforcement in one-way beam and slab construction. (Note: 1 in. = 25.4 mm.)

does not apply to two-way prestressed slabs. ACI 318-14, 8.11.6.6, is excluded because the distribution of moments between column strips and middle strips is based on tests of reinforced concrete slabs and the concept of column strips and middle strips is virtually never used in prestressed slabs, almost all of which use a banded tendon distribution (Fig. 3.3.1). Further, simplified methods of analysis using average coefficients do not apply to prestressed concrete slab systems. All other provisions of ACI 318-14, 8.11, specifically including the arrangement of live loads specified in ACI 318-14, 6.4.3, are applicable for the analysis of post-tensioned slabs.

ACI 318 requires that two-way prestressed slab systems be designed as Class U, with a maximum permissible concrete flexural tensile stress of $6\sqrt{f'_c}$ psi ($0.5\sqrt{f'_c}$ MPa) under service loads. The lateral load stiffness should be assessed considering the effects of slab cracking (ACI 318-14, 8.11; Kang and Wallace 2008b; Han et al. 2006). For lateral load analysis, the cracked section bending stiffness should be used and the torsional stiffness taken as 1/10 of the torsional member when using the equivalent frame method of analysis and where there is the potential for extensive cracking; where slabs have highly irregular shapes; where there are long pour lengths between construction, expansion joints, or both; or where slabs have unfavorable locations of walls. The cracked section bending stiffness should always be used for the computation of drift under seismic loads. Strength under lateral loads should be evaluated using the load factor combinations given in ACI 318-14, 5.3, in conjunction with the provisions of ACI 318-14, 8.4.1. Evaluation of strength

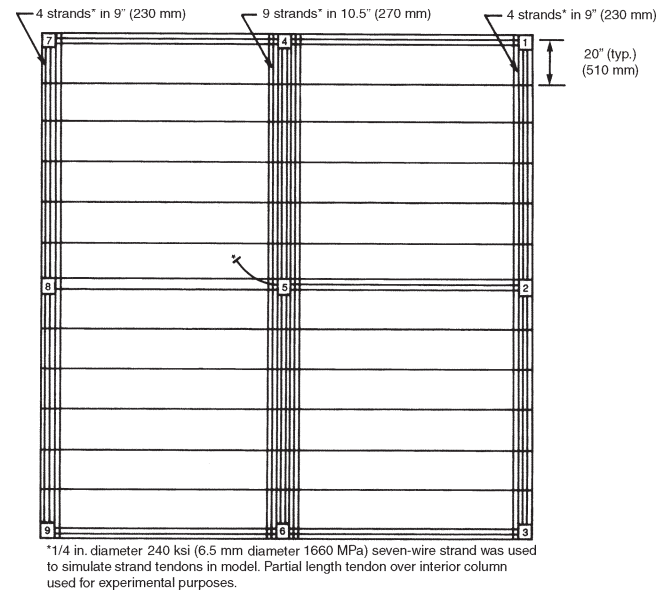


Fig. 3.3.1—Banded tension distribution (Kosut et al. 1985).

requirements under lateral loads may disclose the need for reinforcement to resist moment reversals (Han et al. 2006). Such reinforcement should be located within a distance of $1.5h$ outside opposite faces of the column, where h is the slab thickness.

3.3.2 Limits for reinforcement—Two-way post-tensioned slabs with unbonded tendons are waived from the $1.2M_{cr}$ requirement of ACI 318-14, 8.6.2.2, because the undesirable behavior due to the sudden transfer of tensile force from concrete to prestressing reinforcement at first cracking in lightly reinforced slabs does not occur in members with unbonded tendons.

Only at load levels beyond the factored design load is the additional cracking extensive enough to cause an abrupt change in the load-deflection pattern. Tests have also shown that it is not possible to rupture, or even yield, unbonded post-tensioning tendons in two-way slabs before a punching shear failure (Post-Tensioning Institute 1977; Burns and Hemakom 1977; Hemakom 1975; Kosut et al. 1985; Scordelis et al. 1959; Gerber and Burns 1971; Smith and Burns 1974; Kosut 1977). The use of unbonded tendons in combination with the minimum bonded reinforcement requirements of ACI 318-14, 8.6.2.3 and 8.7.5, has been shown to ensure post-cracking ductility and that a brittle failure mode will not develop at first cracking.

3.3.3 Minimum bonded reinforcement—Significant changes were made in ACI 318-99 to the requirement for minimum bonded reinforcement in negative moment regions of two-way systems. Prior to ACI 318-99, the amount of reinforcement was based on the span parallel to the direction of the reinforcement. In rectangular panels, this resulted in more reinforcement parallel to the longer span; however, it could also result in less reinforcement than tests have shown is necessary parallel to the shorter span (Burns and Hemakom 1977; Hemakom 1975; Kosut et al. 1985; Smith and Burns 1974; Kosut 1977; Dutch et al. 1990). It also

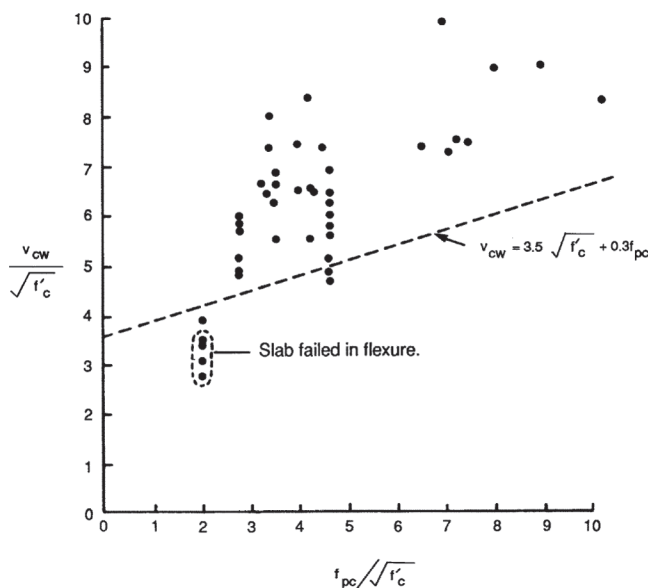


Fig. 3.3.4—Two-way post-tensioned flat plate shear test data versus Eq. (25.8.3.2) of ACI 318-14.

required substantially more reinforcement than tests have shown necessary in square panels parallel to the slab edge at exterior columns. To correct this, minimum bonded reinforcement in negative moment areas of two-way systems, $A_{s,min}$, is given by Eq. (3.3.3a)

$$A_{s,min} = 0.00075A_{cf} \quad (3.3.3a)$$

where A_{cf} is the larger of the gross cross-sectional areas of the slab-beam strips of the two orthogonal equivalent frames intersecting at the column. This addresses the problem of reinforcement parallel to the short span in rectangular panels, and results in an overall increase in reinforcement when compared with ACI 318 Codes prior to 1999.

The aforementioned change does not, however, address the edge panel condition and will still result in roughly twice the amount of minimum reinforcement required parallel to the slab edge at exterior columns. This amount of bonded reinforcement is required within a slab width between lines that are $1.5h$ outside opposite faces of the column support, where h is the slab thickness. Tests (Burns and Hemakom 1977; Hemakom 1975; Kosut et al. 1985; Smith and Burns 1974; Kosut 1977; Foutch et al. 1990) show that it is appropriate to provide bonded top reinforcement parallel to the slab edge at exterior columns on the basis of $0.00075A_c'$, where A_c' is the cross-sectional area of the slab, perpendicular to the slab edge, between the center of the exterior span and the slab edge. At exterior columns of flat plates with square panels and no projection of the slab beyond the exterior column face, the minimum bonded reinforcement parallel to the slab edge should logically be 50 percent of the bonded reinforcement perpendicular to the slab edge. It is recommended that ACI Committee 318 reconsider the minimum reinforcement requirement for this condition and modify the requirement to be more consistent with test results.

It is emphasized that the minimum bonded reinforcement addressed in this section is for the minimum amount required for crack distribution and to ensure sufficient punching shear strength. Flexural strength considerations may require more reinforcement than these minimum amounts.

Where the computed tensile stress in the concrete at service load exceeds $2\sqrt{f'_c}$ psi ($0.17\sqrt{f'_c}$ MPa), required bonded reinforcement in positive moment areas of two-way flat slabs is given by Eq. (3.3.3b) or ACI 318-14, 8.6.2.3.

$$A_s = \frac{N_c}{0.5f_y} \quad (3.3.3b)$$

where the value of f_y of bonded reinforcement is limited to 60,000 psi (420 MPa), and N_c is the tensile force, including the tensile component of the bending moment, in concrete due to unfactored dead load plus live load, plus effective prestress. Placement details for this reinforcement are included in 3.3.5. Slab reinforcement spacing requirements provided in ACI 318-14, 8.7.2.2, do not apply to bonded reinforcement in unbonded post-tensioned slabs.

3.3.4 Shear and moment transfer—ACI 318 revised the shear calculations in two-way members to be based on shear stress rather than force. The revision clarified the torsional stresses generated by the slab rotation at the column interface.

Figure 3.3.4 shows the results of single column-slab specimen punching shear tests and results of multi-panel slabs tested in shear (Kosut et al. 1985). Concrete shear capacity (Eq. (3.3.4)) expressed in terms of the perimeter of critical section for slabs b_o is

$$v_c = \beta_p \lambda \sqrt{f'_c} + 0.3f_{pc} + V_p/b_o d \quad (3.3.4)$$

where β_p is the smaller of 3.5 (0.29) or $(\alpha_s d/b_o + 1.5)/12$; $\alpha_s = 40$ for interior columns, 30 for edge columns, and 20 for corner columns; b_o is perimeter of critical section defined in ACI 318-14, 8.5.3.1.2 and 22.6.4; f_{pc} is average value of f_{pc} for the two directions, with a minimum of 125 psi (0.9 MPa) and a maximum of 500 psi (3.5 MPa); V_p is the vertical component of all effective prestress forces crossing the critical section; and λ is a modification factor to reflect the reduced mechanical properties of lightweight concrete relative to normalweight concrete of the same compressive strength.

It is assumed that no portion of the column cross section is closer to a discontinuous edge than four times the slab thickness, and f'_c does not exceed 5000 psi (35 MPa). This effectively limits the use of Eq. (3.3.4) to interior columns. Edge and corner columns are required to be evaluated using ACI 318-14, 22.6.5.1.

For values of f_{pc} less than 125 psi (0.9 MPa), V_c is limited to the value obtained using ACI 318-14, 22.6.5.1, for nonprestressed construction. In practice, V_p is commonly and conservatively ignored in shear calculations.

Moment transfer from prestressed concrete slabs to interior columns can be evaluated using the provisions of ACI 318-14, 22.6 and 8.4.2.3 (Param. 17/2). In this case, the

factored shear stress v_u should not exceed the value of ϕv_c calculated from ACI 318-14, 22.6.5.5. All reinforcement within a distance of 1.5 times the slab thickness on either side of the column is effective for transferring the portion of the moment not transferred by shear. Effective tendon stress f_{se} should be used in moment transfer capacity calculations. Tendons bundled through the column or over the lifting collar in lift slabs are an effective means of increasing the moment transfer strength of lift-slab connections. The moment transfer strength of lift-slab connections is also controlled by details of the lift slab connection. ACI 318-14, 22.6 and 8.4.2.3, are also applicable to calculations of the moment transfer from prestressed concrete slabs to exterior column connections for moments normal to a discontinuous edge. Bonded reinforcement, detailed as closed ties or hooked so that it can act as torsional reinforcement, should be provided when the calculated upward factored shear stress v_u at the discontinuous edge exceeds $2\sqrt{f'_c}$ psi ($0.17\sqrt{f'_c}$ MPa). Until further research data become available, the maximum calculated shear stress at such exterior columns should be limited to those specified in ACI 318-14 Table 22.6.5.2. Tests of four edge column specimens of a post-tensioned flat plate with banded tendon details support the use of ACI 318-14 Eq. (22.6.5.5a) for shear design (Foutch et al. 1990). Code provisions for the use of headed shear stud reinforcement for two-way shear strength in slabs were introduced in ACI 318-08 and are provided in ACI 318-14, 22.6.8. Recommendations for the use of shearbands for two-way shear strength were introduced in ACI 352.1R. The limited test data available (Kosut 1977; Pillai et al. 1982) do not show beneficial effects on shear strength resulting from the use of nonprestressed shear reinforcement with anchorage device details such as conventional headed studs in post-tensioned flat plates. The use of headed shear studs or stirrup reinforcement with modified anchorage details has been shown to increase shear strength (Dilger and Ghali 1981; Mokhtar et al. 1985; Muller et al. 1984; ACI 421.1R; Pilakoutas and Li 2003; Kang and Wallace 2008a; Kang and Park 2012).

3.3.5 Tendon and bonded reinforcement distribution and spacing—Within the limits of tendon distributions that have been tested, research indicates that the moment and shear strength of two-way prestressed slabs is controlled by total tendon strength in a given bay and by the amount and location of nonprestressed reinforcement rather than by horizontal tendon distribution (Ritz et al. 1975; Burns and Hemakom 1977; Hemakom 1975; Kosut et al. 1985; Parme 1972; Cleland et al. 1979). While it is important that some tendons are located within the shear perimeter over columns, distribution elsewhere is not critical, and any rational method that satisfies static equilibrium may be used. For uniform loading, ACI 318-14, 8.7.2.3, specifies that the maximum spacing of single tendons or groups of tendons in one direction shall not exceed eight times the slab thickness, with a maximum spacing of $8h$ or 5 ft (1.5 m). In addition, tendons are spaced to provide a minimum average prestress of 125 psi (0.9 MPa) on the local slab section tributary to the tendon or tendon group, the section being one-half of the spacing on either side of the center of the tendon or tendon group.

The spacing of individual single-strand tendons is usually governed by the minimum average prestress requirements. For groups of two or more tendons, the $8h$ criterion usually controls maximum tendon spacing. Tendon spacing may need to be adjusted to accommodate concentrated loads.

Horizontal curvature of bundled single-strand tendons should be avoided. If this is not possible, additional transverse reinforcement, such as hairpins, and other accessories may be required at points of horizontal curvature to maintain the horizontal plane of tendon bundles during stressing. Bundles should be limited to a maximum of four tendons where significant horizontal curvature is required.

Transverse reinforcement may also be required to control horizontal splitting cracking that can occur due to in-plane forces from horizontally-curved banded tendons, particularly those curved to avoid openings.

3.3.5.1 Recommended details of reinforcement for banded tendon distribution—The predominant and recommended method of placing tendons in two-way slab systems is the banded distribution illustrated in Fig. 3.3.1. The use of a banded tendon distribution greatly simplifies the process of placing tendons, and therefore provides a significant reduction in field labor cost. The number of tendons required in the design strip—that is, the center-to-center of adjacent panels—may be banded close to the column line in one direction and distributed in the other direction. At least two tendons are required by ACI 318-14, 8.7.5.6, to be through the region bounded by the longitudinal reinforcement of the columns in each direction.

For lift-slab construction, the same general details of tendon distribution apply and provisions should be made for tendons to pass through or over the lifting heads. Even though no tendons are provided in one direction between bands, the maximum spacing of tendons normal to bands ensures one-way reinforcement for this part of the slab. Except for small triangular sections adjacent to the slab edge and closure strips, the area between bands is also prestressed in both directions. For widely spaced tendons, consideration should be given to placing reinforcement similar to ACI 318 (Fig. 3.3.5.1) in these triangular regions.

Recommended details for nonprestressed reinforcement are:

a) Minimum bonded slab reinforcement $A_{s,min}$ at columns is $A_{s,min} = 0.00075A_{cf}$, given in Table 8.6.2.3 of ACI 318-14, where A_{cf} is the larger of cross-sectional areas of the slab-beam strips of the two orthogonal equivalent frames intersecting at the column (refer to 3.3.3). At least four No. 5 (No. 16) bars should be provided in each direction in negative moment areas at columns. The minimum area of bonded reinforcement parallel to the slab edge at exterior columns should be based on $0.00075A'_c$, where A'_c is the cross-sectional area of the slab, perpendicular to the slab edge, between the center of the exterior span and the slab edge.

b) Bonded reinforcement should be placed within a slab width between lines that are $1.5h$ outside opposite faces of columns (ACI 318-14, 8.7.5.6.3). Maximum spacing of these bars is 12 in. (300 mm).