14.1 PCI Standard Design Practice

Precast and prestressed concrete structures have provided decades of satisfactory performance. This performance is the result of the practices reported herein, conformance with ACI 318-05, *Building Code Requirements for Structural Concrete*,[1] incorporation of industry-specific research programs, and a plant certification program that provides an industry-wide quality control system beyond those found in onsite construction.

Precast and prestressed concrete design is based on the provisions of ACI 318-05. In most cases, these provisions are followed explicitly. Occasionally, the interpretation of some sections of ACI 318-05 are required to ensure maintenance of quality in conjunction with the unique characteristics of precast and prestressed concrete fabrication, shipping, and erection. Members of the PCI Building Code Committee, along with other experienced precast concrete design engineers, have identified code provisions that are detailed in this chapter, which require clarification or interpretation. These design practices are followed by a majority of precast concrete design engineers and have produced safe, economical precast/prestressed concrete structures and provided a consistent approach for the members of the design and construction team.

Occasionally, strict compliance with the ACI provisions as applied to precast concrete products can cause design, performance, and production problems that may unnecessarily increase the cost of a structure and/or may actually result in an inferior product. In such cases, PCI-sponsored and nationally sponsored research projects have been used to support alternative design and construction practices. Section 1.4 of ACI 318-05 specifically allows variances when analysis, research, or testing demonstrates adequate structural performance. Suggested changes to code provisions resulting from experience, analysis, or testing can provide a point for discussion with building officials for acceptance of revised provisions within the guidance and scope of Section 1.4 of ACI 318-05.

This list of provisions is based on ACI 318-05, and the numbers refer to sections in that document and are presented in numerical order. For notation used within this document, refer to the notation in Chapter 2 of ACI 318-05. References to the *PCI Design Handbook: Precast and Prestressed Concrete* are to the seventh edition, unless otherwise noted. Excerpts from ACI 318-05 are reprinted here with permission of the American Concrete Institute.

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CHAPTER 1 - GENERAL REQUIREMENTS

1.2 Drawings and Specifications

1.2.1(e) Size and location of all structural elements, reinforcement, and anchors.

1.2.1(e) *Reinforcement in this case does not refer to prestressing steel. In precast concrete members, reinforcement may be shown only on the piece drawings. (Reference* PCI Design Handbook*, Section 14.4.4.1)*

1.2.1(g) Magnitude and location of prestressing forces.

1.2.1(g) *For pretensioned concrete products, the prestressing design and detailing may be left to an engineer employed or retained by the manufacturer and may be shown only on the piece drawings and design calculations. (Reference* PCI Design Handbook*, Sections 14.4 and 14.5)*

1.2.2 Calculations pertinent to design shall be filed with the drawings when required by the building official. Analyses and designs using computer programs shall be permitted provided design assumptions, user input, and computer-generated output are submitted. Model analysis shall be permitted to supplement calculations.

1.2.2 *Product calculations and frequently other items such as connections are usually performed by an engineer designated by the precast concrete manufacturer. They are then submitted to the Engineer or Architect of Record, who is responsible for filing these documents with the building official. (Reference* PCI Design Handbook*, Sections 14.4 and 14.5)*

1.3.1 Concrete construction shall be inspected as required by the legally adopted general building code. In the absence of such inspection requirements, concrete construction shall be inspected throughout the various work stages by or under the supervision of a registered design professional or by a qualified inspector.

1.3.1 *Precast concrete products produced by PCI member producers are inspected by internal quality control inspectors under the guidance of PCI's* Manual for Quality Control for Plants and Production of Structural Precast Concrete Products *(MNL-116-99)*[2] *or* Manual for Quality Control for Plants and Production of Architectural Precast Concrete Products *(MNL-117-96).*[3] *These PCI member producers are required to follow these procedures and are periodically monitored by independent quality certification inspectors. PCI-Certified plants are "Approved Fabricators," as defined in the model codes and satisfy the special inspection requirements.*

CHAPTER 2 - DEFINITIONS

2.1 Code Notation

b_w = web width, or diameter of circular section, in., Chapters 10–12, 21, 22, Appendix B

2.1 *The quantity* b_w *is the sum of the average stem width of an individual stem in tapered stem members such as double-tees. This is critical in Eq. 11-14. In hollow-core units,* b_w *is the minimum web width.*

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2.2 Definitions

Moment frame. Frame in which members and joints resist forces through flexure, shear, and axial force. Moment frames shall be categorized as follows:

Intermediate moment frame. A cast-in-place frame complying with the requirements of 21.2.2.3 and 21.12 in addition to the requirements for ordinary moment frames.

Ordinary moment frame. A cast-in-place or precast concrete frame complying with the requirements of Chapters 1 through 18.

Special moment frame. A cast-in-place frame complying with the requirements of 21.2 through 21.5, or a precast frame complying with the requirements of 21.2 through 21.6. In addition, the requirements for ordinary moment frames shall be satisfied.

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2.2 *Design of precast concrete moment frames is discussed in Chapter 4 of the* PCI Design Handbook. *Designs consistent with ACI T1.1-01[4] (which has been replaced by ACI 374-1.05[5]) are in full compliance with ACI 318-05 (see Section 3.8.8).*

Definitions of these terms are also located in Chapter 21 of ACI 318-05. Definition of special moment frame in Chapter 21 is more specific in its references to sections that require compliance.

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Structural walls. Walls proportioned to resist combinations of shears, moments, and axial forces induced by earthquake motions. A shear wall is a structural wall. Structural walls shall be categorized as follows:

Intermediate precast structural wall. A wall complying with all applicable requirements of Chapters 1 through 18 in addition to 21.13.

Special precast structural wall. A precast wall complying with the requirements of 21.8. In addition, the requirements of ordinary reinforced concrete structural walls and the requirements of 21.2 shall be satisfied.

Special reinforced concrete structural wall. A cast-in-place wall complying with the requirements of 21.2 and 21.7 in addition to the requirements for ordinary reinforced concrete structural walls.

Design of precast concrete shear wall buildings is discussed in Chapter 4 of the PCI Design Handbook. *Designs consistent with ACI ITG 5.1[6] are in full compliance with ACI 318-05.*

Precast concrete walls that are designed to conform to ACI 318-05 Section 21.8, and by reference to 21.7 and 21.13, are special reinforced concrete shear walls, with the design factors as defined in ASCE 7-05,[7] Table 12.2-1.

Definitions of these terms are also located in Chapter 21 of ACI 318-05. Definitions of special precast concrete structural wall and special reinforced concrete structural wall in Chapter 21 are more specific in their references to sections that require compliance.

Tendon. In pretensioned applications, the tendon is the prestressing steel. In post-tensioned applications, the tendon is a complete assembly consisting of anchorages, prestressing steel, and sheathing with coating for unbonded applications or ducts with grout for bonded applications.

Precast, prestressed concrete products are nearly always pretensioned with seven-wire strand. Thus, the terms tendon, prestressing steel, and strand are used interchangeably.

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CHAPTER 3 – MATERIALS

3.5.2 Welding of reinforcing bars shall conform to *Structural Welding Code — Reinforcing Steel* (ANSI/AWS D1.4)[8] from the American Welding Society (AWS). Type and location of welded splices and other required welding of reinforcing bars shall be indicated on the design drawings or in the project specifications. ASTM reinforcing bar specifications, except for ASTM A 706,[9] shall be supplemented to require a report of material properties necessary to conform to the requirements in ANSI/AWS D1.4.

3.5.2 *A significant amount of connection field welding is common in precast concrete construction. AWS and the American Institute of Steel Construction (AISC) recommendations are generally followed, as modified in the* PCI Design Handbook *and the PCI manual* Design and Typical Details of Connections for Precast and Prestressed Concrete.[10] *Other connection devices, such as welded headed studs and deformed bar anchors, are also shown in these publications. AWS specifications should be followed when welded stainless- or galvanized steel reinforcing bars or plates are used. (Reference* PCI Design Handbook*, Section 6.5.1)*

3.5.5 Prestressing steel

3.5.5.1 Steel for prestressing shall conform to one of the following specifications:

(a) Wire conforming to *Standard Specification for Uncoated Stress-Relieved Steel Wire for Prestressed Concrete* (ASTM A 421);[11]

(b) Low-relaxation wire conforming to *Standard Specification for Uncoated Stress-Relieved Steel Wire for Prestressed Concrete*, including ASTM A 421;

(c) Strand conforming to *Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete* (ASTM A 416);[12]

(d) Bar conforming to *Standard Specification for Uncoated High-Strength Steel Bars for Prestressing Concrete* (ASTM A 722).[13]

3.5.5.2 Wire, strands, and bars not specifically listed in ASTM A 421, A 416, or A 722 are allowed provided they conform to minimum requirements of these specifications and do not have properties that make them less satisfactory than those listed in ASTM A 421, A 416, or A 722.

3.5.5 *Nearly all strand used in precast, prestressed concrete products is seven-wire strand conforming with ASTM A416, manufactured with low-relaxation wire conforming with the supplement to ASTM A421. Other prestressing steel that is occasionally used includes three-wire strand, deformed prestressing wire, and higher-strength strand. These prestressing steels are acceptable provided the requirements of 3.5.5.2 are met.*

3.8.8 *Acceptance Criteria for Moment Frames Based on Structural Testing* (ACI T1.1-01) is declared to be part of this code as if fully set forth herein.

3.8.8 *ACI T1.1-01 (which has been replaced by ACI 374.1-05) is primarily intended to address precast concrete moment frames using unbonded post-tensioning and is in compliance with ACI 318-05.*

CHAPTER 4 – DURABILITY REQUIREMENTS

4.2 Freezing and Thawing Exposures

4.2.1 Normalweight and lightweight concrete exposed to freezing and thawing or deicing chemicals shall be air-entrained with air content indicated in Table 4.2.1. Tolerance on air content as delivered shall be ±1.5%. For specified compressive strength f_c' greater than 5000 psi, reduction of air content indicated in Table 4.2.1 by 1.0 % shall be permitted.

4.2.1 *Some studies have shown that the very low water–cementitious materials ratios used in most precast concrete products require less air entrainment than cast-in-place concrete. (Reference* Some Physical Properties of High Strength Concrete[14] *and* Frost and Scaling Resistance of High Strength Concrete.[15]*)*

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4.2.2 Concrete that will be subject to the exposures given in Table 4.2.2 shall conform to the corresponding maximum water-cementitious materials ratios and minimum specified concrete compressive strength requirements of that table. In addition, concrete that will be exposed to deicing chemicals shall conform to the limitations of 4.2.3.

4.2.2 *(Note: See ACI 318-05 for the table referenced in this section.) The exposures discussed in this section affect the cover requirements given in Chapter 7 of ACI 318-05. While the high-quality concrete produced in precasting plants is generally resistant to severe exposure, the use of deicing chemicals directly on all concrete surfaces is strongly discouraged.*

4.4.1 For corrosion protection of reinforcement in concrete, maximum water soluble chloride ion concentrations in hardened concrete at ages from 28 to 42 days contributed from the ingredients including water, aggregates, cementitious materials, and admixtures shall not exceed the limits of Table 4.4.1. When testing is performed to determine water-soluble chloride ion content, test procedures shall conform to ASTM C 1218.[16]

4.4.1 *Calcium chloride or other admixtures containing chlorides are rarely used in precast concrete, and never in prestressed concrete, as required in ACI 318-05 Section 3.6.3. The requirements of this section regarding prestressed concrete are assumed to be met when all materials used in the concrete meet the appropriate ASTM specifications. See* PCI Journal *article, "Concrete, Chlorides, Cover and Corrosion."*[17] *(Reference* PCI Design Handbook*, Section 9.6.6)*

CHAPTER 5 – CONCRETE QUALITY, MIXING, AND PLACING

5.2.3 Concrete proportions shall be established in accordance with 5.3 or, alternatively, 5.4, and shall meet applicable requirements of Chapter 4.

5.2.3 *Producers of precast concrete products use standard mixtures that have been designed and substantiated in accordance with this section unless specifically stated for unusual conditions.*

5.11.3.2 Accelerated curing shall provide a compressive strength of the concrete at the load stage considered at least equal to required design strength at that load stage.

5.11.3.2 *The Commentary states "...the modulus of elasticity* E_c *of steam-cured specimens may vary from that of specimens moist-cured at normal temperatures." It is, however, most common for the ACI equation to be used to calculate* E_c *even when accelerated curing is used. Some producers may recommend other values based on testing. (Reference* PCI Design Handbook*, Section 9.2.2.4.) Also note that curing by direct exposure to steam is seldom used in precasting plants.*

CHAPTER 7 – DETAILS OF REINFORCEMENT

7.5.2 Unless otherwise specified by the registered design professional, reinforcement, including tendons, and post-tensioning ducts shall be placed within the tolerances in 7.5.2.1 and 7.5.2.2.

7.5.2 *Precast concrete products conform to PCI tolerance standards specified in PCI's* Tolerance Manual for Precast and Prestressed Concrete Construction *(MNL-135-00)*[18] *and Chapter13 of the* PCI Design Handbook*, unless specifically stated. There are some situations in which production practices warrant wider tolerances, which are explained further in the* PCI Tolerance Manual *(Reference* PCI Design Handbook*, Section 13.2.4)*

7.7.5 Corrosive environments

In corrosive environments or other severe exposure conditions, amount of concrete protection shall be suitably increased, and denseness and nonporosity of protecting concrete shall be considered, or other protection shall be provided.

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7.7.5.1 For prestressed concrete members exposed to corrosive environments or other severe exposure conditions, and which are classified as Class T or C in 18.3.3, minimum cover to the prestressed reinforcement shall be increased 50%. This requirement shall be permitted to be waived if the pre-compressed tensile zone is not in tension under sustained loads.

7.10.3 It shall be permitted to waive the lateral reinforcement requirements of 7.10, 10.16, and 18.11 where tests and structural analysis show adequate strength and feasibility of construction.

7.10.4 Spirals

Spiral reinforcement for compression members shall conform to 10.9.3 and to the following:

7.10.4.1 Spirals shall consist of evenly spaced continuous bar or wire of such size and so assembled to permit handling and placing without distortion from designed dimensions.

7.10.4.2 For cast-in-place construction, size of spirals shall not be less than $^3/_8$ in. diameter.

7.10.5 Ties

Tie reinforcement for compression members shall conform to the following:

7.10.5.1 All non-prestressed bars shall be enclosed by lateral ties, at least #3 in size for longitudinal bars #10 or smaller, and at least #4 in size for #11, #14, #18, and bundled longitudinal bars. Deformed wire or welded-wire reinforcement of equivalent area shall be permitted.

7.12 Shrinkage and Temperature Reinforcement

7.12.3.3 When spacing of tendons exceeds 54 in., additional bonded shrinkage and temperature reinforcement conforming to 7.12.2 shall be provided between the tendons at slab edges extending from the slab edge for a distance equal to the tendon spacing.

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7.7.5.1 *Nearly all precast, prestressed concrete members will be in compression in the precompressed tensile zone under sustained loads. Because of the compression and the high-quality concrete achieved in precasting plants, members that meet the requirements of this section have met the requirement of Section 7.7.5.*

7.10.3 *Section 7.10.3 waives minimum lateral ties with "tests and structural analysis..." Section 18.11.2.3 specifically excludes prestressed walls with a minimum average prestress of 225 psi from lateral (transverse) reinforcement requirements where structural analysis shows adequate strength and stability . (Reference* PCI Design Handbook, *Example 5.7.1)*

7.10.4 and 7.10.5 *Precast, prestressed concrete columns frequently use continuously wound wire in a rectangular configuration for lateral reinforcement. PCI Prestressed Columns Committee recommendations state that for such members, spiral ties may be substituted for individual lateral ties if the spiral has an area equivalent to that of ties spaced in accordance with Section 18.11.2.2. For further information on this topic, see report by PCI Prestressed Concrete Columns Committee,* Recommended Practice for the Design of Prestressed Concrete Columns and Walls.[19] *Section 7.10.4.2 specifically applies to only cast-in-place construction and Section 7.10.5.1 refers to non-prestressed bars, so the committee's recommendations are in full compliance with ACI 318-05.*

7.12 *The nature of fabrication and storage of precast, prestressed concrete stemmed members is such that the flanges of stemmed members are not subjected to restraint forces caused by initial shrinkage. Section 16.4.1 waives the requirement for shrinkage and temperature reinforcement in one-way precast concrete slabs and wall panels that are not wider than 12 ft where mechanical connections do not cause restraint. The flexural reinforcement in the flange of a stemmed member is transverse to the stems, and is usually welded-wire reinforcement. Practice varies, but the Wire Reinforcement Institute requires that the longitudinal wires have an area at least 0.4 times that of the transverse wires. Section 7.12.3 is intended for post-tensioned slabs as illustrated in the commentary and Fig. R7.12.3.*

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CHAPTER 8 – ANALYSIS AND DESIGN – GENERAL CONSIDERATIONS

8.1.3 Anchors within the scope of Appendix D, "Anchoring to Concrete", installed in concrete to transfer loads between connected elements shall be designed using Appendix D.

8.1.3 *Appendix D has specific provisions allowing modifications based on research. PCI has sponsored research on connections using welded headed studs that are in full compliance with the requirements of Appendix D. The design methods provided in Chapter 6 of the PCI Design Handbook reflect the results of this testing.*

8.3.2 Except for prestressed concrete, approximate methods of frame analysis shall be permitted for buildings of usual types of construction, spans, and story heights.

8.3.2 *The intent of this section is to prohibit Section 8.3.3 to be used for post-tensioned concrete framing. Approximate (that is, portal) methods are sometimes used to design precast concrete litewalls in parking structures.*

8.10.2 Width of slab effective as a T-beam flange shall not exceed one-quarter of the span length of the beam, and the effective overhanging flange width on each side of the web shall not exceed:

(a) Eight times the slab thickness;

(b) One-half the clear distance to the next web.

8.10.2 *Section 18.1.3 states that this section does not apply to prestressed concrete. Commentary R18.1.3 states that the effective flange width is left to the experience and judgment of the engineer. Eight times the slab thickness is often used as a guide for determining the topping width to be used in designing composite beams. Thin flange members are commonly designed including the entire flange width in the compression block. (Reference* PCI Design Handbook, *Examples 5.2.1.5 and 5.3.5.1)*

CHAPTER 9 – STRENGTH AND SERVICEABILITY REQUIREMENTS

9.2 Required Strength

9.2.1 Required strength U shall be at least equal to the effects of factored loads in Eq. (9-1) through (9-7). The effect of one or more loads not acting simultaneously shall be investigated.

$$U = 1.4(D + F) \quad (9\text{-}1)$$

$$U = 1.2(D + F + T) + 1.6(L + H) + 0.5(L_r \text{ or } S \text{ or } R) \quad (9\text{-}2)$$

$$U = 1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (1.0L \text{ or } 0.8W) \quad (9\text{-}3)$$

$$U = 1.2D + 1.6W + 1.0L + 0.5(L_r \text{ or } S \text{ or } R) \quad (9\text{-}4)$$

$$U = 1.2D + 1.0E + 1.0L + 0.2S \quad (9\text{-}5)$$

$$U = 0.9D + 1.6W + 1.6H \quad (9\text{-}6)$$

$$U = 0.9D + 1.0E + 1.6H \quad (9\text{-}7)$$

except as follows:

(a) The load factor on L in Eq. (9-3) to (9-5) shall be permitted to be reduced to 0.5 except for garages, areas occupied as places of public assembly, and all areas where the live load L is greater than 100 lb/ft^2.

9.2.1 *It should be emphasized that volume changes, settlement, and other movements* T *are not to be considered simultaneously with wind or earthquake forces. Structural effects of* T *need only be considered when the structural element is restrained and can produce internal forces as a result of* T. *See* PCI Design Handbook *Examples 5.8.5.2 and 5.9.2.1 for computation of restraint forces.*

The load factor modification of 9.2.1(a) must be distinguished from live-load reductions allowed in the applicable building code. Where allowed, the reduced live loads establish a value for L *to be used in the load combinations of 9.2.1 and 9.2.1(a).*

9.2.3 Estimations of differential settlement, creep, shrinkage, expansion of shrinkage-compensating concrete, or temperature change shall be based on a realistic assessment of such effects occurring in service.

9.2.3 *Chapter 4 of the* PCI Design Handbook *provides guidelines for estimating creep, shrinkage, and temperature changes in precast concrete structures that are in compliance with ACI 318-05.*

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R9.2.3 The designer should consider the effects of differential settlement, creep, shrinkage, temperature, and shrinkage-compensating concrete. The term realistic assessment is used to indicate that the most probable values rather than the upper bound values of the variables should be used.

9.3.2.7 Flexural sections in pretensioned members where strand embedment is less than the development length as provided in 12.9.1.1:

(a) From the end of the member to the end of the transfer length = 0.75

(b) From the end of the transfer length to the end of the development length, shall be permitted to be linearly increased from 0.75 to 0.9.

Where bonding of a strand does not extend to the end of the member, strand embedment shall be assumed to begin at the end of the debonded length. See also 12.9.3.

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9.5 Control of Deflections

9.5.4 Prestressed concrete construction

9.5.4.1 For flexural members designed in accordance with provisions of Chapter 18, immediate deflection shall be computed by usual methods or formulas for elastic deflections, and the moment of inertia of the gross concrete section I_g shall be permitted to be used for Class U flexural members, as defined in 18.3.3.

9.5.4.2 For Class C and Class T flexural members, as defined in 18.3.3, deflection calculations shall be based on a cracked transformed section analysis. It shall be permitted to base computations on a bilinear moment-deflection relationship, or an effective moment of inertia I_e, as defined by Eq. (9-8).

9.5.4.3 Additional long-term deflection of prestressed concrete members shall be computed taking into account stresses in concrete and steel under sustained load and including effects of creep and shrinkage of concrete and relaxation of steel.

9.5.4.4 Deflection computed in accordance with 9.5.4.1 or 9.5.4.2, and 9.5.4.3 shall not exceed limits stipulated in Table 9.5(b).

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9.3.2.7 *Section 5.2.3 of the* PCI Design Handbook *shows examples of designing for partially developed strands.*

9.5.4 *Deflections are always calculated for precast, prestressed concrete members in building structures. Calculations will usually include both instantaneous and long-term camber and dead and live load deflection. The engineer or architect of record will determine if this meets requirements, for example, Table 9.5(b). Satisfactory performance may depend on many non-structural considerations. (Reference* PCI Design Handbook*, Section 5.8)*

The PCI Design Handbook *provides guidance for deflection computations that exceed the requirements of ACI 318-05.*

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CHAPTER 10 – FLEXURE AND AXIAL LOADS

10.4.1 Spacings of lateral supports for a beam shall not exceed 50 times b, the least width of compression flange or face.

10.6.4 The spacing of reinforcement closest to the tension face s shall not exceed that given by

$$s = 15\left(\frac{40,000}{f_s}\right) - 2.5c_c \qquad (10\text{-}5)$$

but not greater than $12(40,000/f_s)$, where c_c is the least distance from surface of reinforcement of prestressing steel to the tension face. If there is only one bar or wire nearest the extreme tension face, s used in Eq. (10-4) is the width of the extreme tension face.

Calculated stress f_s in reinforcement closest to the tension face at service load shall be computed based on the unfactored moment. It shall be permitted to take f_s as $^2/_3 f_y$.

10.9.3 Volumetric spiral reinforcement ratio ρ_s shall be not less than the value given by

$$\rho_s = 0.45\left(\frac{A_g}{A_{ch}} - 1\right)\frac{f_c'}{f_{yt}} \qquad (10\text{-}5)$$

where the value of f_{yt} used in Eq. (10-5) shall not exceed 100,000 psi. For f_{yt} greater than 60,000 psi, lap splices according to 7.10.4.5(a) shall not be used.

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10.4.1 *The spans of non-load-bearing and load-bearing spandrels on parking structures have frequently exceeded 50 times the width of the top of the member and no problems have been observed. Lateral supports are provided to these spandrel beams by connection to the floor diaphragm near mid-depth of the section to address the effects of lateral stability, lateral impact loads, and the orientation of the spandrel beam principal axis for non-rectangular sections. The practical spacing of these connections is usually much less than the limit imposed by this section.*

10.6.4 *Note that Section 10.6 is specifically excluded for prestressed concrete (Section 18.1.3), except as specified in 18.4.4. (Reference* PCI Design Handbook*, Section 5.2.2.1)*

10.9.3 *See discussion of Sections 7.10.4 and 18.11.2.2.*

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10.10 Slenderness Effects in Compression Members

10.10.1 Except as allowed in 10.10.2, the design of compression members, restraining beams, and other supporting members shall be based on the factored forces and moments from a second-order analysis considering material nonlinearity and cracking, as well as the effects of member curvature and lateral drift, duration of the loads, shrinkage and creep, and interaction with the supporting foundation. The dimensions of each member cross section used in the analysis shall be within 10% of the dimensions of the members shown on the design drawings or the analysis shall be repeated. The analysis procedure shall have been shown to result in prediction of strength in substantial agreement with the results of comprehensive tests of columns in statically indeterminate reinforced concrete structures.

10.10.2 As an alternate to the procedure prescribed in 10.10.1, it shall be permitted to base the design of compression members, restraining beams, and other supporting members on axial forces and moments from the analyses described in 10.11.

CHAPTER 11 SHEAR AND TORSION

11.1.3.2 For prestressed members, sections located less than a distance $h/2$ from face of support shall be permitted to be designed for the same shear V_u as that computed at a distance $h/2$.

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10.10 *The* PCI Design Handbook*, Chapter 5, addresses the application of this section to precast and prestressed concrete columns. (Reference* PCI Design Handbook*, Section 5.9)*

10.10.2 *The moment magnifier method is not recommended for prestressed concrete compression members.*

11.1.3.2 *In beams with loads applied near the bottom, such as L-beams or inverted tees,* h *is taken as the depth of the ledge for shear calculations, but not necessarily for torsion. (Reference* PCI Design Handbook*, Section 5.3)*

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11.5.6 Minimum shear reinforcement

11.5.6.1 A minimum area of shear reinforcement, $A_{v,min}$, shall be provided in all reinforced concrete flexural members (prestressed and non-prestressed) where factored shear force V_u exceeds $0.5\phi V_c$, except:

(a) slabs and footings;

(b) concrete joist construction defined by 8.11; and

(c) beams with h not greater than the largest of 10 in., 2.5 times thickness of flange, or 0.5 the width of web.

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11.5.6 *If* V_u *is less than* ϕV_c *at the end region of prestressed double-tees not subjected to point loads, shear reinforcement may be omitted with a nominal minimum provided for 5 ft to 10 ft from the ends. This is based on research by Alex Aswad and George Burnley, "Omission of Web Reinforcement in Prestressed Double Tees."[20] The approach is permitted by Section 11.5.6.2. A reduction in the* ϕ*-factor in flexure may be warranted when* P_o/A *levels are low. See recommendations by Aswad, et al, "Load Testing of Prestressed Concrete Double Tees without Web Reinforcement."[21] Since the effective shear performance of the tee stems at the ends is dependent on the prestressing, this exception should only be used when the strand bond has been qualified as meeting ACI transfer and development-length provisions. (Reference* PCI Design Handbook*, Sections 5.3 and 5.3.4)*

Prestressed hollow-core and flat slab units fall under (a) slabs and footings, and require no shear reinforcement, provided $V_u \le \phi V_c$*. R11.5.6.1 indicates that deeper hollow-core sections may have reduced web shear strength. ACI 318-05 does not require minimum area of shear reinforcement* $A_{v,min}$ *in hollow-core units where the untopped depth is not greater than 12.5 in. or where* V_u *is not greater than* $0.5\phi V_{cw}$.

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11.6 Design for Torsion

Design for torsion shall be in accordance with 11.6.1 through 11.6.6, or 11.6.7.

11.6 *Torsion design has typically been done using the Zia-McGee method (*PCI Design Handbook *second edition[22]) or Zia-Hsu method (fourth edition[23]). See also Zia-Hsu article, "Design for Torsion and Shear in Prestressed Concrete Flexural Members."[24] The thin-walled tube model, which has been in ACI 318 since 1995, typically requires significantly greater reinforcement than the previous methods in, for example, spandrel beams in parking structures. Based on performance of beams designed by the previous methods, this additional reinforcement is unnecessary and uneconomical, and most precast concrete engineers are using the methods indicated previously in this section, which is in full compliance with Section 11.6.7. The Zia-Hsu method usually is more economical for spandrel beams with large aspect ratios, but still may result in conservative designs. (Reference* PCI Design Handbook*, Section 5.4), and see paper by Lucier, et al, "Precast Concrete, L-Shaped Spandrels Revisited: Full-Scale Tests."[25] Research is available and underway to address the design of beams with large aspect ratios for eccentric loading in a more comprehensive and more cost-effective manner.*

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11.7 Shear-friction

11.7.3 A crack shall be assumed to occur along the shear plane considered. The required area of shear-friction reinforcement A_{vf} across the shear plane shall be designed using either 11.7.4 or any other shear-transfer design methods that result in prediction of strength in substantial agreement with results of comprehensive tests.

11.7.3 *The effective shear-friction method described in the* PCI Design Handbook *is most often used. Use is permitted under Section 11.7.3. (Reference* PCI Design Handbook, *Section 5.3.6)*

11.7.7 Net tension across shear plane shall be resisted by additional reinforcement. Permanent net compression across shear plane shall be permitted to be taken as additive to the force in the shear-friction reinforcement $A_{vf}f_y$ when calculating required A_{vf}.

11.7.7 *At shear-wall bases, for example, the sustained dead load on the wall (including the weight of the wall) is added to the force developed in the bars across the shear plane. The minimum positive anchorage requirements of Chapter 16 still apply.*

11.9.1 Brackets and corbels with a shear span-to-depth ratio a_v/d less than 2 shall be permitted to be designed using appendix A. Design shall be permitted using 11.9.3 and 11.9.4 for brackets and corbels with:

(a) a_v/d not greater than 1; and

(b) subject to horizontal tensile force for N_{uc} not larger than V_u.

The requirements of 11.9.2, 11.9.3.2.1, 11.9.3.2.2, 11.9.5, 11.9.6, and 11.9.7 shall apply to design of brackets and corbels. Effective depth d shall be determined at the face of the support.

11.9.1 *Section 5.9.4 of the* PCI Design Handbook *describes a method of corbel design that has been used successfully. It is consistent with the strut-and-tie method of Appendix A permitted by this section.*

11.9.3.2 Design of shear-friction reinforcement A_{vf} to resist shear V_u shall be in accordance with 11.7.

11.9.3.2.1 For normalweight concrete, V_n shall not be taken greater than the smaller of $0.2f'_c b_w d$ and $800 b_w d$.

11.9.3.2.1 *The* PCI Design Handbook *allows* V_n *up to 1000*$b_w d$. *This is consistent with the effective shear-friction approach when concrete strengths of 5000 psi and greater are used. (Reference* PCI Design Handbook, *Table 5.3.6.1)*

11.9.3.2.2 For all-lightweight or sand-lightweight concrete, V_n shall not be taken greater than the smaller of $(0.2 - 0.07a_v/d)\ f'_c b_w d$ and $(800 - 280a_v/d)\ b_w d$.

11.9.3.2.2 *It is worth noting that equations given here for lightweight concrete are more conservative in relation to normalweight concrete than the use of the λ factor in the effective shear-friction coefficient applied to the expressions of Section 11.9.3.2.1.*

11.9.3.4 Reinforcement A_n to resist tensile force N_{uc} shall be determined from $\phi A_n f_y \geq N_{uc}$. Factored tensile force N_{uc} shall not be taken less than $0.2V_u$ unless special provisions are made to avoid tensile forces. N_{uc} shall be regarded as a live load even if tension results from restraint of creep, shrinkage, or temperature change.

11.9.3.4 *Bearing pads are used to avoid tensile forces. The* PCI Design Handbook *suggests that a value of* N_{uc} *that will cause the pad to slip is the maximum that can occur, or, alternatively, a value of 0.2 times the shear attributable to the factored dead load is used as a guide. (Reference* PCI Design Handbook, *Chapter 6)*

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11.9.6 At front face of bracket or corbel, primary tension reinforcement shall be anchored by one of the following:

(a) By a structural weld to a transverse bar of at least equal size; weld to be designed to develop f_y of primary tension reinforcement;

(b) By bending primary tension reinforcement back to form a horizontal loop; or

(c) By some other means of positive anchorage.

PCI PRACTICE

11.9.6 *Frequently, front-face anchorage is ensured by welding to an angle or a plate with vertical anchors. This is permitted by Section 11.9.6(c).*

11.9.7 Bearing area on bracket or corbel shall not project beyond straight portion of primary tension reinforcement, nor project beyond interior face of transverse anchor bar (if one is provided).

11.9.7 *If primary tension bars are anchored by welding (Section 11.9.6), the bearing area can be considered to extend to the exterior face of the anchoring bar or plate. This section is not typically applied to beam ledges where ledge reinforcement is typically anchored by bending bars near the front face. Research sponsored by PCI and Development Project No. 5, "Design of Spandrel Beams,"[26] addressed this issue and found that placement of bars is critical.*

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11.10.8 Where V_u is less than $0.5\phi V_c$, reinforcement shall be provided in accordance with 11.10.9 or in accordance with Chapter 14. Where V_u exceeds $0.5\phi V_c$, wall reinforcement for resisting shear shall be provided in accordance with 11.10.9.

11.10.8 *For precast concrete walls, the reference should be to Section 16.4.2 rather than to Chapter 14.*

11.10.9 Design of shear reinforcement for walls

11.10.9.1 Where V_u exceeds ϕV_c, horizontal shear reinforcement shall be provided to satisfy Eq. (11-1) and (11-2), where V_s shall be computed by

$$V_s = \frac{A_v f_y d}{s} \tag{11-31}$$

where A_v is area of horizontal shear reinforcement within spacing s, and d is determined in accordance with 11.10.4. Vertical shear reinforcement shall be provided in accordance with 11.10.9.4.

11.10.9 *Section 11.10.9 applies only when the in-plane shear* $V_u > 0.5\phi V_c$ *as described in Section 11.10.8. Otherwise, minimum reinforcement required by Section 16.4 for precast concrete walls applies (0.001 times the gross cross-sectional area in the case of Section 16.4.2). Where* $V_u > 0.5\phi V_c$ *and* $V_u < \phi V_c$*, the reinforcement ratios and spacing limitations set forth in Section 11.10.9.2 through 11.10.9.5 must be satisfied. In situations where* $V_u > \phi V_c$*, Section 11.10.9.1 must be satisfied as well.*

CHAPTER 12 – DEVELOPMENT AND SPLICES OF REINFORCEMENT

12.5 Development of Standard Hooks in Tension

12.5.1 Development length for deformed bars in tension terminating in a standard hook (see 7.1) ℓ_{dh} shall be determined from 12.5.2 and the applicable modification factors of 12.5.3, but ℓ_{dh} shall not be less than the larger of $8d_b$, nor less than 6 in.

12.5.1 *Reinforcing ties in beam ledges are assumed to be developed with a hook, even when the straight portion measured from the end of the hook to the face of the beam web is less than 6 in., measured to the stem face. See the research project listed as Reference 11-53 in ACI 318-05.*

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12.11.1 At least one-third the positive moment reinforcement in simple members and one-fourth the positive moment reinforcement in continuous members shall extend along the same face of member into the support. In beams, such reinforcement shall extend into the support at least 6 in.	***12.11.1*** *Does not apply to precast concrete construction. Excluded by Section 16.6.2.3.*
12.13.2.4 For each end of a single leg stirrup of welded-wire reinforcement, two longitudinal wires at a minimum spacing of 2 in. and with the inner wire at least the greater of $d/4$ or 2 in. from $d/2$. Outer longitudinal wire at tension face shall not be farther from the face than the portion of primary flexural reinforcement closest to the face.	***12.13.2.4*** *Figure R12.13.2.4 shows how welded-wire reinforcement is used as shear reinforcement in double-tee stems. For further information, see the Joint PCI/WRI Ad Hoc Committee on Welded Wire Fabric for Shear Reinforcement report, "Welded Wire Fabric for Shear Reinforcement."*[27]

CHAPTER 13 – TWO-WAY SLAB SYSTEMS

13.2.4 For monolithic or fully composite construction, a beam includes that portion of slab on each side of the beam extending a distance equal to the projection of the beam above or below the slab, whichever is greater, but not greater than four times the slab thickness.	***13.2.4*** *Section 18.1.3 states that Chapter 13 does not apply to prestressed concrete. Commentary R18.1.3 states that the effective flange width is left to the experience and judgment of the engineer. See Section 8.10.2 for more information.*

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CHAPTER 14 – WALLS

14.3 Minimum Reinforcement	***14.3*** *Minimum reinforcement for precast concrete walls is specified in Sections 16.4.1 and 16.4.2. Section 18.11.2.3 states that Section 14.3 does not apply for walls with effective prestress force equal to or greater than 225 psi where structural analysis shows adequate strength and stability.*
14.6.1 Thickness of nonbearing walls shall not be less than 4 in., nor less than $^1/_{30}$ the least distance between members that provide lateral support.	***14.6.1*** *Minimum thickness is not applicable to prestressed walls. See Section 18.1.3.*

CHAPTER 15 – FOOTINGS

15.8.3.1 Connection between precast concrete columns or pedestals and supporting members shall meet the requirements of 16.5.1.3(a).	***15.8.3.1*** *Note reference to Chapter 16.*

CHAPTER 16 – PRECAST CONCRETE

16.2.4 In addition to the requirements for drawings and specifications in 1.2, (a) and (b) shall be included in either the contract documents or shop drawings: (a) Details of reinforcement, inserts, and lifting devices required to resist temporary loads from handling, storage, transportation, and erection; and (b) Required concrete strength at stated ages or stages of construction.	***16.2.4*** *Connection design is typically a part of the precast concrete contract, and connection forces are typically developed by the precast concrete engineer, or sometimes listed by the Engineer of Record on the contract drawings. It is common practice for stripping, handling, and design criteria to be documented in the design calculations prepared by the precast engineer. (Reference* PCI Design Handbook, *Sections 14.4 and 14.5)*

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16.5.1.3 Vertical tension tie requirements of 7.13.3 shall apply to all vertical structural members, except cladding, and shall be achieved by providing connections at horizontal joints in accordance with (a) through (c):

(a) Precast concrete columns shall have a nominal strength in tension not less than $200A_g$, in pounds. For columns with a larger cross section than required by consideration of loading, a reduced effective area A_g, based on cross section required but not less than one-half the total area, shall be permitted.

(b) Precast concrete wall panels shall have a minimum of two ties per panel, with a nominal tensile strength not less than 10,000 lb per tie.

(c) When design forces result in no tension at the base, the ties required by 16.5.1.3(b) shall be permitted to be anchored into an appropriately reinforced concrete floor slab on grade.

PCI PRACTICE

16.5.1.3(b) *Some panels may be too narrow to accommodate two connections. The engineer may determine that the behavior of such members justifies classifying the panel as cladding (cladding is exempt from the requirements of this section).*

This section applies to structures composed of many elements that must be tied together. Structures that use modules, or boxes, will require different details to ensure integrity. (Reference PCI Design Handbook, Section 4.3.2, note 5).

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16.5.1.4 Connection details that rely solely on friction caused by gravity loads shall not be used.

16.5.1.4 *Connections designed in accordance with the shear-friction provisions of Section 11.7 are in compliance with this section. See Section 11.7.7 for more information.*

16.6.2.2 Unless shown by test or analysis that performance will not be impaired, (a) and (b) shall be met:

(a) Each member and its supporting system shall have design dimensions selected so that, after consideration of tolerances, the distance from the edge of the support to the end of the precast concrete member in the direction of the span is at least $\ell_n/180$, but not less than:

For solid or hollow-core slabs....................2 in.

For beams or stemmed members...............3 in.

(b) Bearing pads at unarmored edges shall be set back a minimum of $^1/_2$ in. from the face of the support, or at least the chamfer dimension at chamfered edges.

16.6.2.2 *When shorter bearing lengths occur in the field, analysis by the precast engineer for the approval by the Engineer of Record is usually the basis for acceptability. When designing bearing lengths, the effects of member shortening and movement at expansion joints should be considered.*

16.6.2.3 The requirements of 12.11.1 shall not apply to the positive bending-moment reinforcement for statically determinate precast concrete members, but at least one-third of such reinforcement shall extend to the center of the bearing length, taking into account permitted tolerances in 7.5.2.2 and 16.2.3.

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CHAPTER 17 – COMPOSITE CONCRETE FLEXURAL MEMBERS

17.5.3.1 Where contact surfaces are clean, free of laitance, and intentionally roughened, V_{nh} shall not be taken greater than $80b_vd$.

17.5.3.3 When ties are provided in accordance with 17.6, and contact surfaces are clean, free of laitance, and intentionally roughened to a full amplitude of approximately $^1/_4$ in., V_{nh} shall be taken equal to $(260 + 0.6\rho_v f_y)\lambda b_v d$, but not greater than $500b_vd$. Values for λ in 11.7.4.3 shall apply and ρ_v is $A_v/(b_vs)$.

17.6.3 All ties shall be fully anchored into interconnected elements in accordance with 12.13.

CHAPTER 18 – PRESTRESSED CONCRETE

18.3.3 Prestressed flexural members shall be classified as Class U, Class T, or Class C based on f_t, the computed extreme fiber stress in tension in the precompressed tensile zone calculated at service loads, as follows:

(a) Class U: $f_t \le 7.5\sqrt{f_c'}$;

(b) Class T: $7.5\sqrt{f_c'} < f_t \le 12\sqrt{f_c'}$

(c) Class C: $f_t > 12\sqrt{f_c'}$

Prestressed, two-way slab systems shall be designed as Class U with $f_t \le 6\sqrt{f_c'}$.

PCI PRACTICE

17.5.3.1 *The 80*b_vd *horizontal shear-strength level can be obtained by many finishes that appear smooth when compared with the roughness required in 17.5.3.3. Examples include floated, light-broomed, or machine extruded surfaces. (Reference* PCI Design Handbook*, Section 5.3.5) Because the strength of the interface in this case is developed by cementitious bond, proper preparation of the surface is of utmost importance.*

17.5.3.3 *The surface should not be so rough as to allow bridging of the cast-in-place coarse aggregate and the formation of voids at the interface. The most important element is the statement "clean, free of laitance."*

17.6.3 *Ties for horizontal shear in precast concrete members are typically U-shaped reinforcing bars that are embedded after the member has been cast and the top surface has been intentionally roughened and finished. The anchorage of the tie in the precast concrete member is achieved by embedding the bar for the required development length without hooks. See also R16.7.1.*

Anchorage of hooked or bent ties in cast-in-place topping is considered adequate if a minimum distance of 2 $^1/_4$, 2 $^3/_4$, and 3 $^1/_4$ in. is provided between the shear transfer interface and the outside ends of standard hooks or U-bends of #3, #4, and #5 ties, respectively, based on research cited in PCI Design Handbook*, Section 5.3.5.*

18.3.3 Table R18.3.3 *clearly defines the differences between Class U (uncracked), Class T (transition), and Class C (cracked) prestressed concrete members. Most members are designed as Class U or T, and, thus, the design procedures are essentially unchanged from previous editions of the code. For special cases, a member may be designed as Class C, but more attention must be paid to performance using the provisions of 18.3.4 and 9.5.4. Chapter 5 of the* PCI Design Handbook *provides examples of detailed transformed cracked section analysis.*

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R18.4.1(b) and (c) Where tensile stresses exceed the permissible values, the total force in the tensile stress zone may be calculated, and reinforcement proportioned on the basis of this force at a stress of $0.6f_y$ but not more than 30,000 psi.

18.4.1 Stresses in concrete immediately after prestress transfer (before time-dependent prestress losses) shall not exceed the following:

(a) Extreme fiber stress in compression. $0.60\,f'_{ci}$

(b) Extreme fiber stress in tension except as permitted in (c)

$3\sqrt{f'_{ci}}$

(c) Extreme fiber stress in tension at ends of simply supported members

$6\sqrt{f'_{ci}}$

Where computed tensile stresses f_t exceed the limits in (b) or (c), additional bonded reinforcement (nonprestressed or prestressed) shall be provided in the tensile zone to resist the total tensile force in concrete computed with the assumption of an uncracked section.

18.4.4 For Class C prestressed flexural members not subject to fatigue or to aggressive exposure, the spacing of bonded reinforcement nearest the extreme tension face shall not exceed that given by 10.6.4.

For structures subject to fatigue or exposed to corrosive environments, special investigations and precautions are required.

18.4.4.1 The spacing requirements shall be met by nonprestressed reinforcement and bonded tendons. The spacing of bonded tendons shall not exceed $^2/_3$ of the maximum spacing permitted for nonprestressed reinforcement.

Where both reinforcement and bonded tendons are used to meet the spacing requirement, the spacing between a bar and a tendon shall not exceed $^5/_6$ of that permitted by 10.6.4. See also Section 18.4.4.3.

18.4.4.3 In applying Eq. (10-4) to prestressing tendons, the magnitude of Δf_{ps} shall not exceed 36,000 psi. When Δf_{ps} is less than or equal to 20,000 psi, the spacing requirements of 18.4.4.1 and 18.4.4.2 shall not apply.

PCI PRACTICE

R18.4.1(b) and (c) *Where beam tops are in tension at transfer of prestress forces, but are in compression under service load, and are not exposed to weather, the large amounts of steel indicated by this commentary item is excessive. Experience has shown that nominal top reinforcing bars or prestressing strand will adequately control temporary top cracking. Use of* f_y *(up to 60,000 psi) for the steel stress has been shown to be adequate. Bars must be detailed (for example, hooks, C-bars, U-bars) to ensure development in the top tensile region.*

18.4.1 *Recent research[28] has shown that the compression limitations at transfer are more conservative than necessary and have an effect on economy and safety due to the potential need for debonding or depressing prestressing strands.. It has been common practice to allow compression up to* $0.70f'_{ci}$. *Utilizing a compression limit of* $0.70f'_{ci}$ *at the ends of simply supported members is in full compliance with ACI 318-08. For beams, it has been common practice to allow tension limit* $6\sqrt{f'_c}$ *throughout their length since service load compression in the top is higher at midspan. Even when tension limits are not exceeded, it is recommended that nominal reinforcement (at least two #4 or nominally tensioned strands) be provided in tops of beams.*

18.4.4 *This section refers to maximum spacing requirements by applying Eq. (10-4) to prestressed concrete:*

$$s = 15\left(\frac{40{,}000}{f_s}\right) - 2.5c_c$$

where s *is the maximum spacing and* c_c *is the clear cover to the reinforcement nearest the tension face. Note that these requirements are for Class C members only (that is, those in which the concrete tension under service loads exceeds* $12\sqrt{f'_c}$ *). In checking this requirement, first check Section 18.4.4.3. If the spacing requirements can be met by substituting 36,000 psi for* f_s *in Eq. (10-4), no further check is necessary. If not, check to verify that* Δf_{ps} *is less than 20,000 psi (which will often be the case). If so, no further check is necessary.*

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18.6 Loss of Prestress

18.6.1 To determine effective stress in the prestressing steel f_{se}, allowance for the following sources of loss of prestress shall be considered:

(a) Prestressing steel seating at transfer;

(b) Elastic shortening of concrete;

(c) Creep of concrete;

(d) Shrinkage of concrete;

(e) Relaxation of prestressing steel stress; and

(f) Friction loss due to intended or unintended curvature in post-tensioning tendons.

PCI PRACTICE

18.6 *Most structural engineers who specialize in the design of prestressed concrete follow the recommendations of ACI-ASCE Committee 423 task force given in Reference 18.6, which is in compliance with the code. (Reference* PCI Design Handbook*, Section 5.7)*

18.7.2 As an alternative to a more accurate determination of f_{ps} based on strain compatibility, the following approximate values of f_{ps} shall be permitted to be used if f_{se} is not less than $0.5f_{pu}$.

(a) For members with bonded tendons:

$$f_{ps} = f_{pu}\left\{1 - \frac{\gamma_p}{\beta_1}\left[\rho_p \frac{f_{pu}}{f_c'} + \frac{d}{d_p}(\omega - \omega')\right]\right\} \qquad (18\text{-}3)$$

Where ω is $\rho f_y/f_c'$, ω' is $\rho' f_y/f_c'$, and γ_p is 0.55 for f_{py}/f_{pu} not less than 0.80; 0.40 for f_{py}/f_{pu} not less than 0.85; and 0.28 for f_{py}/f_{pu} not less than 0.90.

If any compression reinforcement is taken into account when calculating f_{ps} by Eq. (18-3), the term

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

shall be taken not less than 0.17 and d' shall be no greater than $0.15d_p$.

18.7.2 *Many engineers and most computer programs use strain compatibility analysis for determining* f_{ps}*, which is a more accurate determination as indicated in R18.7.2. Others use Eq. (18-3). With low-relaxation strand, the results are not substantially different. (Reference* PCI Design Handbook*, Section 5.2.1)*

18.8.2 Total amount of prestressed and non-prestressed reinforcement shall be adequate to develop a factored load at least 1.2 times the cracking load computed on the basis of the modulus of rupture f_r, specified in 9.5.2.3. This provision shall be permitted to be waived for:

(a) Two-way, unbonded post-tensioned slabs; and

(b) Flexural members with shear and flexural strength at least twice that required by 9.2.

18.8.2 *This provision only applies at critical flexural sections where cracking will first occur. (Reference* PCI Design Handbook*, Section 5.2.1.) This provision is intended as a precaution against abrupt flexural failure immediately after cracking. Cracking and the subsequent considerable deflection prior to the fracture of the prestressed reinforcement are the desired distress indicators that will be apparent.*

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18.11.2 Limits for reinforcement of prestressed compression members

18.11.2.1 Members with average compressive stress in concrete due to effective prestress force only less than 225 psi shall have minimum reinforcement in accordance with 7.10, 10.9.1, and 10.9.2 for columns, or 14.3 for walls.

18.11.2.2 Except for walls, members with average compressive stress in concrete due to effective prestress force only equal to or greater than 225 psi shall have all tendons enclosed by spirals or lateral ties in accordance with (a) through (d):

(a) Spirals shall conform to 7.10.4;

(b) Lateral ties shall be at least #3 in size or welded-wire reinforcement of equivalent area, and shall be spaced vertically not to exceed 48 tie bar or wire diameters, or the least dimension of the compression member;

(c) Ties shall be located vertically not more than half of a tie spacing above top of footing or slab in any story, and not more than half a tie spacing below the lowest horizontal reinforcement in members supported above;

(d) Where beams or brackets frame into all sides of a column, ties shall be terminated not more than 3 in. below lowest reinforcement in such beams or brackets.

PCI PRACTICE

18.11.2.1 *Columns which, for architectural or other reasons, are larger than necessary to carry the applied loads will use the level of prestress for the size of column needed. For example, if a 16 in. × 16 in. column will carry the load, but a 24 in. × 24 in. column is used, the total prestress force necessary is 225(16 × 16) = 57,600 lb. This practice is supported by Sections 10.8.4 and 16.5.1.3(a).*

18.11.2.2 *Columns that are prestressed to the effective average prestress of 225 psi are not subject to longitudinal reinforcement buckling and have been shown not to require ties or spirals by research and practice. Where prestressed columns gain additional strength by the addition of longitudinal, nonprestressed reinforcement, where high moments may occur at joints or connections, and where the column may be subject to high shear forces, ties or spirals should be provided.*

Note that walls are excluded from the lateral tie requirements.

CHAPTER 21 – SPECIAL PROVISIONS FOR SEISMIC DESIGN

Chapter 4 of the PCI Design Handbook*, PCI's* Seismic Design of Precast/Prestressed Concrete Structures *(MNL-140-07),*[29] *and other publications and research reports are available to assist the designer in the design of precast concrete structures in seismic areas.*

1 APPENDIX A – STRUT-AND-TIE MODELS

Strut-and-tie modeling may have many applications in precast concrete construction, including corbels and dapped ends of beams. The design procedures for these elements given in the PCI Design Handbook *have certain limits of applicability, and strut-and-tie methods may be used for cases that fall outside these limits.*

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2 APPENDIX D – ANCHORING TO CONCRETE

D4.2 The nominal strength for any anchor or group of anchors shall be based on design models that result in predictions of strength in substantial agreement with results of comprehensive tests. The materials used in the tests shall be compatible with the materials used in the structure. The nominal strength shall be based on the 5% fractile of the basic individual anchor strength. For nominal strengths related to concrete strength, modifications for size effects, the number of anchors, the effects of close spacing of anchors, proximity to edges, depth of the concrete member, eccentric loadings of anchor groups, and presence or absence of cracking shall be taken into account. Limits on edge distances and anchor spacing in the design models shall be consistent with the tests that verified the model.

PCI PRACTICE

The PCI Design Handbook *and the* PCI Connections Manual[30] *have given design recommendations for connections that use welded headed studs and other anchorage devices for many years. Connections designed by these recommendations have performed satisfactorily.*

D4.2 *PCI has sponsored tests of stud assemblies that meet these requirements and result in design criteria that are in full compliance with the requirements of this appendix. For further information on this topic, see* PCI Design Handbook, *Section 6.5, and "Design Criteria for Headed Stud Groups in Shear: Part 1 – Steel Capacity and Back Edge Effects."*[31]